THE MANAGEMENT OF RELIABILITY IN A MULTI-LEVEL SUPPORT ENVIRONMENT

BY

ARIE WESSELS

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RELIABILITY MANAGEMENT
IN A
MULTI-LEVEL SUPPORT ENVIRONMENT

ABSTRACT

In this thesis aspects of reliability management in a multi-level support environment are researched.

Complex systems are generally supported over a number of support levels due to the specialist nature and support infrastructure requirements of the individual subsystems. Such a support approach also ensures optimum availability of the system whilst the subsystems are still in the repair cycle. Once a new system is put into service, it is exposed to the actual operational environment and not the simulated environment that was used to qualify the system during its development. In the operational environment, the system is also exposed to the support infrastructure. These factors, as well as any latent design and production defects, impair the achieved operational reliability of such a system. False removals and premature failures after a repair action further degrade the actual operational reliability of the system.

It is generally not possible to qualify the logistic support infrastructure fully before placing a new system into operational service. Support stabilisation should take place early on in the support phase of such a system to correct all latent defects and deficiencies of any of the logistic elements required to support the system. Any latent design and production process defects not eradicated from the system will also surface during the support stabilisation period. Support stabilisation will ensure a constant failure rate for the operational life of the system at the lowest life-cycle cost.

The methodology used to achieve system reliability growth during the support phase is similar to reliability growth during the development phase. However, additional variables of the operational and support environment are now included in the reliability growth process. The process is also further compounded by the geographic separation of the different levels of support each generally with their own support management infrastructure.

The proposed approach is:

- get total management commitment and close the management loop over the different levels of support.
- establish the root cause of every system failure
- implement a test, analyse and fix policy
- eliminate ineffective repair actions
- ensure that the system operational environment is within the system specification
- remove latent design defects from the system
- correct deficiencies in the logistic elements.

BETROUBAARHEIDSBESTUUR
IN 'n
MULTI-VLAK STEUN OMGEWING

OPSOMMING

In hierdie verhandeling word enkele aspekte van betroubaarheidsbestuur in 'n multivlak steunomgewing nagevors.

Komplekse sisteme word oor die algemeen gesteun oor 'n aantal steunvlakke as gevolg van die gespesialiseerde aard van die steuninfrastruktuurvereistes van die onderskeie substelsels. So 'n steunbenadering sal voorts optimale beskikbaarheid van die stelsel verseker terwyl die substelsels nog in die herstelsiklus is. Sodra 'n nuwe stelsel in diens gestel word, word dit blootgestel aan die werklike operasionele omgewing en nie die gesimuleerde omgewing wat gebruik was tydens die ontwikkeling en kwalifikasie van die stelsel nie. Tydens die operasionele omgewing, word die stelsel ook blootgestel aan die steuninfrastruktuur. Hierdie faktore sowel as enige latente ontwerps- en produksieprosesdefekte benadeel die bereikte operasionele betroubaarheid van so 'n stelsel. Verkeerdelike substelselruilings asook voortydige falings na 'n herstelaksie versleg die betroubaarheid van die werklike operasionele stelsel verder.

Dit is in die algemeen nie moontlik om die logistieke infrastruktuur te kwalifiseer alvorens 'n nuwe stelsel nie in bedryf gestel word nie. Steunstabilisasie behoort vroeg in die steunfase plaas te vind om alle latente defekte en tekortkomings van enige van die logistieke elemente wat gebruik word om die stelsel te steun, reg te stel. Enige latente ontwerp- en produksieprosesdefekte wat nie uit die stelsel verwyder is nie sal nou ook tydens die steunstabilasie na vore kom. Steunstabilisasie sal verseker dat 'n konstante falingstempo vir die operasionele lewe van die stelsel teen die laagste lewensikluskoste, gehandhaaf kan word.

Die metodiek wat gebruik word om betroubaarheidsgroei tydens die steunfase te behaal, is soortgelyk aan die betroubaarheidsgroei tydens die ontwikkelingsfase. Addisionele veranderlikes van die steunomgewing word nou egter ook in die betroubaarheidsgroeiproses ingesluit. Die proses word verder gekompliseer deur die geografiese verspreiding van die verskillende vlakke van steun, ieder met sy eiesoortige bestuursinfrastruktuur.

Die aanbevole benadering is:

- verkry algehele bestuursverbintenis en vestig 'n geslotekring bestuurstelsel oor die verskillende steunvlakke
- bepaal die kern oorsaak van elke stelsel defek
- implementeer 'n toets, ontleding- en korrektiewe aksiebeleid
- skakel alle oneffektiewe herstelaksies uit
- verseker dat die stelsel binne stelselspesifikasie bedryf word
- skakel latente ontwerpstekortkominge uit die stelsel
- korrigeer tekortkominge van die logistieke elemente.

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RELIABILITY MANAGEMENT
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PART I

SYNOPSIS

1. INTRODUCTION

Reliability as a management tool in the support phase of a system and the application of reliability management techniques to optimise life-cycle cost and solutions to support problems are introduced in this research work.

In part II, a literature survey detailing the findings, applications and development of system reliability are evaluated.

In part III, logistic engineering in a reliability context is discussed.

In part IV, a case study detailing the reliability turn around of a complex electronic system that suffered rapid reliability degradation soon after introduction into service, is provided.

2. PURPOSE

The purpose of this research work is to provide the tools and techniques necessary to achieve more optimal availability at the lowest life-cycle cost when managing the reliability performance of a system during the support phase.

In particular, emphasis will be placed on reliability measurement in a generalised multi-level support environment.

The management of reliability during the support phase of a system is generally more complex than during the development phase. The main reasons for the increased complexity are:

- impact of the operational and logistical support elements on the system reliability
- complex systems are generally supported over a number of levels of support which are normally geographically separated, complicating reliability data collection, (Pohlenz [4]).

2.1 SCOPE AND OBJECTIVES

The scope of this research work is to provide:

(i) an extensive literature overview in chronological order of the development of reliability engineering and management. This includes the development of theoretical modelling techniques and their applications in practice.

(ii) a detailed case study performed by the author demonstrating how reliability growth techniques together with sound management principles can be translated and applied to a complex system whose availability has deteriorated prematurely to unacceptable levels early in the system's support phase.

(iii) a guideline of the availability improvement process and a model on how system availability problems can be addressed and managed and life-cycle cost reduced, during the support phase.

It is envisaged that this research work will help users of complex systems in optimising their support management techniques and thereby reducing their system's life-cycle costs.

2.2 OVERVIEW

This research work covers an extensive literature overview on the topics of reliability theory and applications covering the status and growth of knowledge in chronological order from the pre-Duane [14] period to the present.

The literature searches have been extensive and after detailed analysis and careful selection, 60 references have been retained for discussion in this research work. Additional literature references have been provided in appendix D to provide the reader with further background to the subject.

The main focus of the literature in general is aimed at design influence and optimisation of the system during the development phase. Not much literature could be found covering reliability in the support phase of a system despite the fact that this phase covers the major part of a system's life cycle and contributes the largest portion to the total system's life-cycle cost.

There appears to be a shortage of literature on the subject of reliability theory and applications in the support environment and the impact of the logistic elements on the availability performance of a complex system. Only general broad statements on some of these aspects could be found in the literature - reference Lincoln [2], Koon [5] Patterson [11] and Malec [15]. This may lead to the erroneous impression that once a system has been developed, qualified, produced and delivered to the customer, its reliability will automatically follow an exponential failure rate distribution, provided the customer complies with the system supplier's prescribed maintenance servicing requirements and schedules.

Most proponents of system reliability subscribe to the bath-tub hazard function of complex systems with its three distinct phases namely:

(i) Reliability growth phase (during system development and production)

(ii) Constant failure rate during the useful life of the system (support phase).

(iii) Wear-out region when the system reaches end-of-life (phase out).

(Blanchard [59], O' Connor [50]).

Figure 2.2.1 shows the system hazard function as described by Ramakumar [51]

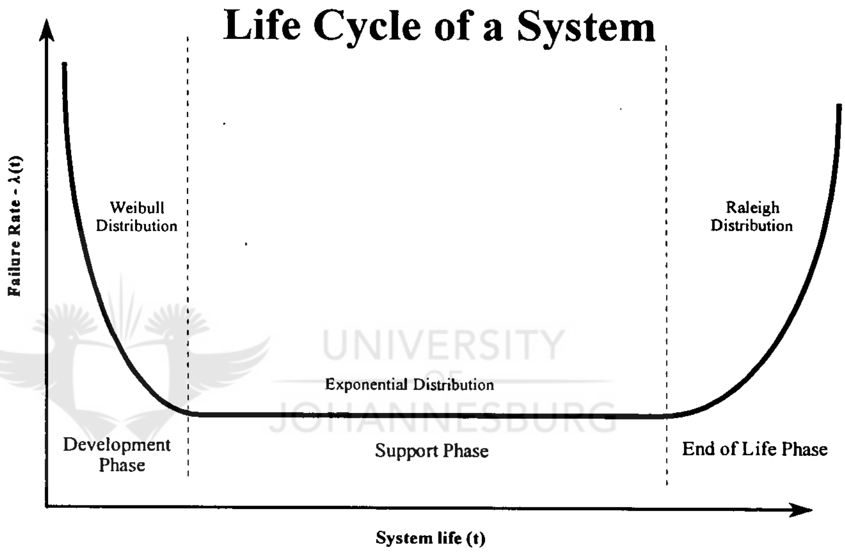


Figure 2.2.1: A typical system life cycle

The supporters of this function, with few exceptions, focus on reliability growth in the development and production phases of a system - reference Wright [7], Duane [14] and Barlow [52].

The literature only describes the effect of the end-of-life phase or wear-out region of the bath-tub hazard function and does not identify nor describe the mechanisms leading to this effect where the failure rate rapidly escalates until the system becomes uneconomical to support. Ramakumar [51] describes this stage in the system life cycle by means of a Raleigh distribution function.

Moltoft [20] analyses the effect of two failure modes on the reliability growth distribution function and sets out techniques for separating the different modes from the raw data.

The impression created that once reliability growth has been completed during the development phase, the system goes into a constant failure rate phase is only true if the system is comprehensively supported utilising all 12 logistic elements described in part IV. Wong [39] and [48] mentions that for complex electronic systems there are no such phenomena as constant failure rates. According to him, the system follows a *roller-coaster* failure trend throughout its operational life. This wavelike motion with decreasing failure rate deep into the system's operational life agrees with the author's experience with telecommunications and aircraft avionics systems.

During the system's development phase, environmental and support variables are controlled to ensure that the reliability improvement effort is directed at the inherent design integrity. The lack of latent system defects, be they of design origin or component weaknesses, alone will not ensure a reliable system.

The system once it is in the support phase, must be assessed in its macro environment to include the environmental, utilisation and support infrastructure for the assessment to be meaningful and objective.

The reliability growth techniques described in the literature and which is primarily aimed at application during the system development phase, has been adapted in this work to be applicable during the support phase by taking cognisance of operational and support environmental factors.

A system that reveals premature reliability degradation during the support phase can be effectively turned around to provide many years' operational service at acceptable reliability and life-cycle cost levels.

The application of these techniques and their success, are demonstrated in the case study in part IV where a complex system that is premature rapidly deteriorating reliability with a resultant escalation in life-cycle cost has been turned around to acceptable levels. Monitoring of this system for a period of five years after the recovery action, reveals a smooth declining trend in failure rate and life-cycle cost.

The reliability management techniques in the support phase, although similar to the original reliability growth programme during the development and production phases, has subtle differences such as the following:

- reliability growth must be performed on operational instead of development and production items.
- reliability growth must be managed over the different levels of support instead of in-house reliability management.
- operational and environmental factors must be incorporated into the reliability growth model.
- special management actions related to 'unproductive' failures are required.

The role and importance of failure data collection and the different data fields as well as their interpretation will be discussed. The failure data fields for effective management, must be grouped as follows:

- Reliability data fields
- Maintainability data fields
- Unproductive failure data fields such as:
    - unconfirmed failures (No Fault Found - NFF)
    - repeat failures (RF)
    - wrong diagnosis (Fault Confirmed, Not Related - FCNR)

This is followed by detailed analysis of the system engineering acquisition process, in particular, the reliability, availability and maintainability (RAM) elements and logistic elements. These elements must be evaluated against achieved operational performance.

3. PROBLEM STATEMENT

Availability problems are very often experienced during the support phase of a system. These problems are generally of the initial *teething* trouble (infant mortality) variety and are often of a relatively minor nature. These deficiencies (non conformance items) will normally be sorted out under warranty by the supplier.

The causes of these premature failures are primarily as a result of insufficiently achieved reliability growth during development and production phases of the system and subsequent premature release of the system, to the user (product immaturity).

Premature failures may also be the result of deficiencies in the utilisation of the system and support system. Support system failures often manifest themselves only some time after the warranty period has expired and generally fall outside the supplier's warranty coverage.

The effect of utilisation and support system deficiencies is a degradation of system availability and escalation of support costs.

The rate of degradation is not linear but follows a failure rate as a function of time similar to the end-of-life portion of the product/system life bath-tub curve. In other words, there appears to be an accelerated system ageing towards the end of its life under these circumstances.

The system becomes uneconomical to operate and very often impossible to support. Life-cycle cost escalates rapidly and availability takes a nose dive.

Generally, management and support personnel alike become rapidly disillusioned with such a system and tend to *write* the system off as a bad investment. They then start feasibility studies for the procurement of a replacement system without ever learning from the mistakes made during the acquisition of the original system.

The original supplier of the system, who is an important stake holder in this process, has virtually no control over his system once the warranty has expired, unless his continued involvement is covered by some form of support contract.

These problems often originate from deficiencies upstream in the acquisition process of the system and associated support infrastructures as well as poor operational practices and support management by the user.

Such a collapsed system can be recovered cost-effectively, provided a renewed reliability growth programme is implemented to bring the system back to acceptable reliability levels. In other words, a renewed bath-tub hazard function for the system is established as shown in figure 3.1.

Setting of priorities and sequences of corrective actions in such a reliability growth programme is of paramount importance in order to achieve success. The achievement of success with the remedial actions is complicated by the human factor element in that the different stakeholders (user/operator, different support level personnel and management) have lost trust in one another as well as faith in the system. The supplier on the other hand is generally geographically removed from the problem area and quite often as a result of the emotions is barred from direct access to the system.

The approach, techniques used and success achieved by the author will be demonstrated and verified by means of a real life case study complete with comprehensive history data and performance records.

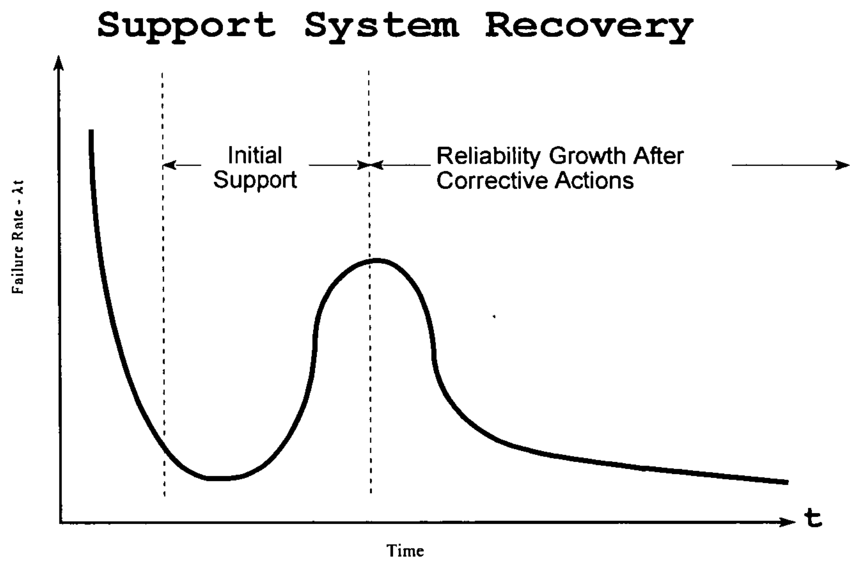


Figure 3.1: Support system reliability recovery

4. CONCLUSION

The applicability of reliability growth during the development phase to the support phase must be established. Also the additional factors to be taken into account must be determined.

The applicability of the bath-tub hazard function with constant failure rate during the support phase will be further researched in the next parts. Part II starts with a comprehensive literature survey from the early 1960's to date, covering reliability in the military and commercial environments. The survey is augmented from theoretical research papers published over the same period.

PART II

LITERATURE SURVEY

1. LITERATURE OVERVIEW

This section covers selected relevant system reliability literature published since the early 1960's to assess and evaluate the development of system reliability theory and practices as well as the applicability to the support phase of a system.

1.1 GENERAL

The literature covers primarily the reliability growth characteristics of systems under development and reliability performance during the early support phase. Malec [15], states that the reliability as seen from the manufacturer's point of view is different from the reliability perceived by the customer.

A concerted effort has been made during the literature survey to collect and collate as many different sources as possible. The bulk of the literature has been taken from American sources. From world-wide topic searches it is evident that the Americans are the world leaders in terms of the number of papers published. Halliday [3], states that United Kingdom development philosophy has moved for reasons of economy towards an integrated development test programme to ensure product reliability. The objective of the test programme is to rationalise all types of testing including performance, environmental and reliability testing. This methodology is particularly effective for once-off developments.

It appears that the European countries take a much more informal line on reliability management. Regarding the theory of reliability modelling and reliability growth predictions, they appear to be on par with their American counterparts. Reference Moltoft [20] and Limestadt [41].

In essence the USA approach to reliability and reliability management is much more formal than that of the UK and is in the main driven by the military sector. Reference Halliday [3] and O' Connor [50].

The literature search has been limited to publications in the English language only.

The literature can be divided into the following broad categories:

a. Theory

   - Text books
   - Technical papers

b. Military

  - Development (Military & Military Industry)
  - Operations
  - NASA and nuclear

c. Commercial Industry

  - Development
  - Operations

1.2 DISCUSSION OF RELIABILITY THEORY

Textbook references provide broad theory and practices, a solid foundation and background to engineering reliability and reliability management subjects.

Military handbooks and standards, will also be covered under this heading since they are in essence the equivalent of textbooks and are developed for the use of primarily military personnel.

1.2.1 DISCUSSION OF RELIABILITY THEORY TEXT BOOKS

Notation:

To assist the reader to obtain further information on specific aspects, whenever any of the references under this heading are referred to, the page number of the applicable section will also be quoted..

If the reference has more than one author, the specific author's name will then be quoted together with the compiler's name.

Mil-Hdbk-189, [27]

This is a comprehensive handbook on reliability growth management covering system reliability growth management and analysis aspects. It is intended as a guide for reliability managers and reliability analysts for both USA military personnel and contractors.

The handbook is structured into detailed tasks to facilitate the setting of priorities and allocation and re-allocation of resources such as funds and human resources.

This reference provides a comprehensive guide on the management of system reliability during the acquisition phase of a system. This knowledge can be fruitfully applied with adaptations to address reliability problems during a system's support phase as a result of reliability acquisition deficiencies.

Mil-Std-2155 [28]

This standard covers the following facets:

- Definitions of the closed loop corrective action process and associated terms.
- FRACAS planning
- Failure Review Board composition, responsibilities and functions
- The process of identifying and controlling of failed items
- The relationship between FMECA and FRACAS is that FMECA identifies the potential failure hazards whilst FRACAS identifies the actual operational failure performance of the system.

The standard provides the overall management guide for managing reliability growth of a system during the development and support phases.

Mil-Std-756B [29]

This military standard is the recognised USA DOD standard to be applied in all acquisition programmes of military systems and provides the contractor with almost step-by-step instructions.

The standard specifies each task to be carried out in detail during the development phase of the system.

It provides a very structured approach and details the reliability engineering tasks to be performed during the different contract phases as well as the methods needed to contract these tasks.

Mil-Std-785B [30]

This military standard specifies the basic reliability management and programme application requirements.

Programme tasks can be tailored to suite the specific requirements.

The appendix provides an application matrix and guidance rationale for task selection and task tailoring.

Formats are provided for the compilation of reliability programme plans as well as detailed application matrix and instructions to be applied during the monitoring of contractors and suppliers.

Although the standard covers only the development and production phases of a system, the guidelines and management structures are also very useful during the support phase. For small-volume, low-budget, acquisition programmes a portion of the reliability growth is very often realised during the early support phase (warranty period) in order to save costs on reliability qualification.

Kempthorne [32]

This is a comprehensive reference covering the complete field of probability and statistics as well as data analysis.

The book has detailed explanations and examples of the underlying theory to form an excellent reference.

The reference is however, not specific enough in the field of reliability engineering or any other engineering field but rather a pure academic reference on probability, statistical and data analysis theory. The reference is relevant for the processing of raw statistical data and subsequent trending analysis.

Lloyd [35]

This is a comprehensive reference on reliability and reliability management of systems covering topics such as:

- management organisation and communication
- problems and activities of planning and operating a reliability programme
- reliability mathematics
- reliability demonstration and decisions
- reliability testing
- reliability design of systems
- examples of reliability evaluation of two large systems.

On page 3, Lloyd makes the following important statement: 'The root of the unreliability problem is due to the dynamic complexity of system development concurrent with a background of urgency and budget restrictions'. This statement is also very relevant during the support phase of a system where the dynamic complexity of the system is increased as a result of exposure to the operational and support environments.

The practical nature of this reference is supported by sound theory.

Lloyd identifies and recognises that reliability related problems stretch much further than the physical system design.

Particular relevance of this reference to the subject of this research work, is the discussion of reliability related problems that stretch much further than the physical system design.

Bleuel [49]

This is a somewhat dated but still relevant general reference covering all the common facets of service management and is written for the general system support manager.

The reference provides a broad outline and management philosophy of system support management.

Bleuel makes the following important statement: 'The focus of the service function is on the customer.'

The following topics proved to be of particular interest for this study:

- the maintenance relationships (fig 9-1, p122)
- the typical hazard function bath-tub curve illustrated with broad maintenance actions for each phase of the curve (fig 9-2, p122)
- the chapter on field data and the rationale behind the purpose for their collection. (p215)
- the chapter on data processing and in particular the recognition of the influence of human factors (p217)
- the chapter on field service performance measures and tabulation with definition of each service elements and performance measures, (table 16-1 p241).
- identification and recognition of the repeat failure or as Bleuel terms it the 'Call-Back'. This failure is an important measure of service inefficiency (p244).

Relevance to research work subject:

- the reference provides a broad outline and management philosophy of system support management.
- discusses the importance of closing the management loop.

O'Connor [50]

This is a comprehensive, up-to-date primer on reliability engineering with a very practical approach that is particularly relevant to the aircraft avionics industry.

The book covers the following fundamental topics:

- theory and application
- failure mechanisms in mechanical and electrical designs
- basic reliability testing and analysis
- maintainability, maintenance and availability
- reliability management.

The book touches on relevant topics such as fault tree analysis (FTA), failure modes and criticality analysis (FMECA) and failure reporting and corrective actions system (FRACAS) and also provides relevant USA military standard references for further reading.

In the chapter on reliability management, O'Connor stresses the importance of corporate reliability management commitment and provides the basic tools to set up a reliability-driven business and management organisation.

The European (UK) view on reliability engineering as an integrated part of the design process is discussed.

Ramakumar [51]

The book covers most of the statistical theory and applications that engineers involved in the reliability and maintainability fields are likely to find. In this regard, the book forms an excellent theoretical reference that is easily understood. It is liberally augmented with numerous practical worked-out examples.

Relevance:

Ramakumar provides a sound theoretical background to further reading in engineering statistics and reliability engineering and better understanding of the fundamental underlying principles of the subject of this research work.

Pecht [58]

This is a compendium of research papers from experts in their fields for engineers to enlarge their knowledge of the practical aspects of reliability, maintainability and supportability. The following topics are covered:

- product effectiveness and worth
- probability concepts
- statistical inference concepts
- practical reliability concepts
- hardware reliability
- software reliability
- maintainability concepts and analysis
- design for product effectiveness
- reliability analysis of redundant and fault tolerant products
- reliability models and data analysis for repairable products

- continuous reliability improvement
- logistic support
- product effectiveness and cost analysis.

This is a good general reference on reliability and maintainability topics. In particular the descriptions of mechanical failure mechanisms in chapter 5, provide a good background on designing and planning accelerated testing and reliability growth.

Blanchard [59]

The emphasis of this reference is on logistics in the total design and development process.

It provides an introduction to logistic engineering and management.

Blanchard covers the fields of systems engineering, cost/system effectiveness, reliability and maintainability and the application of statistical techniques in logistics illustrated with real-life practical examples and problems.

This is an excellent reference on general logistic management. It leans heavily towards the practical aspects rather than the pure theoretical aspects of the field.

The mainstay of this research work is based on the fundamental concepts of Blanchard's work.

Lamb [60]

This is a practical reference that focuses on plant availability and covers the complete systems engineering process from conceptual design through to plant support. The chapter on support practices provide another view on particularly 'one-shot' large systems and their support methodology.

Summary and Discussion of textbook references

The textbook references can be divided into three subgroups namely:

- Military specifications and handbooks
- General theoretical reference works
- Applied theoretical reference works

The military references provide general methodologies for performing the tasks at hand but generally lack the fundamental theoretical rationale behind their prescribed processes. They also tend to focus on the USA military industry wich is different to the European and the South African military industry. Nonetheless, these references contain much wisdom as long as readers are sensitive to these limitations and apply the necessary tailoring to suit the local situation. ([27], [28], [29], [30], [61], [64], [65]).

Regarding the reliability prediction in accordance with Mil-Hdbk-217F [61], it must be noted that this method calculates the inherent reliability of a *mature* design.

Although not mentioned in this reference, the parts-count method for reliability calculation is used early in the design phase during trade-off analysis for selection of an optimal design concept. Once the design has been finalised, the parts-stress method is used to confirm that the inherent system reliability meets or exceeds specification.

The implication is that a new design's reliability must grow towards the calculated inherent reliability value by elimination of latent design defects from the design.

Theoretical textbook references such as Kempthorne [32] and Lloyd [35], cover the theoretical aspects of probability theory and statistical analysis, and are not specifically aimed at a field of engineering. These textbook references provide an excellent theoretical understanding of the principles behind systems reliability.

The applied textbooks references cover entry level topics essential for any further study of the subject of reliability management and provide the basis for the research of this thesis. In section 1.2.2 the specialised advanced topics will be covered to provide a sound theoretical background to the subject of this research work.

1.2.2 DISCUSSION OF TECHNICAL RESEARCH PUBLICATIONS

This section of the study is a collection of relevant technical papers published since 1963. The papers will be discussed in chronological order to facilitate following the changing trends in reliability analysis and engineering reliability modelling.

April 1964, is particularly significant in that this was the date on which Duane [14] published his benchmark paper on reliability growth which changed the entire thought on reliability monitoring, reliability modelling and reliability growth management.

Some of the published papers are purely theoretical in nature, discussing statistical modelling, analysis and trending techniques in general and are not specifically aimed at system reliability, whilst others are specifically aimed at system reliability modelling and failure data analysis and trending.

Zelen [34] - 1962

This reference is a compendium of research papers delivered by recognised authorities, working at the time on statistical theory of reliability, held at a seminar sponsored by the Mathematics Research Centre, USA Army.

The research papers presented were mainly expository in content and the aim of the seminar was to survey current important work and bring seminar participants to the frontiers of research at the time.

In particular, the research papers by Weiss and Wolman illustrates the pre-Duane reliability state of system reliability knowledge and emphasises the impact that Duane [14] made with his research paper published in 1964.

Weiss, [34], p41

Weiss discusses and models maintenance policies and their effects on overall system reliability and dependability in his research paper: 'A Survey of some mathematical models in the theory of reliability'. In particular, he develops mathematical models for the following different maintenance policies:

- block changes in which components of a certain type are replaced simultaneously.
- preventative replacement on the basis of age.
- system check-outs of components used intermittently. A component which fails during a period of non-use does not induce a system failure until it is called into use.
- marginal testing - if a component is discovered to be in a critical state, it is preventively replaced.

Weiss concludes that the developed equations are too complex to solve with the result that very little can be said about the advisability of choosing one of the four maintenance policies from a purely theoretical point of view.

Weiss further discusses a model of marginal testing using a semi-Markov analysis and a model of the *repair man problem*, using a negative exponential failure distribution.

Wolman, [34], p149

Wolman's research paper: 'Problems in system reliability analysis', distinguishes between inherent failures whose assignable causes cannot be determined and are due to the interaction of the system and the environment and cannot be eliminated by design changes and those assignable cause failures which can be eliminated by design changes.

The reference further develops a reliability growth model from the reliability at the beginning of a test programme until the inherent reliability of the system has been achieved.

Wolman's model makes a distinction between inherent (random) failures and assignable cause failures due to latent defects.

Both Weiss and Wolman in their research papers attempt the mathematical modelling of near real-life situations to facilitate prediction and prevention of failures as well as optimisation of maintenance policies.

Menon [26] - 1963

Menon proposes a mathematical technique for the determination of the shape and scale parameter of the Weibull distribution function by first estimating the shape parameter and then determining the scale parameter from the knowledge:

$$f(t) = e^{\ln^{b}} \tag{1.1}$$

Menon recognised the fact that field data is usually limited and shows theoretical techniques to analyse and determine the reliability from limited field data as accurately as possible. This reference provides the theoretical basis for the Duane postulate [14].

Duane [14] - 1964

Duane postulates the concept that any system reveals a normal or natural reliability growth trend without any active intervention against which active reliability growth must be measured.

This bench-mark reference changed the engineering reliability thinking at the time and is referenced in virtually every research publications on reliability.

The current techniques up to 1964 considered reliability at a single point in time. Duane states that complete treatment of system reliability requires careful consideration of the time variations in reliability resulting from design and maintenance practice changes.

Duane claims that time variation reliability presents problems only in the early stages of development. Reliability stabilises at a relatively fixed value once the system has been in service for some time.

He proposes the use of a learning curve to evaluate reliability performance changes during development and design improvement activities. According to him, repeatable growth trends occur irrespectively of the system.

He also highlights the conflict between design engineers and reliability engineers namely:

- design engineers prefer to ignore failures once corrected.
- reliability engineers view corrected failures as the only meaningful data available.

Duane shows that failure data when plotted on log-log graph paper will result in a straight line, decreasing at approximately -0.4 to -0.5 power of operating hours. Straight line growth function results in more accurate predictions and by extrapolation, reliability predictions can be made of the system.

Duane states that normal system reliability growth is 0.5 (no active reliability growth). Any active reliability growth programme's performance must be measured against this minimum growth line.

Barlow [52] - 1966

This is the first post-Duane [14] - (1964) research reference and here Barlow proposes the development of a reliability growth model that closely reflects the 'test-fix-test-fix' philosophy (Mil-Hdbk 189, [27].

He also discusses a Trinomial model approach where the test programme is conducted in ***K*** stages versus the traditional Binomial model approach using the negative exponential function.

Barlow states that maximum likelihood estimates are meaningless under the Binomial model while valid under the Trinomial model. Therefore, the Trinomial model can reflect real-life system support better by means of consecutive test-repairs/fix cycles.

He disputes the validity and accuracy of the Wolman (Zelen, [34]) approach and model and suggests that the Trinomial model reflects real life more closely in those equipment items under reliability tests which are normally first fixed and then retested.

This research reference illustrates that the Duane model did not get immediate acceptance.

Crow [46] - 1974

Crow reviews the theoretical and practical implications of the nonhomogeneous Poisson process reliability model of minimum repair of systems.

He provides estimation, hypotheses testing, comparison and goodness fit procedures when the process has a Weibull intensity function:

$$\lambda(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \tag{1.2}$$

Where β is the shape factor and α is the scale factor. According to him, for repairable systems, predicting the probability of system failure as a function of system age is more important than predicting the time to first failure.

He further states that after the initial burn-in period, the constant intensity of failure is approximately representative of complex electronic systems and follows a homogeneous Poisson process:

$$f(t) = \frac{(\lambda t)^{x} e^{-\lambda t}}{x!} \tag{1.3}$$

For studies involving the consideration of mission reliability, reliability growth, maintenance policies, overhaul and trade-in times, Crow maintains that it is important that realistic models be applied.

He proposes a generalisation of the homogeneous Poisson process by allowing for changes of trends in the intensity of system failures of the non-homogeneous Poisson process. He claims that any results from the nonhomogeneous Poisson process are also valid for the homogeneous Poisson process.

Crow illustrates the homogeneous Poisson process with examples of a non-homogeneous Poisson process that has a Weibull intensity function. The application of the nonhomogeneous Poisson process with Weibull intensity function during the reliability growth phases of complex electronic systems is also discussed.

This reference shows acceptance of the Duane postulate but indicates that real life situations are a bit more complex but that these can be solved using the simpler continuous process.

Hollander [57] - 1974

Hollander states that in many applications of the Poisson process, finding out whether or not the associated mean value function is linear, is important (corresponding to a homogeneous Poisson process)

He further describes a conditional test to verify that the Poisson process is homogeneous.

Crow [23] - 1975

In this follow-up research publication by Crow [46], the statement is made that it is common practice for a system under development to be subjected to a 'test-fix-test-fix' process. During this process, the system is tested until a failure occurs, design and/or engineering modifications are then made to the system under test in an attempt to eliminate the failure mode(s). The upgraded/modified system is then subsequently tested again. This process is continued until the desired reliability has been achieved.

Crow identifies the problem that usually limited test data is available and that the changes in reliability very often make it difficult to estimate the growth in reliability to relate this to the final reliability goal.

In this reference Crow provides a simple technique for tracking system reliability through the development process and illustrates these procedures with a numerical example.

He develops the mathematical AMSAA (USA Army Materiel Systems Analysis Activity) reliability growth model according to which test failures occur according to a nonhomogeneous Poisson process with a Weibull type intensity function.

A refinement on the Duane [14] model, is the AMSAA model, which only identifies the criteria of when to take corrective action during reliability testing.

Crow shows that reliability growth of a system under development subjected to a 'test-fix-test-fix' process follows a Weibull reliability density function of the type:

$$r(t) = \frac{d}{dt}En(t) = \alpha\beta t^{(\beta - 1)} \tag{1.4}$$

Where r(t) is the instantaneous failure rate and En(t) the system change per unit time. The reference illustrates a technique whereby both λ (failure rate) and β (shape parameter), may be calculated from failure data.

Lewis [56] - 1976

Lewis discusses the approach and statistical techniques used to address and analyse failures of large central database computer systems. He concludes that failures are a function of workload and that they follow a stochastic process.

Methods for manipulating raw data and presentation of intensity functions to reveal actual failure trends are discussed.

Finkelstein [55] - 1976

Finkelstein explores the use of the Weibull process (nonhomogeneous Poisson process with Weibull intensity) as a model for production learning curves and reliability growth of complex systems.

He shows that the maximum likelihood indicators β and μ are easily obtained and he provides mathematical proof that the joint density of first time of occurrence is independent of β and μ. Monte Carlo methods are used to illustrate this.

The confidence bounds when limited data sets are available to determine the Weibull parameters are calculated mathematically.

Engelhardt [53] - 1978

Engelhardt states that the time to first failure occurrence follows a Weibull process whilst the time to failure for subsequent occurrences follows a truncated Weibull distribution.

A detailed analysis is made of how to determine the prediction intervals of the subsequent failures based on the assumption that failures are random events. Engelhardt substantiates his viewpoint by means of a Monte Carlo simulation of random data and comes to the conclusion that inter failure times are generally increasing.

He identifies the limitation of the statistical Weibull process, particularly during the support phase, when subsequent statistical processes come about after each repair/corrective action.

Lee [54] - 1978

Lee identifies and expounds on the problems that arise when the Weibull process is used to model reliability.

The cause is identified due to changes to the system during the fail-fix methodology in the development phase which affects the accuracy of the model as the component composition of the system keeps changing.

Lee concludes that the Weibull process is strictly for non-repairable items and care must be taken to ensure validity when extending it to repairable systems.

Moltoft [20] - 1987

Moltoft discusses constant failure rate analysis techniques as well as the pitfalls and shortcomings of these techniques

He emphasises that MTTF has nothing to do with the working life of a system and should not be intermixed since the MTTF is a view of a small portion of the system hazard function over the total system working life. A typical reliability testing process is illustrated by means of a flow diagram.

Moltoft identifies hard failures (catastrophic) and soft (degradation) failures and cautions that they should not be used together for bath-tub curve plotting.

He discusses in detail the Weibull distribution over the constant hazard rate and wear-out regions and plots electronic component failure data on log-log graph paper for trending analysis. He uses the example of a single component that reveals two failure modes and shows that this in an S-type curve on the Weibull plot on log-log graph paper. Techniques employed to separate these two failure modes from the raw data enabling analysis of each individual failure mode is illustrated.

The reference augments Ramakumar [51] and O Connor [50] by illustrating the finer points of reliability analysis.

Wong [48] - 1988

Wong states that the constant failure rate region of the bath-tub hazard function for electronic equipment is the exception rather than the rule.

Wong further explores in more detail the shape of the hazard rate curve and that electronic systems have a decreasing hazard curve. He finds that electronic systems have a decreasing hazard curve with humps on them and assigns the reason for this phenomenon 'freak' failures. He calls the decreasing hump effects on the hazard rate curve 'Roller-Coaster' as illustrated in figure 1.2.1.

According to him, apart from gross wear-out failures, other failures develop from latent flaws in the components. He proposes a mind-set change on the bath-tub hazard function shape, in particular the bottom constant hazard rate exponential distribution law, since this causes many erroneous decisions.

Wong uses the example of system reliability test demonstrations such as per Mil-Std-781 [65], which are based on the constant hazard rate concept. The generally accepted practice in order to accumulate total test time fast by testing several pieces of equipment simultaneously, is flawed since the failure rate decreases through the useful life of the piece of equipment.

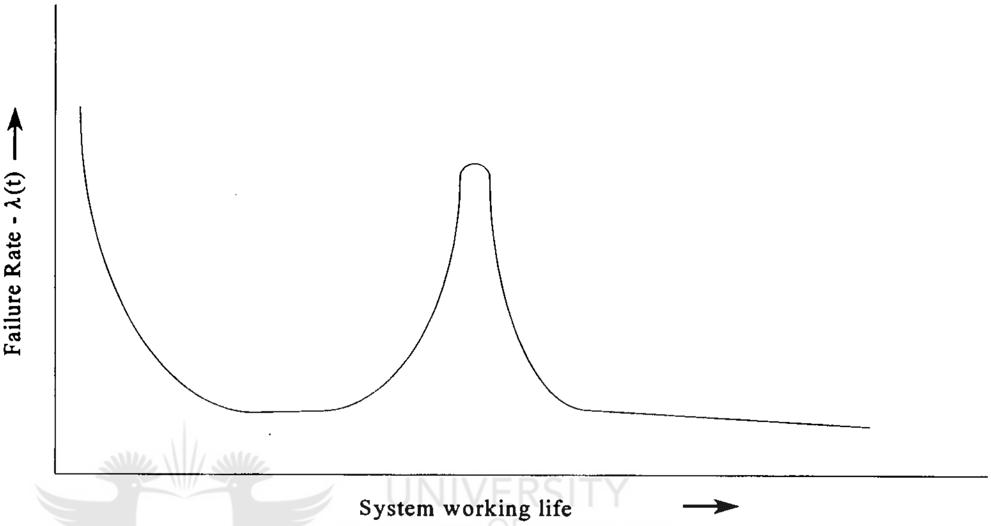


Figure 1.2.1: The *Roller-Coaster* hazard function

Wong is firmly of the opinion that there are no random failures in a complex piece of equipment and that each failure has a cause. He substantiates this viewpoint by concluding that most failures are as a result of flaws either in the equipment, components or natural base materials used to manufacture the components of the system. The result is that these flaws are built-in and develop over time with operational use into failures in the system.

He postulates that the humps develop as a result of flaw detection down to a certain level during the various production stages of components and equipments. The undetected flaws eventually lead to failures once the components have been stressed sufficiently, causing humps in the hazard curve.

This viewpoint is substantiated by description of flaw propagation mechanisms and the fact that electronic equipment in operational use is subjected to stress cycles which cause failure rate humps rather than a smooth failure pattern.

Limestadt [41] - 1990

Limestadt analyses the field failure patterns of 10 000 to 15 000 electronic systems.

He states that unlike component failures, system failures result in repair by replacing the failed component. The rest of the system parts have not been renewed and their reliability are deteriorating.

Limestadt proposes a M(t) (mean cumulative number of failures) plot instead of the more usual failure intensity function plot. The example used, points out that the M(t) plot versus cumulative operating time shows a clearer system failures trend. This is further illustrated with examples of the M(t) trends for systems showing constant, decreasing and increasing failure rates.

Limestadt shows that the M(t) curve for a constant hazard rate is a homogeneous Poisson process and therefore must be a straight line. The field data however actually indicates a rapidly increasing function as the units of operational time increases. This is due to the fact that the component mean lifetime distributions are different.

He claims that this is the fundamental reason why the Mil-Hdbk-217 [61] parts-count and parts-stress methods, where all the component information is attempted be in incorporated into one number, yield dramatically different results from real-life experience.

He states that the homogeneous Weibull distribution is only applicable to components that are replaced and does not take into account repairable systems where only one component is replaced.

Limestadt proposes the concept of M(t) versus cumulative operating time data plotting for complex repairable electronic systems. Blanchard [63], as well as Mil-Hdbk 189 [27] concurs with this approach.

He cautions against over simplification when analysing failure data, as well as the Mil-Hdbk-217 methods which have fundamental shortcomings and very often do not correlate with actual field data.

This very aspect is the subject of this research thesis where the operational reliability generally differs substantially (always smaller) from the inherent reliability even for mature systems that have been in operational use for some time.

Sears [42] - 1991

Sears develops an unreliability growth model to determine the cost of correcting *unreliability* during the development cycle of a product. This will assist management in directing corrective effort for maximum results.

He accepts that the MTTF of a system can be considerably worse than might be expected from fundamental analysis of lifetimes and from standard theory.

He shows that the cost of defect removal escalates dramatically the further the product is in the development process.

He concludes that the development of unreliable systems is the result of processes that permit defects to proliferate as development proceeds.

He substantiates his viewpoint with examples and demonstrates the value of early effort to remove defects even when unreliability growth is small.

Mudholkar [25] - 1995

Mudholkar generalises the Weibull reliability function by introducing an additional shape parameter θ. This enables the complete system hazard bath-tub curve to be represented. In this research work he illustrates the analysis of real-life failure data using his technique.

A similar proposal is made by Ramakumar [51], p 125, to enable the plot of the complete bath-tub hazard function.

Finkelstein [13] - 1989

Finkelstein states that it is important to effectively manage test analyse and fix (TAAF) and reliability growth development tests (RDGT) programs. He found that reliability growth modelling had little success until Duane [14] and that RDGT generally takes a long time to achieve significant reliability growth with the result that reliability growth models have been developed to assist management rather than the reliability program. He discusses the pre and post Duane reliability growth models and provides the theoretical basis for reliability that proceeded from the Duane model as well as the characterisation of these models. The measure of reliability divides the RDGT into the discrete and continuous classes. Finkelstein identifies all the characteristics RDGT that lead to the classification according to discrete and continuous classes.

The most distinguishing feature of a Finkelstein's growth model is how the model parameters reflect the failure acceleration factors and the efficiency of the analysis and fix process. His growth models have been classified by:

- parametric vs non-parametric
- continuous vs non-continuous
- pre-Duane vs post-Duane

Finkelstein illustrates the generic reliability growth model inputs and outputs. The models developed by Finkelstein can be applied to reliability growth during development as well as support phases of complex systems.

Summary and Discussion of research publications

The chronological listing of the research publications provides a clearer perspective of the development of engineering reliability knowledge evolution.

This group of research publications has been specifically identified in order to get a clearer view of the evolution and of the theoretical aspects of reliability engineering.

There was a quantum leap in the engineering reliability technology after Duane [14], hence attempts were made to get a perspective of the philosophies during the pre-Duane period and the change in direction and subsequent knowledge growth during the post-Duane period to the present.

Table 1.2.1 summarises the theoretical knowledge trends in reliability engineering.

There appears to be a certain amount of initial stagnation after the Duane [14] postulate and some vacillation between periods exemplified by the clinging to the random-failure school of thought.

The reasons for this may be the following:

(i) The development of ever more complex systems and the shift in emphasis towards high reliability from the late 1980s onwards.

(ii) From these references it appears that most of the proponents of reliability engineering theory do not always address actual real life system failure and support process realities. The reason may be as Weiss and Wolman (Zelen, [34]) pointed out, that the real life equations are too complex for practical solutions. This could explain the trend towards more simplified stochastic and other statistical processes rather than the fundamental engineering failure mechanisms and causes of failures in complex systems (Pardue [47], Finkelstein [55], Lewis [56] and Hollander [57]).

(iii) Viewed from the micro scale, every failure must have a cause as confirmed by Wong [39]. Viewed from the macro scale for modern complex multi-component systems, each of which reveals its own unique failure life characteristics, the failure behaviour of such a large group of different components may indeed appear to be stochastic in nature. Although Moltoft [20], provides a technique for separating two different failure modes from failure data, this technique becomes totally impractical for multi-failure modes of complex systems.

PERIOD	RELIABILITY ENGINEERING PHILOSOPHY	AUTHOR
1962	Recognition of the fact that not all system defects are random and of the influence of the environment on system reliability.	Weiss Wolman (Zelen [34])
1963	Identification of an exponential component in the reliability growth curve and an early attempt to determine trends in reliability.	Menon [26]
1964	Identification of a natural reliability growth effect with a log-log function	Duane [14]
1966	Attempts to refine the Duane model by inclusion of the effect of the fix after failure in a test-fix-test process	Barlow [52]
1974	Failures are random and recognition of the impact of fix stoppages resulting in system change which result in a NHPP	Hollander [57] Crow [46]
1975	Development of the AMSAA model recognising a NHPP and that the failure rate during testing follows a Weibull function.	Crow [23]
1976	Determining that failures are random and a function of workload (non-military viewpoint) The stochastic nature of failures and reliability growths are NHPP	Lewis [56] Finkelstein [55]
1978	Recognition of the difference between first time to failure and subsequent failures after repair (difference between a new system and repaired system).	Engelhardt [53]
1987	Recognition that causes of failure have an effect on the hazard function and causes S-type humps in the Weibull plot.	Moltoft [20]
1988	Negation of the random failure school of thought and identification of the roller-coaster effect on the hazard function for complex electronic systems.	Wong [48]
1990	Recognition of the difference between component replacement and repaired system. Develops an alternate way of presenting trends	Limestadt [41]
1991	Identification of attempts to explain the large difference between calculated reliability and field experience.	Sears [42]
1995	Introduction of an extra parameter to the Weibull density function to describe the complete bath-tub hazard function.	Mudholkar [25]

Table 1.2.1: Chronological summary of reliability engineering

The reliability engineer must take cognisance of both the macro and micro levels of failure trends. At the macro level he must assess total system behaviour whilst at the micro level, he homes in on the culprit components and removes them from the system, (Koon [5], Kritter [6] and Wright [7]). This process will be further discussed in part IV of this research work.

The publications on theory provide the practising reliability engineer with better tools to improve the accuracy and speed of trending the normally limited field data in order to facilitate more effective reliability management.

It is important for the practising reliability engineer to recognise the limitations of the tools and techniques available and apply these judiciously. These tools are excellent when used in practice to obtain relative figures of reliability merit. That is the use of the same technique as a yard-stick, implement changes and measure again using the same yard-stick in the same environment. These tools also assist excellently in identifying reliability or rather unreliability (Sears [42]) drivers in a complex system. This enables the corrective action effort to be directed to the best effect which will be discussed in section 1.2.3.

1.2.3 DISCUSSION OF ENGINEERING AND OTHER APPLIED RESEARCH PUBLICATIONS FROM THE MILITARY INDUSTRY

Lincoln [2] - 1985

Lincoln examines by means of a case study the adequacy of the USAF damage tolerance inspection criterion for protecting safety of flight of an ageing military aircraft. This is done through a risk assessment based on cracks found during strip-down inspections of retired aircraft wings.

The crack population is combined with stress probabilities from service experience to determine single flight probability of failure and the single aircraft probability of failure after a given time. These quantities are then used as a basis for judging the required inspection interval.

Risk assessment is done by using the Weibull fit to raw data and determining the Weibull scale and shape factors. The relationship of inspection reliability and physical size of non-conformance (crack length in the case study), is determined.

Lincoln sets out the single probability of failure (crack propagation vs utilisation (hours). His research in particular covers the analysis of a complex system whose components are approaching end-of-life without compromising safety. By the setting of acceptable and unacceptable risk norms, guidelines are provided for acceptable system safety risks in relation to every-day life risks. He quantifies the impact of inspection intervals on probability of failure and presents the data in an understandable manner for management.

The statistical analysis of the results of inspections and methods of data presentation provided by Lincoln are very useful for optimising maintenance of any complex system.

Halliday [3] - 1984

Halliday describes a practical approach to reliability growth management in a rapidly changing environment, highlighting observed advantages and limitations. He contrasts the UK system development philosophy which tends to take passive approach to reliability growth management to that of USA who tends to follow a more dedicated and aggressive reliability growth management.

He identifies that at the centre of the reliability growth process is the identification of failure mechanisms by testing and their elimination through design and hardware modification action. He suggests that the most efficient reliability growth process is to test, analyse and fix through modification rather than continue with testing whilst investigations are conducted in parallel. This agrees with the recommendation by the authors of references [3] and [27].

In this reference, he further states that the following aspects require detailed consideration during growth planning:

- level of testing
- quantity of testing
- test validity
  - new vs old
  - environmental conditions
  - single vs multiple operation
- success/failure criteria.

He suggests that for continuously operating equipment, reliability growth may be a fairly smooth process and growth models such as Duane may be used as a basis. In one shot systems where hardware tends to be tested in batches, reliability growth may take the form of a series of steps between successive hardware design standards.

Halliday stresses the necessity for an efficient data management system and proposes the following process:

- reliability growth monitoring
  - data collection and validation at geographically dispersed test sites
  - success/failure criteria
  - unknown causes
  - non attributable failure against each subsystem to determine worst case reliability
  - interfaces
- data plotting
  - Duane model
- projecting reliability growth.

According to Halliday, the loop must be closed by means of management reviews in terms of:

- policy instructions
- effective communication
- reviews of system and subsystem levels

These findings and recommendations by Halliday are very relevant to reliability management of complex systems in the support phase and have been applied in the case study discussed in PART IV of this research work.

Pohlenz [4] - 1986

Pohlenz discusses a reliability, availability, maintainability and logistic (RAM/LOG) data system developed for the helicopter programme and used universally by the USA. They gather the following FRACA data fields:

- flight
- service
- maintenance
- end item
- parts usage
- utilisation/diagnostic/recorder data
- narrative description of failure and repair actions.

Pohlenz stresses the importance of quality control (QA) to ensure accuracy of data. His proposed system makes provision for the following FRACA data fields:

- potential abort
- failure classification (chargeable/non-chargeable and why)
- maintenance task time chargeable
- contractor or government-furnished equipment
- mission failure

He discusses the importance of keeping failure history files. A computer mathematical model was developed to predict reliability (failure rates), mission and system reliability as well as the effects of design changes. The results of the analysis were plotted to show reliability growth trends as well as maintainability performance assessments.

Pohlenz discusses the major strong points of the RAM/LOG Data System in terms of the recording of detailed failure and maintenance data as well as logistic data generated from each test event. The five forms of collecting the data of each event in relation to the large number of events result in an unwieldy paperwork problem.

Pohlenz provides a methodology for the data collection techniques of the case study discussed in PART IV of this research work. Special care was exercised in the case study that the data fields and paper work was kept to an absolute minimum to ensure data integrity by reducing human errors.

Koon [5] - 1989

Koon discusses reliability growth on the T700 gas turbine engine.

The engine reliability performance was evaluated over 9 years of operational use in very diverse and extreme climates and after a total of 2 million hours was accumulated. According to Koon, the success factor for achieving reliability growth were:

- well defined set of requirements/needs
- dedicated R&M management team
- good basic design with R&M 'built-in' with state of the art technology
- rigorous factory/field integrated development
- reliability improvement warranty program
- good data collection/tracking system
- strong component improvement programme (CIP) to fix residual problems and incorporate advances in technology
- well planned derivative programme to incorporate 'lessons learnt' from the T700 program

During the 1960s gas turbine engines had high removal rates resulting in approximately 10% maintenance-induced failures in the workshop. The corrective actions implemented resulted in technological advances to address high life-cycle cost, technical performance, reliability and maintainability specifically accessibility. Koon made use of accelerated endurance and mission testing.

The reliability growth has been due in a large part to the effectiveness of the FRACAS. Emphasis was placed that problems must first be identified and reported before they can be corrected.

Data collection was by means of 'Field Service' forms. Failure analysis was directed towards establishing the cause of failure first from the data followed by laboratory investigations. Koon followed a TAAF reliability growth process described in reference [27].

Koon states that the reliability growth programme was so successful that GE and the USA DOD entered into reliability improvement warranty where the first 250 hours were for GE's cost, the next 250 hours costs were shared and that GE received incentives for engines that operated without unscheduled maintenance for 500 to 750 hours.

This is a very practical reference providing techniques that can be applied to any system in the support phase.

Kritter [6] - 1989

Kritter focuses on reliability growth which resulted in the Patriot Air Defence system achieving operational reliability similar to that achieved in the factory during initial product assurance acceptance test (PRAT). Continued reliability growth resulted in achievement of four times the initial PRAT.

Kritter states that environmental stress screening (ESS) during production was introduced at many assembly levels and that Raytheon uses two data reporting systems Product Assurance Inspection Reporting (PAIRS) and Product Assurance Test System (PATS).

At Raytheon the cumulative MTBF performance method to evaluate reliability performance in comparison to the predicted reliability is used as recommended in reference [27].

Kritter discusses in detail the quality inspection systems at various production levels and plots production performance percentage acceptance or as he terms it, *performance stoppers*.

Kritter's findings are very applicable to the subject of this research work since from a reliability growth point of view, there is no difference between production and a depot repair facility.

Wright [7] - 1989

Wright discusses a high volume production programme, which produces VHF FM two way radios for USA (> 1500 radios per month). He states that the prime purpose of the programme was to go directly from Advanced Development Model (ADM) to full rate production within 4 years.

The reliability requirement set by the USA DOD had at that stage not been achieved on any tactical radio. The cumulative MTBF over the 4 years development and accelerated testing was measured and compared to projected reliability. Wright also compares the reliability performance of different development teams.

The impact of personnel performance on the overall system reliability is of relevance to the research work subject.

Halsey [9] - 1989

Halsey covers trade-off study parameters and considerations for use in assessing reliability growth plans and results are defined from a cost-benefit point of view.

Halsey identifies three main cost categories namely:

- costs incurred through testing and the associated programmes and engineering support
- in-house costs saved by the design, manufacturing, ILS and testing organisation
- costs saved in the field resulting from less logistics and higher readiness.

Halsey sets up a cost model by increasing from an initial MTBF to a final MTBF and applying the resulting design fixes across a given sample of systems and compare these to untested and unfixed systems. He defines the ratio of V/ΔMTBF (Δ = delta or difference) as the most meaningful ratio where V is the value for growth or no-growth and ΔMTBF is the difference in MTBF before and after corrective actions.

Halsey emphasises that reliability growth of a system requires a corrective action methodology for design or process imperfections and not just a repair or replacement action. He identifies and cautions against a no-growth reliability growth problem as a result of the accumulation of operational time of a no-growth item.

Halsey applies this concept to the three main cost categories to arrive at the results and clarifies the approach by means of an example. He states that the fix policy impacts on the cost model since immediate fixes may result in cost and schedule delays.

Halsey illustrates that the TAAF policy (Patterson [11] and Mil-Hdbk 189 [27]), is not always cost effective.

Patterson [11] - 1989

Patterson point out that the USA Navy uses a test analyse and fix (TAAF) reliability growth policy. A typical Navy TAAF plan entails the following:

- management policy
  - conducting disciplined, rigorous TAAF reliability

- test articles
  - must reflect the latest design configuration
  - should have three test articles
  - eliminate workmanship and part defects before test starts by means of ESS and use of screened parts

- test environments
  - base on worst case mission profile
  - ensure environmental exposure in same sequence per mission cycle
  - do not consolidate like environments

- test time planning
  - use all prior test data and analysis to establish starting point
  - assume start at 30% of requirement and slope of 0.5

- failures
  - concentrate on failure modes, not number of failures.

Patterson uses the example of the USA Navy F/A-18 Hornet development which was subjected to the TAAF reliability growth policy. To overcome the problem of a massive amount of test data, failures were tracked by means of a work unit code, work breakdown structure and reliability critical item.

According to Patterson it does not make much difference if the TAAF policy is applied before or after qualification. He claims that planning an appropriate duration for TAAF is the weakness of the methodology. This in his opinion is a major strength of the Duane/GE model, as described by Koon [5].

This reference shows a practical approach to a TAAF programme for a complex system.

Truman [19] - 1988

Truman states that substantial RAM improvements can result from the careful applications of reliability, availability and maintainability (RAM) technology and a disciplined RAM improvement methodology. He stresses the requirement for high reliability on:

- soldering processes
- environmental stress screening (ESS) of printed circuit boards (PCB) and higher level assemblies.

He mentions that weapon systems must operate reliably not only at production but for a system operational life of 10, 15 or even more years. He developed a simple reliability growth plan in accordance to Mil-Hdbk-189 [27] and identified the RAM parameters of the Patriot Missile System to be improved:

- MTBF
- MTTR
- fault detection and localisation

The RAM growth methodology was based on continuous FRACA activity during integration and field testing. The reliability growth objective was to eventually reduce the actual failure rate of each sub system to the predicted failure rate in accordance with Mil-Hdbk 217F [61].

Truman discusses RAM growth trade-offs through the impact of each corrective action on schedule, funding, performance and design risk. His findings on the programme were that the reliability parameters (MTBF) had a more immediate impact on RAM improvement than the maintainability parameters (MTTR). He found that he could plot these improvements as a straight line on a linear graph.

This reference emphasises the importance of MTBF improvement as a first priority before repair time improvements are addressed and is of direct relevance to this thesis research subject. Since Truman could plot the reliability improvements as a straight line on a linear graph, it appears that the improvement process in the field may not always be Weibull in nature.

Warrington [21] - 1978

Warrington analyses field testing failure data and applies the Weibull distribution plotting techniques to predict failure rates at some future point in time. From this prediction he determines the reliability growth and growth strategy for the programme. The article provides a comprehensive set of actual field FRACA data and illustrates how to manipulate, plot and trend this data.

US Department of Commerce [31] - 1975

The reference provides a comprehensive study of the reliability growth of complex ground and airborne electronic systems. The objectives of the study were twofold namely:

- growth in reliability arising to operation of the equipment in a test environment where failures are reported, analysed, cause pinpointed and corrective action to the design, production process, or material taken.

- growth in reliability in the operational environment by means of the natural weeding out of premature failing weak parts and defective workmanship during repairs.

A total of 186 FRACA records for ground equipment and 86 FRACA records for airborne equipment was used in the study. The data was analysed and fitted to the following reliability growth models:

- Duane model
- IBM model
- Exponential model
- Lloyd-Lipow model
- Aroef model
- Simple exponential model.

Data fit parameters were calculated for each of the models

The study's finding was that although the Duane model was seldom the best fitting model, it almost always fitted all the data. Each model revealed specific advantages with specific types of equipment and environments an aspect very relevant to the subject of this research work.

Feinstein [12] - 1989

Feinstein states that although reliability growth testing (RGT) and ESS have much in common, there are some key differences. Some of these differences make their combination counter productive. ESS ages the equipment beyond the infant mortality rate of the bath-tub hazard function whilst RGT establishes a constant hazard rate over the useful life of the system. Also ESS does not influence the failure rate of a debugged system. ESS targets defects caused by workmanship and improper processes and if they are removed by repair, they will not recur. Design-caused defects will however recur, if not in the factory then later in the operational environment.

Feinstein states that RGT is to mature the design and to eliminate design weaknesses that may lead to premature failures. An RGT programme is a closed-loop FRACAS which identifies the cause of a failure and removes it from the design package permanently. As design flaws are removed, the failure rate of the system approaches that of the parts themselves.

Feinstein clearly distinguishes between low system reliability as a result of latent design defects and low system reliability as a result of poor workmanship (logistic element defects). In the support phase of a system both factors must be taken into account as shown in the case study in PART IV.

Frank [36] - 1989

Frank discusses the results of an investigation into reliability characteristics demonstrated by avionics systems over a major portion of their expected service life. The study shows that avionics equipment items of various types demonstrate remarkably similar trends of a gradual decline in reliability during prolonged service. This data provides a basis for modification of Duane's learning curve approach by extending its applicability to project a reliability profile over the extended service life of equipment.

Frank's investigation results are very relevant to the INS case study provided in PART IV.

Miller [44] - 1991

According to Miller, the significant difference between predicted reliability and actual operational field performance - reliability delta - has been a long outstanding problem in reliability engineering. After an extensive survey of both literature and industry, he concluded that the six most prominent reasons for this difference are the following:

- problems with data collection
- assumptions underlying, and the use of prediction techniques
- lack of understanding of operational environment
- problems with manufacturing processes
- short-term management focus
- design-related problems.

Miller found that the actual operational reliability is almost always *lower* than predicted and confirms the findings of Lloyd [35]. Miller provides an extensive literature survey and collates the following findings with a view of identifying the factors influencing the difference between calculated and actual achieved reliability, namely:

- system definitional
- system operational
- system environmental
- predictions techniques/assumptions
- test plan results

- fault isolation techniques
- analysis and test weaknesses
- improper assumptions
- reliability measurement methods
- management support
- statistical viability
- human performance.

Miller's findings are very relevant to the subject of this research work where reliability growth in the support phase is researched.

Bombara [38] - 1990

Bombara describes the determination of failure trends in a NASA environment where there are very few test samples , by using Pareto plots, normalised trends confirmed by R-square analysis. Bombara illustrates the analysis of FRACA data and sets basic ground rules for data exclusion or inclusion.

He cautions against straight generic analysis of failure codes and recommends studying the failure report in each case, since failure modes may be classified differently by different engineers.

He recommends focussing on areas of concern first and using the R-squared technique to find the best failure model fit.

There are two aspects of this reference that is very relevant to the subject of this research work:

- Bombara deals with low volume systems which is generally more applicable

- stress the importance of failure reviews. This would not be practical in high volume system support environments.

Summary and Discussion of military industry publications

These references written by reliability engineers in the military industry cover the reliability aspects in practice in the development and operational industrial environments of both the military and aerospace industries.

They cover a variety of views and approaches to practical reliability growth techniques and reliability management. Some references describe the practical applications of the modelling techniques developed by the researchers, whilst others such as Patterson [11], provide a more global overview. The reliability growth policy must be clearly established up front prior to commencement of any reliability programme.

The authors of this literature survey segment illustrate the practical applications of the models and techniques developed by the authors of the technical research literature survey segment discussed in paragraph 1.2.2.

The authors concur that data collection must be well planned. The collected data must be carefully screened and analysed. The tools and techniques used in analysis must be optimised to overcome the general problem of lack of sufficient data (Pohlenz [4], Koon [5]).

Accurate predictions and confidence can be achieved despite the problem of lack of data due to cost and timescale constraints, by applying this data to theoretical models. Since the failure data follows a Weibull process, a relatively small number of data points are required to enable the determination of the specific distribution function parameters with a high level of confidence. These findings are significant to the subject of this research work.

1.2.4 DISCUSSION OF ENGINEERING RESEARCH PAPERS FROM INDUSTRY

The reference in the previous section all focussed on the military environment where the emphasis on reliability and availability under extreme operational conditions are very high and operational cost take almost a second place.

In the commercial industry cost effectiveness becomes a major driver for reliability growth.

Silberman [18] - 1967

Silberman focuses on reliability assurance for one-shot systems where mission reliability and safety are of paramount importance. Although the strict formal approach is not practical (and cost effective) in normal support environments, Silberman gives an insight into what can be achieved under these constraints.

The reference provides a formal FRACAS and process outline as well as a formal engineering change process (ECP) and examples of failure reports and failure data forms.

The constraints are typical of those experienced with the reliability growth complex systems and Silberman's findings are very relevant to the subject of this research work.

Sasser [33] - 1979

Sasser's publication is a compendium of articles compiled by experts in their fields in the fast-growing service industry. The manual contains well documented case studies and examples of the approaches by leaders in the service industry.

The article - 'Quality Control in a Service Business' by Hostage, shows relevant management and control structures ensuring a closed-loop service management process.

Of particular relevance to system reliability in the support phase , is the emphasis that the articles place on the importance of management education, human resource planning, training and performance development.

Rumble [22] - 1987

Rumble describes an integrated management information system (MIS) which provides data to engineering facilities, plant operations and maintenance (O&M) facilities and corporate management to enhance both O&M management and system reliability analysis (SRA). He states that the application of SRA at nuclear plants is broadening from its initial focus on safety related design considerations to include operations and maintenance (O&M) issues.

SRA techniques will not release their potential impact unless the proper tools and support equipment are available to efficiently acquire plant feedback information, manage the myriad of logic models and generally provide a productive environment for performing an SRA. The integrated model used by Rumble, shows engineering surrounded by data, logic models and software.

Rumble provides a comprehensive flow diagram showing both the data flow for O&M enhancement as well as SRA and also the interfaces with all the stakeholders in the process.

The findings by Rumble can be applied to the support general complex where the stringent safety rules of the nuclear industry do not apply.

Magnus [1] 1989

Magnus recognises that a cost-effective FRACAS is an important tool recognised by management at GE/RCA in improving quality and productivity.

Diversity of products and customers resulted in individual failure reporting requirements and the establishment of individual data bases for each system. A standardised system will enhance the tool to improve corrective action, LCC and competitiveness.

A number of lessons were learnt at GE/RCA in the standardisation of the corporate FRACAS namely:

- the user's needs, must be analysed
- computer capacity must be adequate to meet present and future needs
- error checking of inputs is necessary to assure quality data
- ease of entering data by minimising operator keystrokes
- data base must be dynamic
- flexibility of data collection and sorting
- data output must be in an understandable format
- failure trends must be identified quickly
- people generally resist change
- cost benefit of standardisation
- standardised system works equally well with small projects and large.
- standard output is used for contractual reports
- better and quicker analysis results in more effective corrective actions
- standardised FRACAS can be used to measure productivity
- data exchange possibilities with client organisations.

Magnus compiles an extensive value system which is very applicable to the general system support environment.

Seusy [8] 1989

Seusy states that reliability growth in most companies results from fixing problems found during development testing. He states that non-military companies generally do little to manage reliability growth. He defines reliability growth as improvement in product reliability resulting from design, component or manufacturing process changes. Problems can only be eliminated by thorough failure analysis and permanent, well documented fixes (TAAF).

Development programmes in most non-military companies do not include a formal reliability growth programme. Instead, they integrate every activity relating to growth into the product development process.

The elements of a product development programme relating to reliability growth and which must be carefully managed, are:

- finding and forcing failures
- analysing failures to find the root causes
- permanently fixing failures
- verifying solutions
- documenting failures, causes and fixes
- tracking and modelling reliability growth.

Seusy relates available reliability improvement techniques and relative cost benefit over the equipment development phase. He stresses the importance of uncovering product weaknesses early on in the design stage.

He states that problems cannot be found only through analysis but must be complemented by testing and observing actual failures. Product knowledge is essential in this process.

He also states that every device embodies weak links and that these must be found by means of active processes. Every tool must be employed to coax narrow margins to reveal themselves. Big players such as HP and Motorola increase test intensities and apply accelerated life tests to drive failures from a design.

He discusses the stress vs strength distribution, and shows that the overlap results in unreliability. He states that strength changes with age. The following types of stress to addresses all failure modes are discussed:

- generic stress
- product-specific stress
- stress levels that go beyond the designer's comfort zone.

The importance of understanding the physical mechanism of the failure by analysing and isolating the root cause, is stressed. Seusy cautions against 'shotgun' fixes of the symptoms instead of eliminating the root causes of the failures. He states that Hewlett-Packard managers are instructed to ask "why" five times or as many times as necessary until asking why is no longer logical during failure review boards in order to get to the root cause of the problem. In table 1.2.2, Seusy equates an example of the questions that should be asked at a failure review board:

ENGINEER	MANAGER
The 8510 failed	Why?
Faulty microprocessor board	Why?
EPROM died	Why?
Electro migration on buried metallization layer	Why?
Violation of current density design rule	Why?
Chip designer did not catch the violation	Why?

Table 1.2.2: Typical questions that should be asked at a FRB

Seusy states that the effectiveness of a fix must always be verified and steps must be taken to ensure that the verification method is valid. He places extreme importance on configuration and documentation management and advocates the use of a 'lessons learned' database

Reliability engineers to be effective must bring the following responses from design engineers under control and illustrates this with actual examples:

- attempts to excuse failures
- attempts to validate poor failure analysis
- attempts to justify shotgun fixes
- attempts to vindicate inadequate verification

Seusy suggests the following reliability growth practices for industry:

- increase the difficulty of obtaining test and specification waivers
- pick a few suppliers and train them in reliability and quality practices
- encourage suppliers to find root causes of failures
- keep list of preferred parts and preferred suppliers
- re use known good parts, assemblies and software modules in future design
- avoid unproven components and process technologies.

Hewlett-Packard improved reliability of their products tenfold the past ten years and Motorola aimed for +/- 6 sigma reliability margins on all their products by 1990.

Seusy concludes his findings of reliability growth in the commercial industry with the following:

- commercial companies extensively use simulation testing, failure analysis and corrective action
- few commercial companies use stress testing, disciplined failure tracking systems and reliability growth models.
- commercial companies do not use formal reliability growth programs, formal reliability growth tests or modelling techniques such as planned or idealised growth curves.

Seusy's findings of reliability growth approach in the commercial high technology industry are very much the same as what Halliday [3] experienced in the UK military industry. His findings and guidelines have been used extensively in resolving the deteriorating reliability of the INS systems discussed in PART IV of this research work.

Kercher [37] - 1989

Kercher states that traditional reliability predictions can differ significantly from actual field incident experience, particularly during the early life of the product. This difference can have a significant impact on the customers' perception of product quality. He finds that the constant failure rate prediction does not adequately represent the actual field experience since the early life of particularly electronic components tend to be dominated by a constantly declining failure rate rather than a constant failure rate.

Kercher recognises that field incidents typically include the no trouble found (NTF) category of reported failures. These could either be as a result of intermittent electrical connections or wrong diagnosis of system problems by the maintenance personnel. He identifies the necessity for estimating the potential total incident distribution of preliminary designs from all sources, including the impact of inherent product and process design reliability, potential design and manufacturing anomalies as well as the NTF possibilities.

Kercher's findings agree with those from Miller [44] and Malec [15] and is very relevant to the subject of this research work.

Wang [40] - 1990

Wang defines the concept of a 'Durability Index' to indicate the inter-relationship between customer expectations and engineering requirements in the motor industry. He discusses the general misconceptions between reliability, durability, failure rate and MTBF and illustrates this by using motor industry examples.

Of relevance is Wang's findings in the motor industry that reliability is a much broader concept of which failure rate and MTBF are subsets. He also identifies the concept of durability which tends to be overlooked during system development.

Smith [43] - 1991

Smith describes the role of availability as part of total quality management (TQM) and the role of preventative maintenance in availability. He addresses the interaction and economic consequences of availability, reliability and maintainability.

He describes an availability improvement programme and produces a flow diagram, showing corporate to work place involvement in addressing reliability and maintainability issues.

Smith's findings are very relevant for the subject of this research in that reliability as a subset of TQM, in particularly a multi-level support environment, must involve and commit all stakeholders.

Klinger [45] - 1992

Klinger discusses:

- background of reliability management
- evolving customer needs
- standardisation of reliability programme management
- reliability programme management at AT&T
- future direction of reliability management.

He states that customers will not tolerate nor accept products that are of a poor quality and reliability and that customers are willing to reward suppliers who offer products with high-quality and reliability standards at a reasonable cost.

Klinger finds that customers send the following messages to their suppliers:

- constantly improve quality and reliability of the product (be as good as the competition)
- minimise cost of ownership (initial and maintenance costs)
- be flexible and responsive to customer's quality and reliability requirements.

Klinger advocates the standardisation of reliability programme management in relation to the European ISO 9000 series standards.

Klinger substantiates Smith's [43] findings that reliability is in essence a subset of TQM and that this can only be achieved by compliance to quality standards.

It would not be possible to achieve product reliability if the quality standards of the organisation are inadequate and as such is very relevant to the subject of this research work.

Pardue [47] - 1994

Pardue states that industrial maintenance is beginning to make the transition from a repair department focus to that of a high-level business function. He finds that at many facilities, rising maintenance costs are contributing from 4% to 14% of production costs and are often greater than plant profits.

He identifies the first step in controlling plant maintenance cost is to realise that *equipment maintenance does produce a product.* That product is the production capacity. The consequences of unreliable capacity are severely interrupted schedules, degraded quality and most importantly, diminished profits. In this reference, a discussion is provided on:

- preventative maintenance
- predictive maintenance technologies
- pro-active maintenance technologies
- reliability based maintenance program
- measuring the results of reliability based maintenance.

Pardue's findings are very relevant and are confirmed by the case study provided in PART IV of this research work.

Malec [15] - 1988

Malec illustrates the manufacturer's and customer's system reliability experience and shows that they are very different and that cognisance of this fact must be taken for good customer relations. He shows that the first shipment to a customer of a new product's reliability starts typically with a low MTBF and a relatively long growth period to a stable MTBF. On subsequent shipments this reliability improves and the growth period reduces to achieve the same stable MTBF.

The manufacturer however, observes a cumulative reliability improvement of his product. Malec states that cumulative reliability growth measurement tends to mask declines in production reliability. Reliability measurements should be produced on a quarterly basis for a faster response to deterioration in reliability.

The customer's reliability growth curves for the different shipments must be parallel for the reliability process to be under control. If this is not the case, premature shipment of particularly the first batch has occurred.

Malec highlights the importance of viewing reliability also from a customer perspective and his findings tend to agree with Truman [19] who also found a straight line reliability improvement relationship of systems in operational use.

The suggestion by Malec to perform reliability measurements at regular operational usage intervals has been extensively used in the case study in PART IV of this research work.

Reyerson [24] - 1989

Reyerson has 50 years' experience as a reliability practitioner. The subjects selected by him are:

- key government documents
- elementary frustrations
- the realistic approach syndrome
- brain pool management
- software reliability management
- optimum packaging
- achievement vs demonstration.

He refutes many of the traditional ways of reliability management and approaches and postulates an open-minded approach by adjusting the hypothesis to best fit all data. He maintains that data analysis programmes must have a fast response time to prevent the danger of becoming after-the-fact history records. Effective control can be cost-effectively achieved by rapid input and analysis.

He identifies the need for a high level of management support to perform reliability analysis and subsequent corrective actions optimally.

Wong [39] - 1990

In this follow up publication by Wong he provides his practical findings on how ESS data can be utilised for reliability growth testing and demonstration with a pre-knowledge of the roller-coaster [48] effect of the hazard curve for electronic systems. He finds that hazard rates of electronic equipment as a result can vary up to two orders and extrapolation of reliability trends other than the test window age should be used for reliability predictions of a system.

The fact that the hazard rate is not smooth but varies with age, complicates the whole process of reliability demonstration. He dispenses the notion that failures are random and instead states that each failure has a cause.

The reference shows a coarse correlation between ESS failures and long-term reliability trend.

Of all the surveyed literature publications, Wong's two articles accurately reflected the case study experience described in PART IV of this research subject.

Summary and Discussion of industry papers

The commercial industry tend to address reliability related issues more as part of the overall management strategy rather than a separate almost stand alone activity as in the military industry.

Seusy [8] shows that it makes commercial sense to ensure that reliable products reach the customer and that management must get actively involved and asked pertinent questions around unreliability issues. This view is also expressed by Wang [40]. Both authors operate in highly competitive multi-national commercial industries where any hint of unreliability of any of their products can mean a large financial disaster as a result of loss of world wide sales.

The lesson learnt from this section of the literature survey is that a clear picture must be established who the actual customer is. This is generally not the top management of the organisation, who is owner of the system to be supported, but rather the actual user/operator of the system who is tasked to provide a service with the operation of the system. The system operator must be satisfied with the overall system performance and availability before the system owner can be satisfied. This aspect will be further discussed in the next chapters of this research work.

1.2.5 DISCUSSION OF RELIABILITY GUIDELINES AND STANDARDS

Healy [10]

Healy defines and explains the common reliability growth terms of which the most important ones are the definitions for reliability growth and MTBF which he subdivides into four types. The relevant definitions for this research work have been provided in appendix C.

Golant [16]

Golant co-ordinated the composition of the reliability guideline and distinguishes between quality reporting and reliability reporting:

- Quality reporting records non-conformance items to standards such as manufacturing specifications, purchase requirements and workmanship standards.

- Reliability reporting records non-conformance incidents to performance specifications of items which are of acceptable quality standards

The guideline states that reliability documentation should cover the design, manufacturing and operational use phases.

The following are the objectives of a reliability documentation system:

- assess historical reliability data
- develop pattern deficiencies
- provide engineering data for corrective action
- develop statistical data for:
    - part failure rates
    - part selection criteria
    - part application reviews

  - future designs and design reviews
  - product improvement programmes
  - spares provisioning
  - life-cycle costing
  - develop contractual conformance data
  - provide warranty information
  - furnish safety and regulatory compliance data
  - assess liability-claim information.

In terms of the guideline, the basic functions of a FRACAS are data recording, reporting to the analysis group, analysis, corrective action and follow-up. The guideline identifies 13 types of reliability tests and suggests the use of Pareto principles to rank failure data. The guideline also identifies the following types of reporting:

- use reporting such as information on the operation of all items in a population
- failure reporting such as information on observed failures and in sufficient detail to identify false failures and maintenance actions amongst other things.
- preventative maintenance reporting, this information should be distinguished from regular failure reports.

In the guideline the following types of data identified:

- performance data
  - attributes
  - variables
  - operating time-cycles
- discrepancy data
- configuration data
- management survey data.

The guideline recommends the following steps for implementation of an effective FRACAS:

- preparation of a system manual or set of procedures tailored to the company environment
- design of reporting forms, these reporting forms must be simple concise and easily understood by people collecting the data.
- tabulating, summarising and analysing procedures for data
- periodic summary reports for distribution to top management.

The guideline identifies the following data processing and reports:

- failed item status report
- open item report such as corrective action pending
- manufacturer's failed item summary
- reporting activity summary
- responsible action area status report such as corrective action items assigned to each area.

The guideline identifies an extensive reliability documentation system and also specifies the following minimum requirements demand that the failure data be adequately identified to allow analysis to be made:

- failure level (system, subsystem, etc)
- failure symptoms and description
- failed part configuration status
- damage to other parts
- visual data such as photographs, recordings and audio data
- test specification number and section and/or operating conditions and environment
- identification of minor, on-the-spot repair and its effect
- part number and lot number, serial number of failed item
- identification number of end product
- nomenclature of that part
- number of next higher level of assembly
- serial number of the next higher assembly
- name of the manufacturer of the discrepant part
- the number of hours or cycles of operation spent on the part prior to its failure
- the replacement part number
- serial number of that part
- name of the manufacturer of that part
- the serial number that the manufacturer has assigned to the replacement part
- any measurements which were taken
- the signature and telephone number of the reporting individual.

This guideline follows the basis of the reliability growth management information system discussed in PART III and implemented in the case study in PART IV of this research work.

1.3 LESSONS LEARNT FROM THE LITERATURE

The literature provides the statistical tools and techniques for analysing, modelling and presenting data for management.

The limitations of the models and techniques must be fully understood for optimum application. The US military standards generally provide a methodology for applying these techniques. They also urge the user to tailor the standard to suit the circumstances yet they provide little guidance in the tailoring process. A typical example is Mil-Std-785 [30].

The general criticism raised against reliability calculations and modelling is that the results in practice can differ substantially from the calculated figures. This is also substantiated by Limestadt [41] and Kercher [37].

Wolman (Zelen, [34]) attempted to develop a model that closely as possible represented specific real life situations but came to the conclusion that the equations can not be solved and no optimisation was possible.

Reliability of a system is highly complex and influenced by many variables. Each reliability model, in order to be workable, must make out of necessity simplifying assumptions. The problem is aggravated as the system development process progresses. During development the reliability influence variables can be controlled and curtailed to a certain extent, during production, the production processes add additional variables and during support, the operational as well as the support environment also impacts on the system reliability performance.

Malec [15] shows that the reliability performance of system as perceived by the customer is totally different to that perceived by the user. The user in fact experiences only small windows for each delivered system of the overall system reliability growth cycle.

The major emphasis of the reliability modelling effort in the literature has been focussed towards the system and its components with the objective of identifying and removing design and component defects early in the system development cycle. These models assume typical component and system stress values that would normally be experienced under environmental conditions.

This to a large extent explains why the impact of environmental factors such as man-induced failures and unproductive failures have to a large extent been neglected by the authors.

This does not imply that these techniques are not valid once the system is exposed to external factors that are typically being experienced in the operational environment. Indeed, the contrary is true provided the environmental conditions are kept identical as far as is practical. Very accurate changes in reliability performance and reliability forecasts can be achieved under operational circumstances. The case study PART IV will demonstrate how this is done in practice.

2. CONCLUSIONS OF THE LITERATURE SURVEY

Authors tend to cover segments of a systems life cycle such as the development, production or support phases (Halliday [3], Wright [7] and Koon [5]). A total life cycle perspective to system reliability is not provided to enable the various findings to be put into context.

The actual operational reliability of a system is different and always lower than the calculated reliability. This also confirmed by Kercher [37], Miller [44] and Malec [15]. The following explanation is suggested:

> During the design and development of a system, the reliability of a system can be sub-divided into the following three fundamental reliability types (Blanchard, [59]). Each of these types are totally different in concept to the other yet they are still related:
>
> **Allocated reliability**
>
> This is a top-down reliability allocation used in the product development specifications as part of the overall system's reliability budget for the different subsystems of the system. This reliability is a contracted reliability figure.
>
> **Calculated reliability**
>
> This is the calculated reliability performed by the system designer by means of summing the intrinsic reliability of all the components used in the design. Mil-Std-756B [29] identifies two types of calculations:
>
> - parts count - intended to assist the design engineer with his trade-off studies
> - parts stress, to calculate the inherent reliability of the design under typical operational stress conditions.
>
> **Tested reliability or achieved reliability**
>
> This is the actual reliability achieved by the design during the test phases of the programme.
>
> When the totally different nature of these reliability types is viewed in perspective, *it will be highly unlikely that they will agree.* In fact, if they do agree, the design reliability integrity must be viewed with suspicion and well for the following fundamental reasons:
>
> - the calculated reliability which is the inherent reliability of the design, should always be ***better*** than the allocated reliability to allow for a safety margin.

- the tested reliability should always be ***worse*** than the calculated reliability since the implicit implication of the calculated reliability is that the design has no latent defects. No design, particularly that of a complex system, can be flawless the first time round. There must be scope for the design reliability to grow towards the inherent calculated reliability.

The relatively straight forward way of inherent reliability calculation in accordance with Mil-Hdbk-217F [61], is used industry wide and provides a very good yardstick to compare competitive systems' reliability. The seller of a system must still prove that his design is indeed mature and will achieve acceptable reliability in operational use.

It is these aspects that prompted the need for further research into the reliability management of complex systems in a multi-level support environment which will be further discussed in PART III - 'Discussion of Logistic Engineering in a Reliability Context', and further illustrated with a case study in PART IV.

PART III

DISCUSSION OF LOGISTIC ENGINEERING IN A RELIABILITY CONTEXT

1. INTRODUCTION

The maintenance of a complex and sophisticated system requires considerable logistics support facilities and infrastructure at all levels of maintenance. Establishing and operating a logistic support system involves considerable effort and resources, (Blanchard [59], Lamb [60] and Mil-Std-1388-1A [64]).

An effective support system must be designed to trade off the customer probability of success needs against the resultant cost of ownership that will be experienced (namely the customer should establish a value system). A logistic system must be planned to satisfy the customer value system. Mechanisms must be provided to measure logistic support system performance against the customer value system. Management systems must be provided through which the logistic system can be optimised, (Blanchard [59] and Mil-Std-1388-1A [64]).

During system acquisition not only the system itself, but also the support system, must be commissioned and set to work. In order to obtain a stable and repeatable support system environment it is necessary to develop the required methods, processes and procedures that define how the support system is to be actually operated.

These logistic engineering processes are applied at Kentron [67]. The descriptions of the logistic elements form part of an in-house training course for system engineers and support managers.

1.1 PROBLEM STATEMENT

A system, once it reaches the support phase, will not naturally go into the constant failure rate as predicted by the bath-tub hazard function. This trend has also been confirmed by Wong [39] and [48].

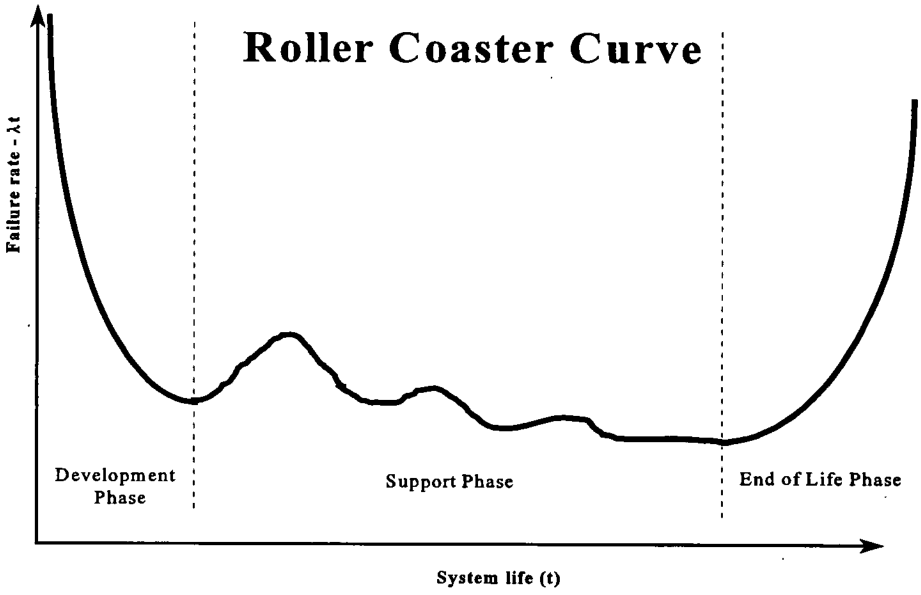


Figure 1.1.1: The *Roller Coaster* hazard curve

From practical experience this effect is also confirmed in that a complex system in the support phase tends to follow a diminishing oscillatory rate as shown in figure 1.1.1.

The end purpose of any system is operational availability at the lowest life-cycle cost (LCC). If the operational availability follows an unpredictable trend, operational and business planning is not really possible. This effect will also impact negatively on the system life-cycle cost, making effective budgeting difficult.

It is therefore essential that the system failure trend be controlled towards a constant failure rate for the duration of the life cycle of the system as illustrated in figure 1.1.2.

From the work done by Wong [39] and also from years of practical engineering experience in the system support environment, the constant failure rate region as predicted in the literature does not take place naturally but requires a holistic support management approach. This effect is also illustrated in the case study presented in PART IV.

A constant failure rate of a system can only be achieved by sound support management backed up by an effective logistic infrastructure.

The literature to a large extent covers the development phase of the product. The modelling and techniques for the development of a reliable product has progressed considerably since Duane's bench mark paper in 1964, [14].

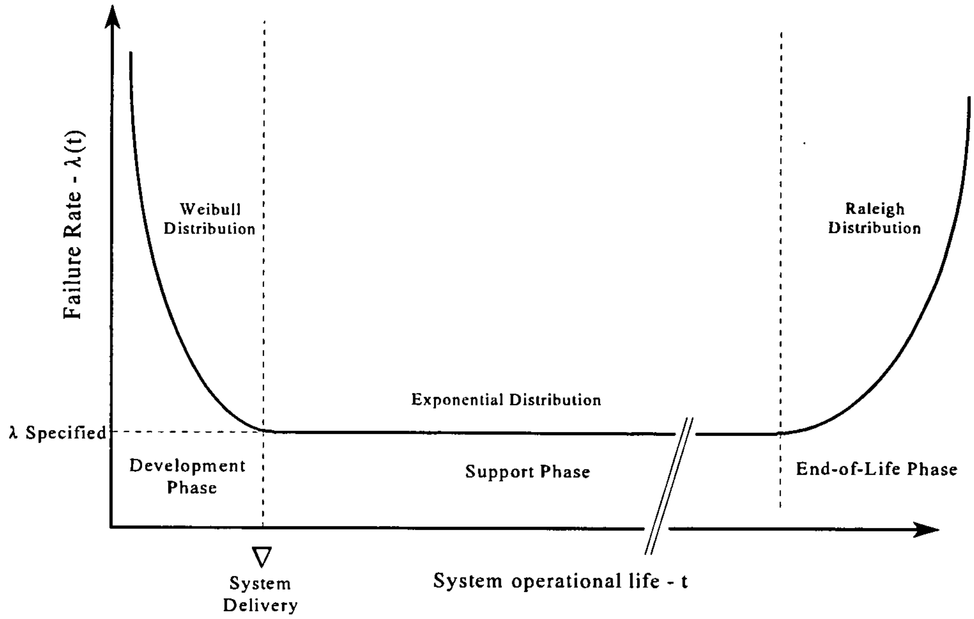


Figure 1.1.2: An optimally managed hazard function

However, as will be shown in this research work, the fundamental difference between the development phase, production phase and the operational phase for a system, is the exposure of the system to the operational environmental conditions and the impact of the logistic elements.

During the development phase, the reliability growth focus is on the system since the development environment is controlled. This reliability is based on predicted operational environmental factors.

During production, the production process impacts on the system reliability and a similar growth must take place to ensure consistent reliable system production.

Once the system is deployed in the operational environment the system is exposed to the actual operational environment and influence of the logistic elements required to support the system as shown in figure 1.1.3 shows the system reliability degradation as it progresses from development to the support phase.

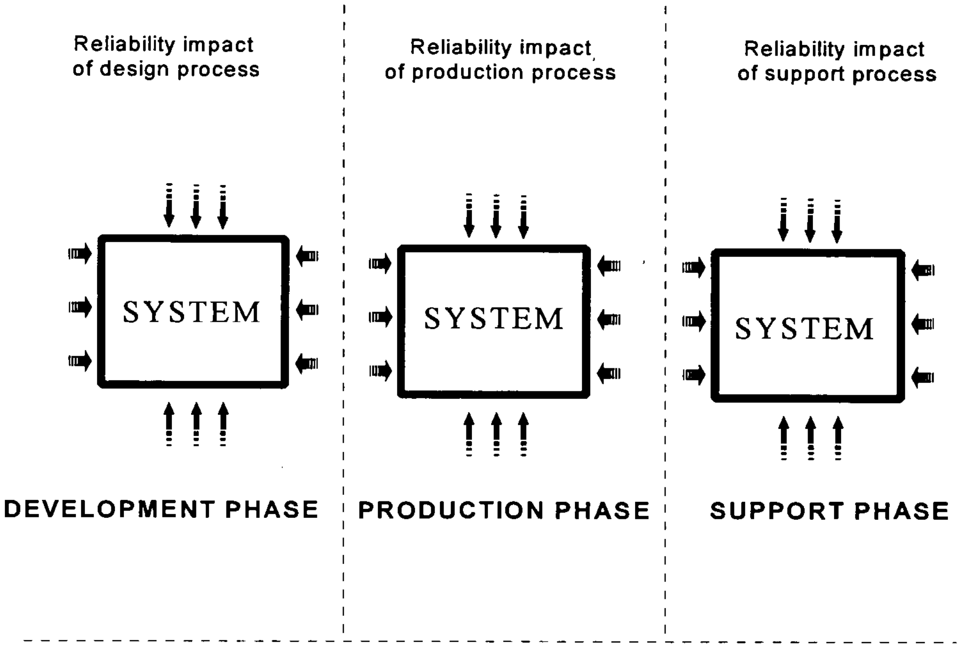


Figure 1.1.3: System reliability degradation

The modelling and techniques developed in the literature to be used during the development phase of the system can be transcribed to the support phase provided that due cognisance is taken of the impact of the logistic elements as well as the operational environment to which the system will be subjected.

Successful recovery of a system displaying poor operational reliability is possible by means of a second reliability growth programme in the support phase as illustrated in figure 1.1.4. There are however a subtle differences to such a reliability growth programme than would be the case during the development phase.

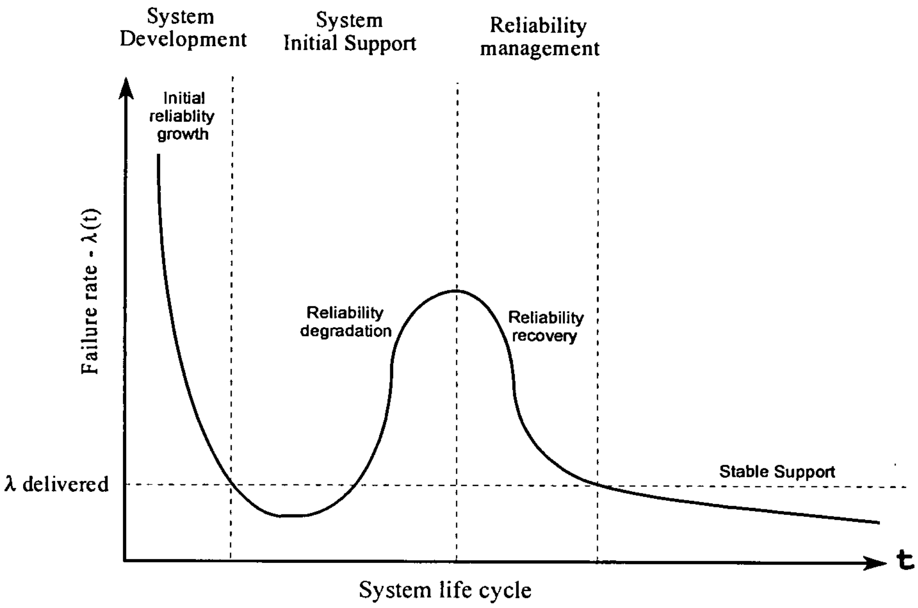


Figure 1.1.4: Reliability management in the support phase

In chapter 2, the system engineering process, reliability growth process, impact of the environment and logistic support infrastructure on reliability will be discussed. This will be followed by a discussion on closed loop support management utilising FRACAS and corrective actions to close the system support management loop.

In chapter 3, the reliability growth in the support phase and a recommended approach will be discussed.

2. PROBLEM ANALYSIS

Reliability growth in the support phase can best be achieved through a thorough understanding of all the underlying processes. A clear view must be obtained of how the system originated and what processes were applied to bring it to the operational support environment: in particular the system engineering process with the logistic engineering process in parallel to provide the logistic infrastructure of the system; also concurrently the reliability growth process of the system from the conceptual design phase.

Once these processes have been understood, a clearer view of the management requirements for reliability growth during the support phase of a system can be achieved.

2.1 SYSTEM ENGINEERING PROCESS

A knowledge of the system engineering process is required for a better understanding of the system once it is deployed in its operational environment, (Blanchard [59] and Lamb [60]).

If abnormal problems with a new system are experienced in the operational environment, there is a strong possibility that something has gone wrong upstream during the development or production processes in the early life of the system.

In fact a reliability problem experienced with a system in the support phase can only be due to latent defects not eradicated during the development and production processes of the system or as a result of deficiencies in one or more of the logistic elements of the support infrastructure of the system.

Since these two effects are mutually independent, they can occur simultaneously taking problem diagnostics and corrective actions difficult.

A good understanding of the integrated system engineering process which result in the development of the system and simultaneous development of the logistic infrastructure to support the system is essential.

The development of a system generally goes through a number of phases depending on the complexity and technology thereof.

Blanchard [62] identifies these phases as:

Conceptual preliminary design phase.

The purpose of this phase is primarily to define the system functional requirements and constraints as well the as the operational environment.

These requirements and constraints are then verified against the client/market needs. Trade-off studies are performed to optimise the system concept. If accepted, the system functional requirements, constraints and operational environmental requirements are incorporated into a functional specification generally referred to as an A-Specification.

Full Scale Development Phase

The functional specification requirements and constraints are allocated and subsystems requirements are specified, typically referred to as a B-specification. It is against the B-specification that the design engineer develops the design of the subsystem.

Once the functional requirements and constraints have been allocated, FMECA is performed parallel with the detail design process. The objective of the FMECA is to predict system behaviour should any of the functions or components fail. The FMECA also classifies the detection of each failure mode in terms of a visible failure or a hidden failure.

Initially the design is influenced from a logistic and system engineering requirement, to improve design robustness against relatively minor functionality failures. Hidden failure modes are as far as practical driven from the design. An effective way of achieving this with complex systems is to incorporate build-in test equipment (BITE) which monitors each sub functionality of the system. Should a functionality fail, a built-in test (BIT) flag is generated to identify the failure and direct the repair action. Those failures that can not be practically covered by BIT, must be classified during the LSA as condition monitoring or inspection tasks.

The FMECA at an early stage identifies the critical functions and components of the system. Reliability analysis is performed to establish the inherent reliability of the design and to confirm that this is at least better than the specified requirements.

Reliability predictions, assumes a mature design. During the early phases of development, the design may have inherent flaws which impact negatively on the initial reliability. These latent defects must be driven from the design using stress testing under simulated environmental conditions and accelerated life testing. This process is referred to in the literature as reliability growth. The design process aims to improve the technical performance as well as the reliability performance of the design through iterative cycles of improvements (Krittter [6], Seusy [8], and Wong [39]). The reliability growth process and management techniques have been collated and summarised in Mil-Hdbk-189 [27].

Maintainability is addressed in a similar fashion during the design process but only after it has been established that the subsystem or component reliability is less than required during exposure to the operational environment over the life cycle of the system. These subsystems and components are identified on the system family tree and classified as maintenance significant items. The design is influenced to that extent that will facilitate easy and cost-effective repair and replacement of the maintenance significant items.

Once the system design has been fixed and no further design influence from a logistic perspective is possible, the logistic infrastructure required to support the system is developed. The logistic infrastructure must be in place before delivery of the first production systems.

The integrated system engineering process is shown in figure 2.2.1

The client could be an actual client for which the system is being developed or the marketing manager for a specific target market for the system.

Any deficiency or incompleteness of this process during a system's development will have direct negative impact on system performance during the support phase where these latent deficiencies are bound to surface as illustrated in the case study in Part IV.

2.2 RELIABILITY GROWTH PROCESS

The literature survey covered a selected cross section of publications from the pre-Duane era to present. Most of the reliability growth principles and techniques have been collated in Mil-Hdbk-189 [27]. It is now widely accepted that reliability growth follows a Weibull process. The constant failure rate region of the bath-tub hazard function is generally accepted to represent the system support phase. This constant failure rate portion of the bath-tub hazard function is a special case of the Weibull distribution where the shape factor, $\beta = 1$ and α is the scale factor, then from equation (1.2) part II:

$$\lambda(t) = \frac{t^{\beta-1}}{\alpha^{\beta}}$$

$$\lambda(t) = \frac{1}{\alpha} \tag{2.1}$$

$\lambda(t)$, the failure rate, is constant resulting in the exponential distribution function. Therefore the exponential distribution is only a special case of the Weibull distribution, (Ramakumar, p115, [51]). From this the conclusion that reliability during the support also follows a Weibull process can be made and as such all the models developed from the technical research papers in part II, chapter 1.2.2, should be valid.

2.2.1 TYPES AND MEANING OF RELIABILITY

Three fundamental types of reliability are applicable throughout the system engineering process from system development to support. The differences and constraints of each type of reliability must be clearly understood for successful management of reliability of system during the support phase.

Allocated reliability

The system engineer specifies the allocated reliability of each configuration item according to a top-down allocation process from the client's reliability requirement in tabular form. Since this will generally lead to unrealistic low reliability requirements of the subsystems, it is therefore recommended that a column be added to the table to list the design goal of each configuration item.

The design goal will be determined by means of bottom-up approach using the practical reliability of known subsystems and components as calibration points to determine the reliability for the remainder of the system.

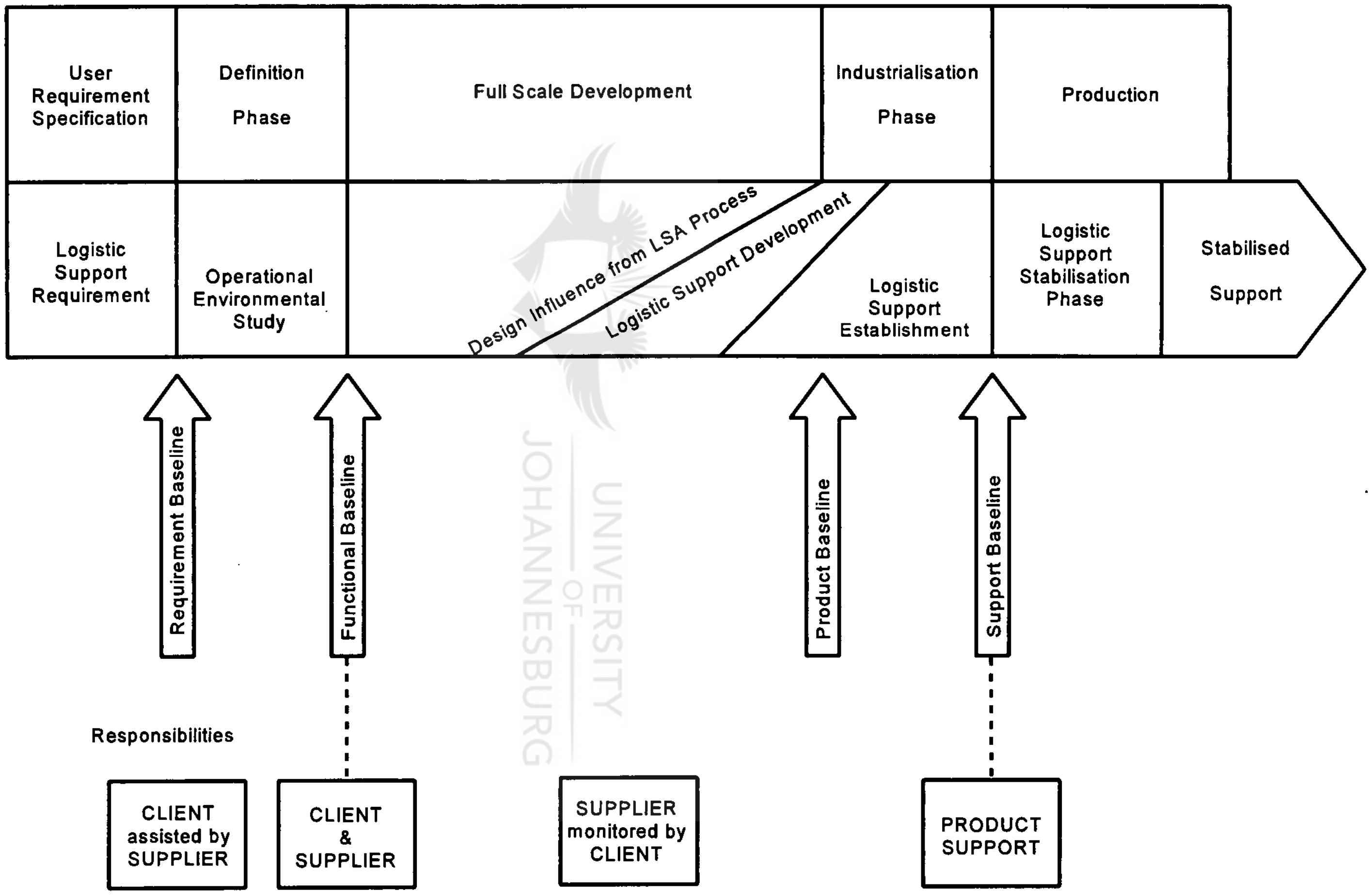


Figure 2.2.1: The integrated systems engineering process

Inherent reliability

The design engineer is responsible for the inherent reliability of his design. This reliability must be calculated using approved data and techniques such as Mil-Hdbk-217F [61]. The Mil-Hdbk-217F parts-count technique is used early in the design during the design trade-off studies whilst the parts-stress technique which takes the anticipated operational environment into account, determines the inherent reliability of the final design.

The inherent reliability calculation may also be based on known similar applications of the applicable components of the design. In this case, the evidence must be included in the design document to substantiate the calculation, (Mil-Std-756B [29]).

The design engineer must optimise his design to ensure that the calculated inherent reliability is better than the specified reliability in the B-Specification.

Achieved Reliability

The objective of the achieved reliability is to be able to demonstrate in a cost effective manner that the design has reached sufficient maturity to achieve the specified reliability once deployed.

Figure 2.2.2 depicts the a typical reliability growth process for a small volume system, during development.

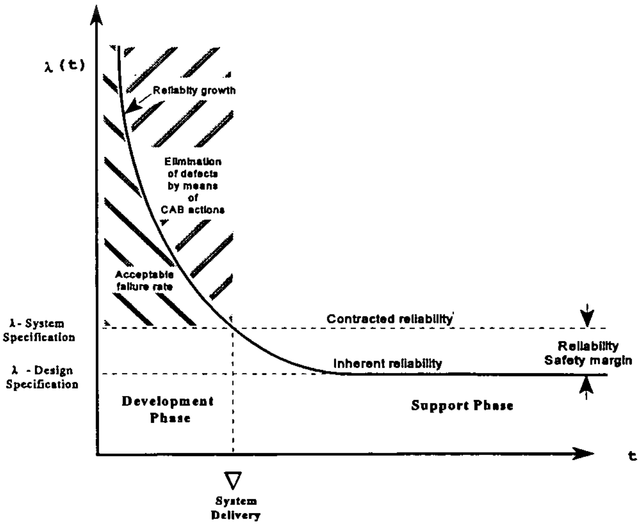


Figure 2.2.2: Typical system reliability growth strategy

Mil-Hdbk-189 [27] states that the failure rate during development follows a Weibull distribution of the type:

$$m(t) = [\lambda \beta t^{\beta-1}]^{-1} \qquad (2.2)$$

Where *m(t)* is the instantaneous MTBF, λ the failure rate and β the shape factor.

O' Connor [50] shows that by plotting the cumulative failure rate on log-log graph paper, enables accurate extrapolation and final reliability prediction.

Premature release of a system before reliability growth has been completed will result in these latent defects to surface during the support phase. This must then be corrected under warranty in the field as illustrated in figure 2.2.3. Apart from the financial implications of retrofitting operational systems, it also leaves a generally negative perception of the system's reliability with the client as illustrated in the case study discussed in part IV.

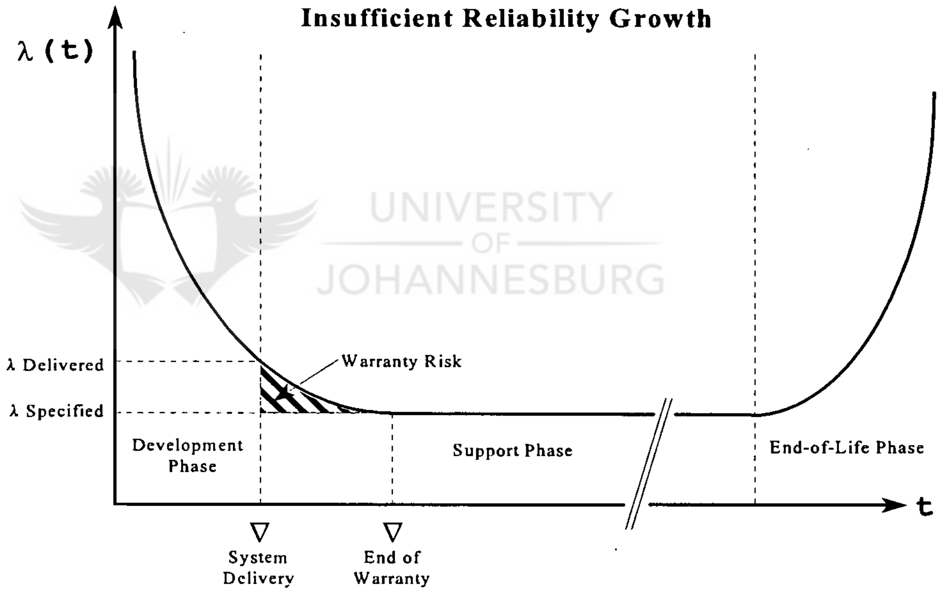


Figure 2.2.3: Premature system delivery

2.3 IMPACT OF ENVIRONMENT ON SYSTEM RELIABILITY

Reliability growth during development, is focussed on driving out any latent defects from the system using a process called reliability growth These techniques are well documented in the literature, Barlow [52], and the complete process summarised in Mil-Hdbk-189 [27].

During development, the system is exposed to development environmental factors. The system is qualified in the development phase, using simulated environmental conditions obtained from environmental studies during the exploratory phase as described by Blanchard [59] and [62].

Operational environmental conditions can only be predicted and can generally not be controlled unless special operational and logistic constraints are utilised. The system should behave orderly as far as practical during abnormal environmental conditions to ensure a robust design. Minor failures in a complex system should not result in total system failure but rather the aim should be a degradation in performance under such circumstances.

The BIT philosophy has a direct impact on design robustness. If BIT is integrated as part of the particular system sub function, it is possible that a failure of the function may not be detected and allowed to propagate to the end function of the system. Any failure of a subsystem function, will result in total system failure in these circumstances as shown in figure 2.3.1.

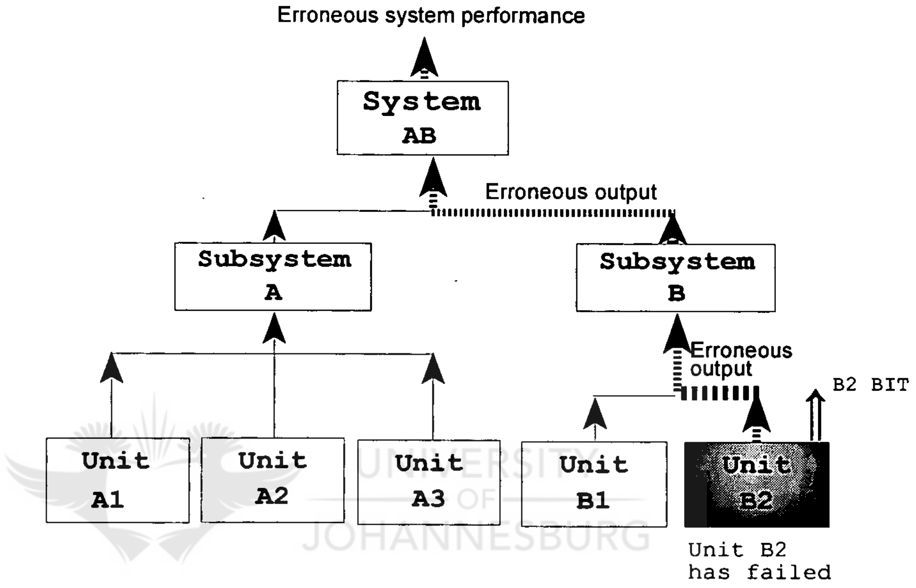


Figure 2.3.1: BIT philosophy as part of the design functionality

However if the BIT philosophy is to monitor the performance of the sub-function at the next higher level, detection of a malfunction will always be possible. The next higher level function could also buffer the effects of the malfunction to prevent its propagation through the system. A failure of a sub-function will not necessarily result in total system failure. The system may be able to continue its intended function, albeit at a reduced performance, as shown in figure 2.3.2.

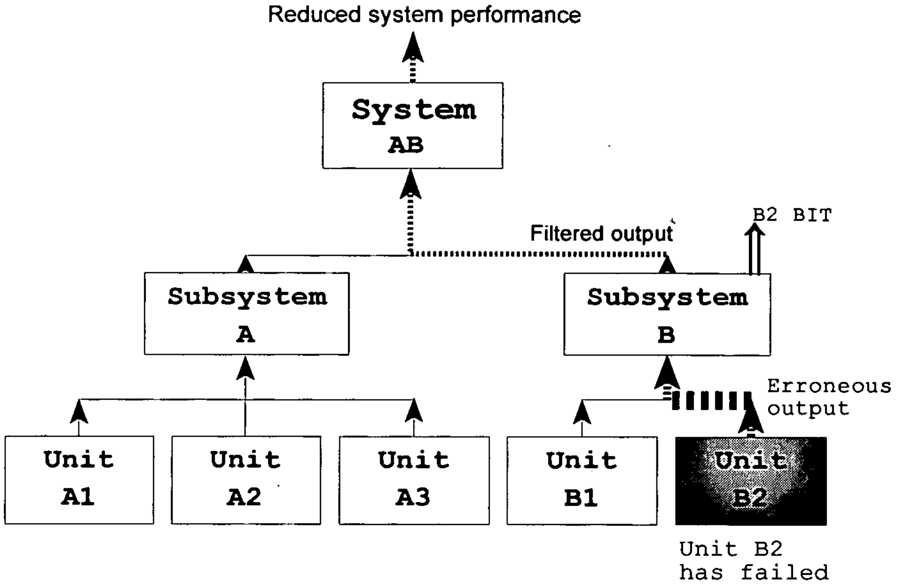


Figure 2.3.2: BIT philosophy as part of the next higher functionality

Once the newly developed system has reached the technical and reliability maturity, the production data pack is released for production. In production the newly developed system is industrialised and prepared for production. The production process is qualified typically by building a number of pre-production or pilot production (PPM) models, (Lamb [60], Wright [7]).

It is important to take cognisance of the fact that the output of any development process is not only the newly developed system data pack but also the production data pack specifying the production processes required to produce the newly developed system.

In production, the system is exposed to new environmental factors and production processes which invariably impact negatively on reliability.

To qualify the production process to ensure a repeatable and reliable system can be consistently produced, it is common practice to produce a number of pre production models or pilot production models (PPM). Once the PPMs have been qualified for repeatable performance and acceptable design reliability, can full scale production start. The objective of the PPM process is therefore amongst others to provide a production process reliability growth of the system to ensure that the system as designed is in fact produced and delivered to the client.

During the support phase a similar reliability growth process must take place after all the logistic elements have been established, the system support must first go into a stabilisation phase where all the logistic elements are fine tuned for optimum system availability at the lowest LCC.

2.4 DESCRIPTION AND PURPOSE OF THE LOGISTIC ELEMENTS

For the management of reliability in a complex support environment, a thorough understanding of all the logistic support elements and their interaction is required since any deficiencies in these areas can also result in poor system reliability performance.

The logistic elements may be grouped and defined differently depending whether it is from a user perspective or from a system supplier perspective.

The reason for the difference is that the supplier of the system will define and group all the logistic elements which he must provide under the system supply contract whilst the user will define and group the logistic elements together which the user must provide to the system supplier as customer furnished items.

In this research work, a holistic view is taken and the completeness and effectiveness of each logistic element will be evaluated. The logistic elements, Mil-Std-1388-1A, [64], can be grouped into two broad categories as illustrated in figure 2.4.1:

- operations logistics which is the primary logistic process
- engineering logistics which is the secondary logistic process

Logistic engineering support tie these two groups together into an integrated support system.

The primary process runs through the logistic chain. The secondary process supports the facilities to ensure that the primary process functions optimally.

Integrated logistic support (ILS) combines the secondary process with the primary process to ensure that the required service levels are maintained. Life-cycle cost is managed through system and support system improvements traded off against maintenance cost as shown in figure 2.4.2, (Blanchard [59]).

OPERATIONAL SUPPORT

Operational support pertain to all the operational logistic activities and resources required to perform repair activities which will bring a failed system back to its original state, (Healy [10]).

The operational logistic activities are those activities required to define the performance parameters, to accumulate data, to evaluate the data, to identify trends and to make these trends visible. These trends are then followed-up by initiation of pro-active steps to adapt the system and the support system to ensure optimum performance.

Infrastructure and Facilities

The infrastructure and facilities logistic element specifies all the infrastructure requirements in order to perform system support. This includes all the facility requirements for the established logistic elements to support the system. Typically this would include buildings (workshop-, storage-, training- and general office areas), facility equipment such as power, compressed air, hoists as well as all test equipment, tools, jigs and fixtures, (Blanchard [59], Mil-Std-1388-1A, [64]).

A deficiency in this element can impact adversely on system reliability in the support phase such as poor electro-static discharge (ESD) protection on work benches can cause latent degradation of electronic components. Also inadequate air conditioning and filtering when opening sensitive mechanical sub-assemblies, can introduce moisture and dust which may seriously degrade the life of these components.

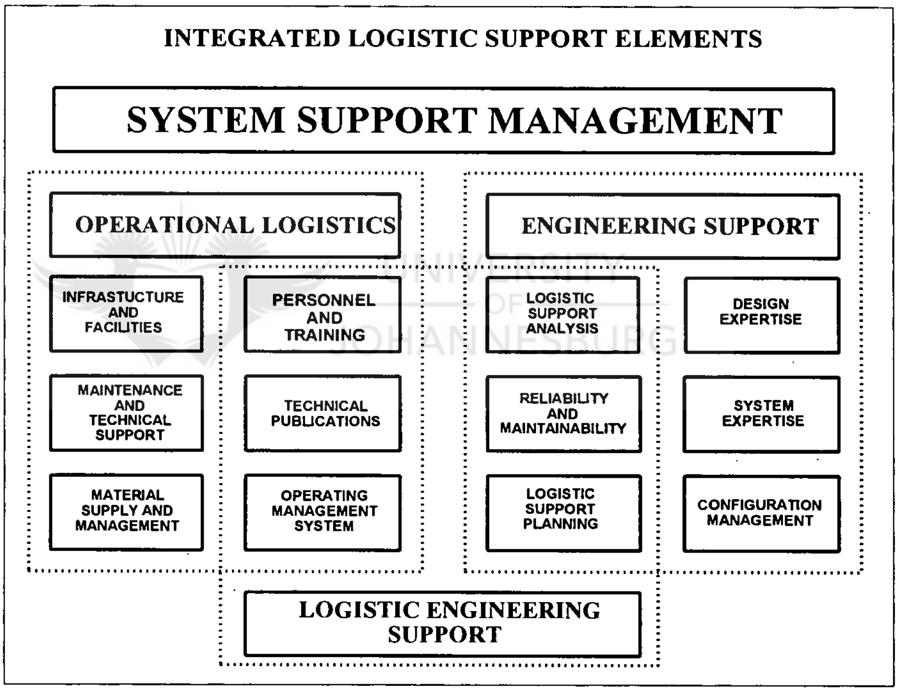


Figure 2.4.1: Logistic support elements

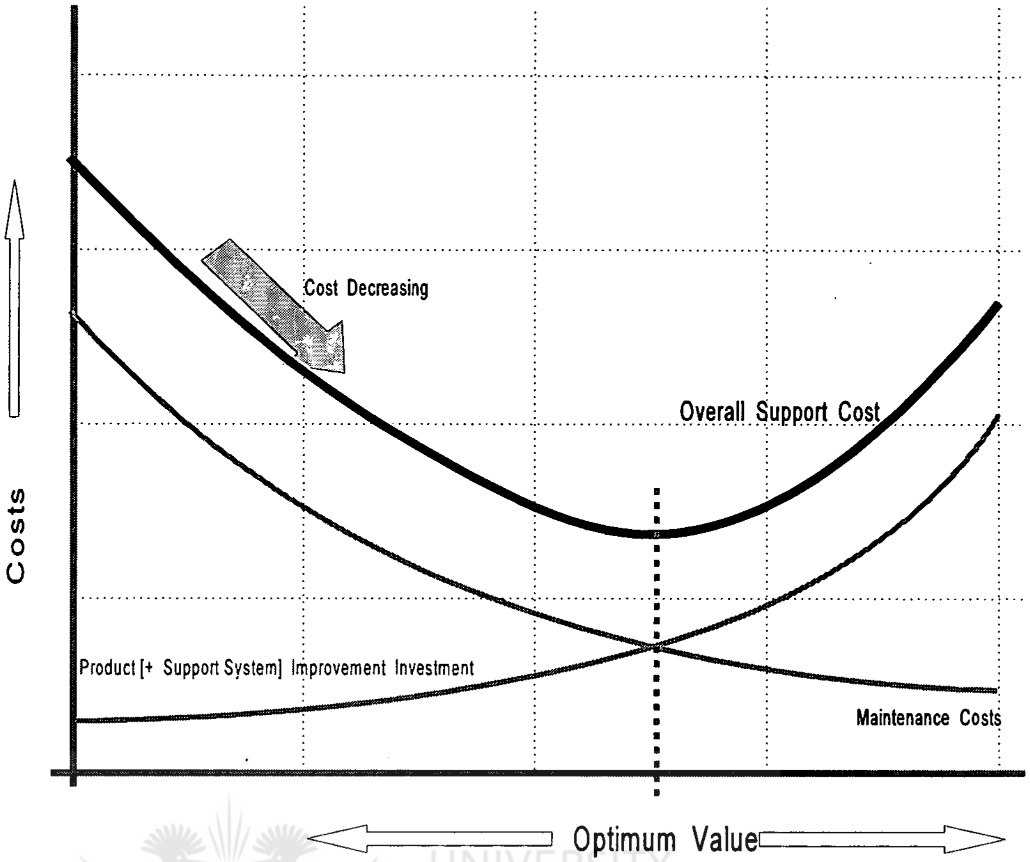


Figure 2.4.2: Support cost trade-off

PERSONNEL AND TRAINING

The *Personnel and Training* logistic element specifies the personnel quantities, skill levels and training requirements to enable effective support of the system. A typical man-profile would include background, academic training, job-level, trade, job-specific training, general skill levels namely competencies, general technical skills such as computer literacy etc., (Blanchard [59], Mil-Std-1388-1A [64]).

Analysis of the overall logistic support requirements must dictate the training which must be optimised on a task driven, competency based philosophy. Follow-up and retraining of personnel must not be neglected to avoid establishment of poor practices. Figure 2.4.3 illustrates the optimisation process and the derived benefits.

Inadequately trained staff may result in faulty diagnosis (Repeat failures, No fault found), incorrect or incomplete repairs and latent or direct damage to equipment.

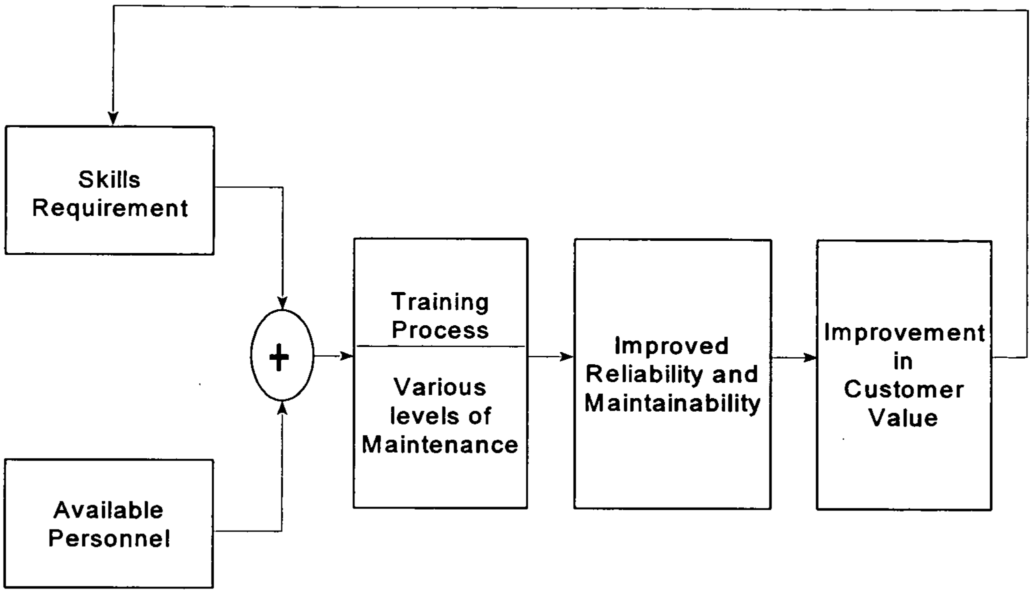


Figure 2.4.3: Optimisation of training

MAINTENANCE AND TECHNICAL SUPPORT

The *Maintenance and Technical Support* logistic element specifies in the form of a maintenance plan, how the maintenance and support processes is to be performed inclusive of the physical repair activities as well as which organisation is responsible for each logistic element.

The maintenance plan for an item of equipment must be tailored to fit the maintenance structure of its ultimate customer. Each individual maintenance structure reflects the customer's organisation philosophical approach to maintenance, or the maintenance philosophy.

The maintenance concept is based on the customer's maintenance philosophy. The maintenance concept is a statement of general guidelines to be used in developing a detailed maintenance plan for a system or an item of equipment.

Maintenance tasks are typically defined as follows:

Corrective maintenance

Corrective maintenance tasks restore a failed item to its specified condition through repair, adjustment, alignment, overhaul or rebuild. This is also referred to in the literature as unscheduled maintenance or breakdowns, (Blanchard [59]).

The flow of repair items through the different levels of support is illustrated in figure 2.4.4. Figure 2.4.5 illustrates the detail repair-item flow in the workshop.

Preventive maintenance

Preventive maintenance tasks systematically inspect, detect and correct incipient failures either before they occur or before they develop into major failures. This is referred to as scheduled maintenance and could typically consist of condition monitoring or inspections, calibrations and servicing tasks.

A support level structure consists of a number of organisational levels where various support activities are accomplished. The three traditional support levels are:

Organisational Support

This level of support is typically the responsibility of the customer and consists of inspection, servicing, adjustment, removal and replacements. A prime objective of organisational support is to restore system availability in the shortest possible elapsed time.

Intermediate Support

This level of support is typically performed by an organisation dedicated to the direct support of the customer's organisational support system and consists of calibration, fault identification, repair and replace.

Depot Support

This level of support is typically performed by the manufacturer of the system, or a dedicated third party organisation, and supports both intermediate and organisational support levels. The depot support level normally employs more extensive facilities and equipment together with personnel with higher level skills than the organisational and intermediate support levels. Depot-level support tasks typically include repair, modification, overhaul and reclaim of parts, assemblies and subassemblies.

Typically depot-level support would be in the country of the operational system whilst manufacturing-level support would be in the country of origin. In this case an extra level of support, manufacturing or M-level, is very often defined for the system.

Depot/M-level support must provide all the engineering logistic elements for the system and technical support for the operational and intermediate levels.

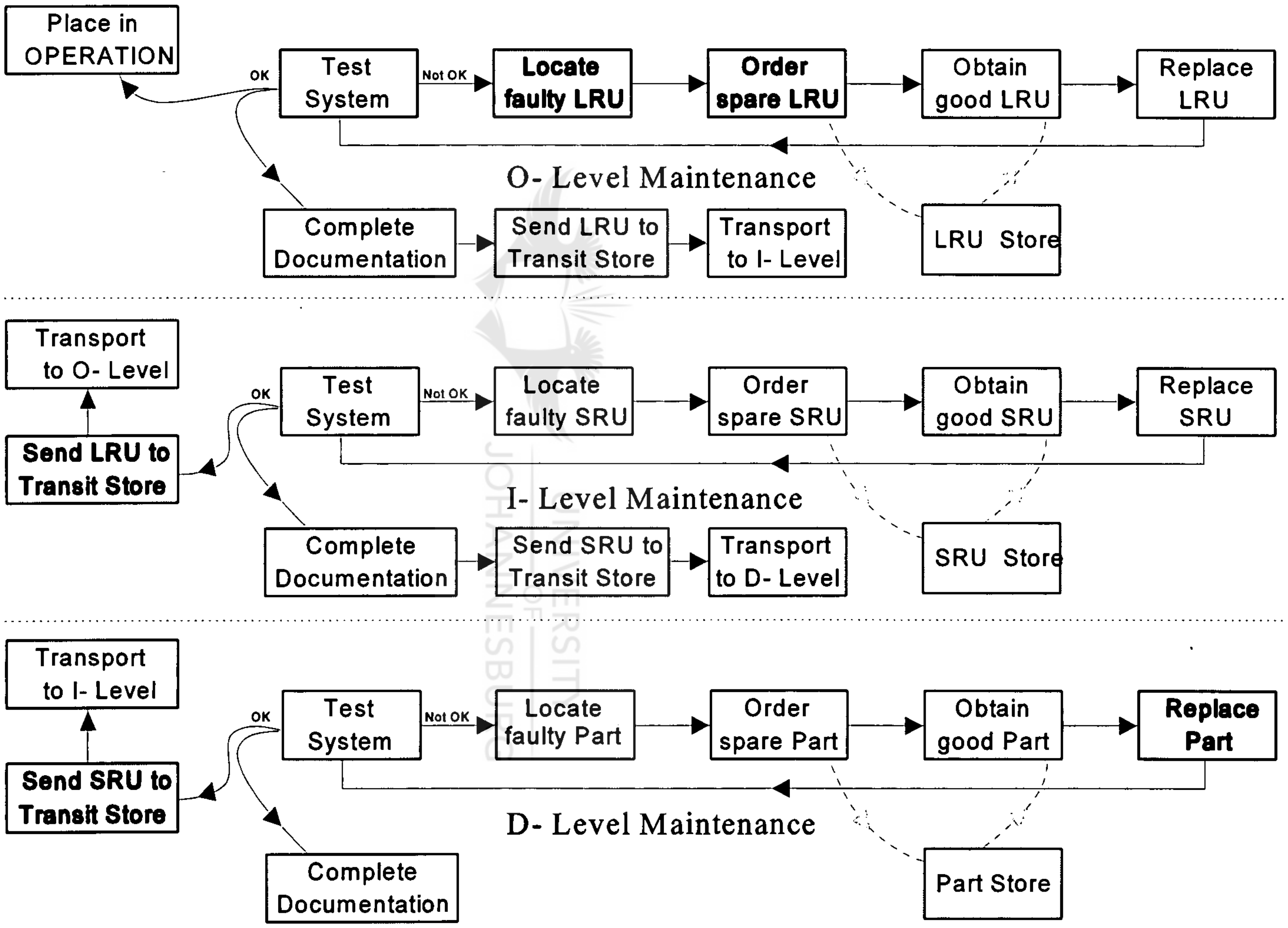


Figure 2.4.4: Maintenance flow over a multi-level support system

The logistic element - *Maintenance,* is the hub for reliability management in a multi-level support environment. All the system repair actions as well as the corrective retrofit tasks flow through the different support levels. Any deficiency in this work flow and repair process at any level, can introduce latent defects into the system, which will impact negatively on the system reliability.

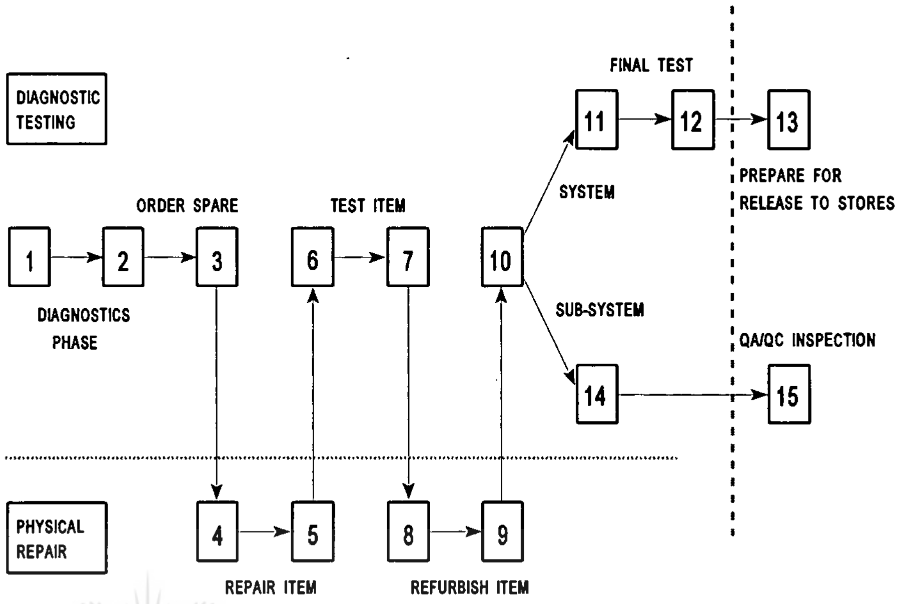


Figure 2.4.5: Typical repair item flow through a workshop

TECHNICAL PUBLICATIONS

The *Technical Publications* logistic element ensures that all the operating and maintenance documentation is available at the different levels of support. Interim updates are typically provided by means of service bulletins until a formal revised issue of the appropriate document, instruction or manual is published.

Technical publications is the activity that ensures that all the operators and maintenance manuals are available at the different levels of support. Interim changes and updates are handled by means of service bulletins. The maintenance manuals and service bulletins must also specify their applicability to the configuration status of the system repair-items.

The logistic element *Technical Publications* must ensure that all changes as a result of corrective action are made available to all maintenance personnel at all the levels of support. A deficiency in this element can result in a permanent fix for a latent system defect, although it has been developed, may not be made available to all maintenance personnel or there may be mistakes in the instruction which could impact negatively on system reliability.

MATERIAL SUPPLY AND MANAGEMENT

The *Material Supply and Management* logistic element specifies the packaging, handling, storage and transportation of both repair-items and the spares with the objective of ensuring optimum availability at the lowest inventory cost. Figure 2.4.6 illustrates the spares management process.

Spares replenishment procurement is also part of the portfolio of this logistic element. Spares inventory management must form an integral part of the support process to be effective and is illustrated in figure 2.4.7.

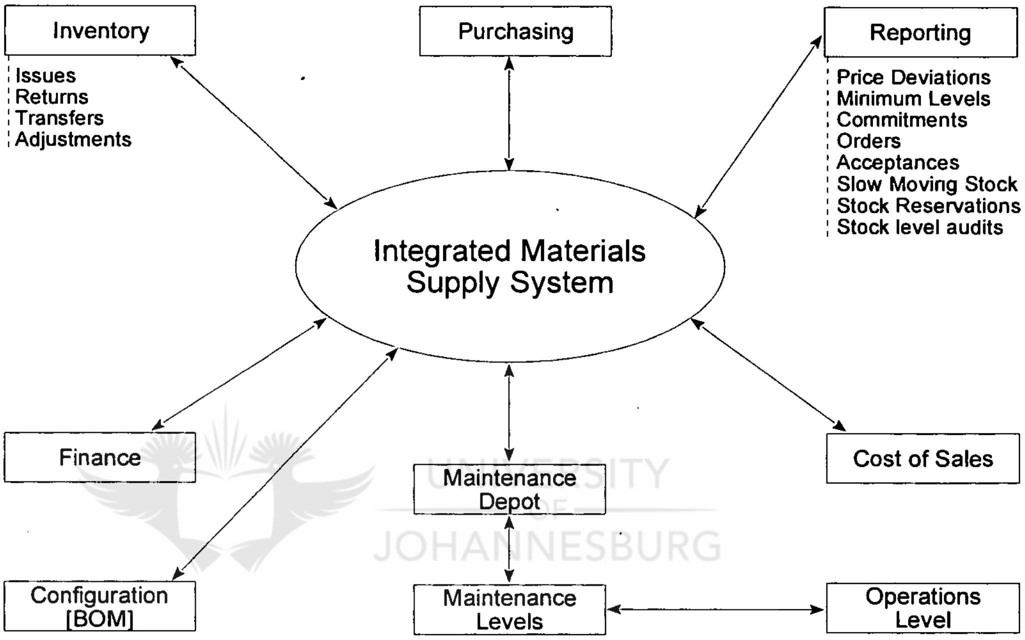


Figure 2.4.6: Spares management as part of the support process

Spares stockholding in general is a very high cost item. Spares quantities must be properly managed to optimise stockholding and ordering costs. The trade-off curve is shown in figure 2.4.8.

This logistic element can have a large impact on the reliability of a system during the support phase. Experience has shown that poor packaging, handling and storage practices to be one of the major causes for poor system performance during the support phase. To ensure a reliable correctly performing system, spares must always be procured from an approved supplier. Spares must remain in the original packaging and handled and stored in accordance with the supplier's prescription. To this effect, spares for support must never be packed in bulk packages but rather in individualised spares-kit packages with sufficient quantities for a single repair action to avoid compromising system reliability.

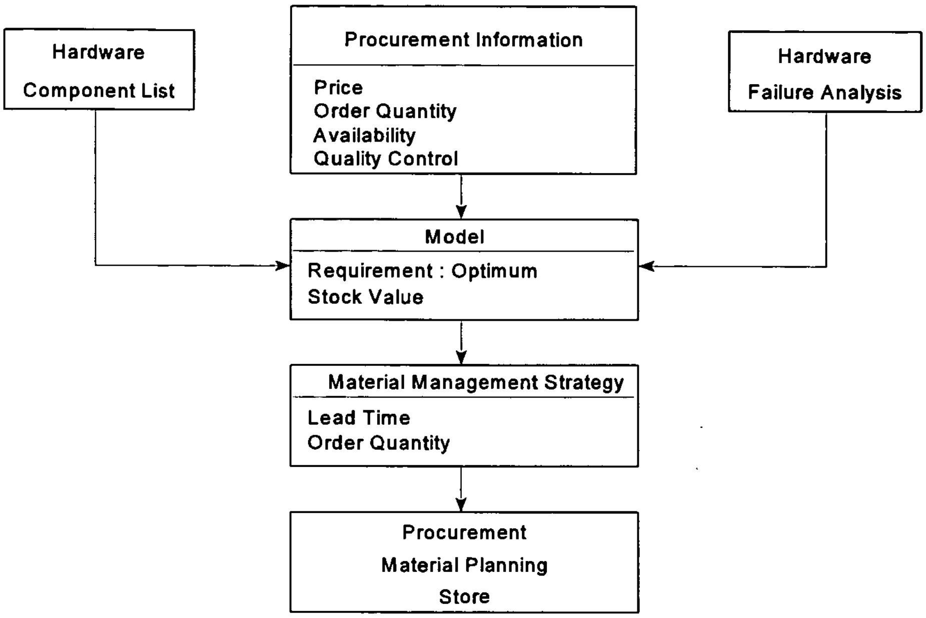


Figure 2.4.7: Spares supply process

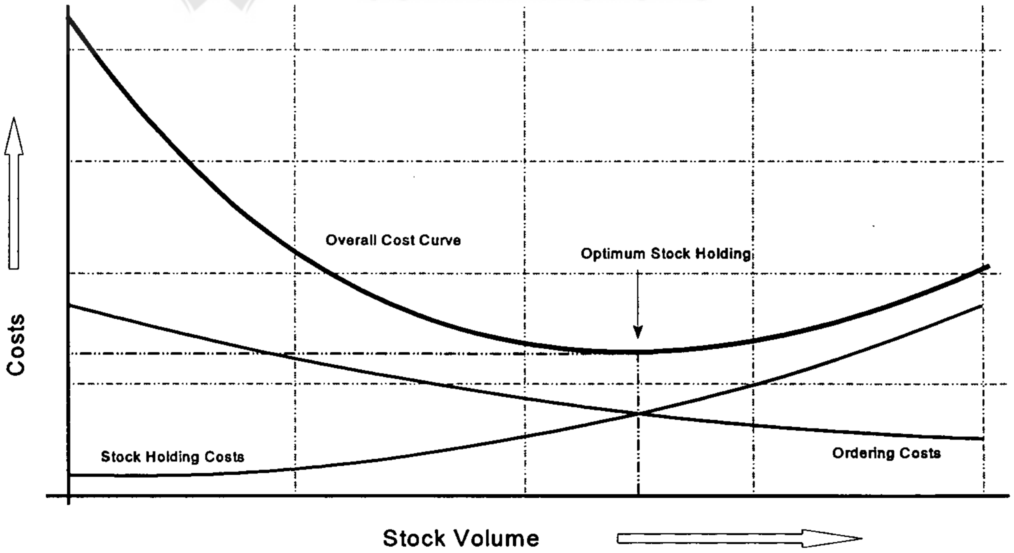


Figure 2.4.8: Stock cost control optimisation

In a multi-level support system at each support site, the *Material Supply and Management* logistic element apply and must be co-ordinated into an integrated system. This will be further described in paragraph 2.5 - Operational support Management.

OPERATING MANAGEMENT SYSTEM

The *Operating Management System* (OMS) logistic element specifies how the operations and repair activities over the different levels of support are to be managed. The maintenance planning and control generally forms the hub of the support activities through the issue and archiving of job-card records. In the support environment, FRACAS is an integral part of the repair job-card since this is the logical vehicle for capturing both reliability data (mean time between failures) and maintainability data (resources consumed such as spares and labour).

The extent to which a support programme can be managed depends on the visibility that exists to assess the status of the individual activities of the programme.

The extensive nature of potentially useful management data such as component part status, location, MTBF and MTTR, cost control, schedule control within a logistic support environment, is such that without the aid of an OMS database visibility and subsequently the management effectiveness and cost optimisation is severely restricted, (Golant [16], Reyerson [24]).

The effectiveness of an OMS depends largely on the capability of the OMS to reliably capture large volumes of elementary data, manipulate and process that data to produce useful report information to management.

Logistic data should be centralised and organised to provide easy access to all parties involved as illustrated in figure 2.4.9.

The OMS must provide a computerised database by which all significant data can be captured, controlled, interrogated and analysed. The OMS provides the visibility structures whereby the overall system support programme is optimised and managed as shown in figure 2.4.11. The figure illustrates the overall management process for repair items starting with maintenance visibility structures, repair work in process management, communications, feedback and follow up and finally closing the management loop through measurement and control.

Typical primary OMS functions are:

- to provide pro-forma user selected visibility into the data associated with logistic support such as equipment, resources and activities
- to provide pro-forma standard data input and validation mechanisms for the users

- to provide pro-forma standard data output reports for the users

- to provide interrogation tools by which users may develop (save and delete) new (non pro-forma) visibility into the data within the OMS.

- to provide reporting tools by which the users may develop new reports types.

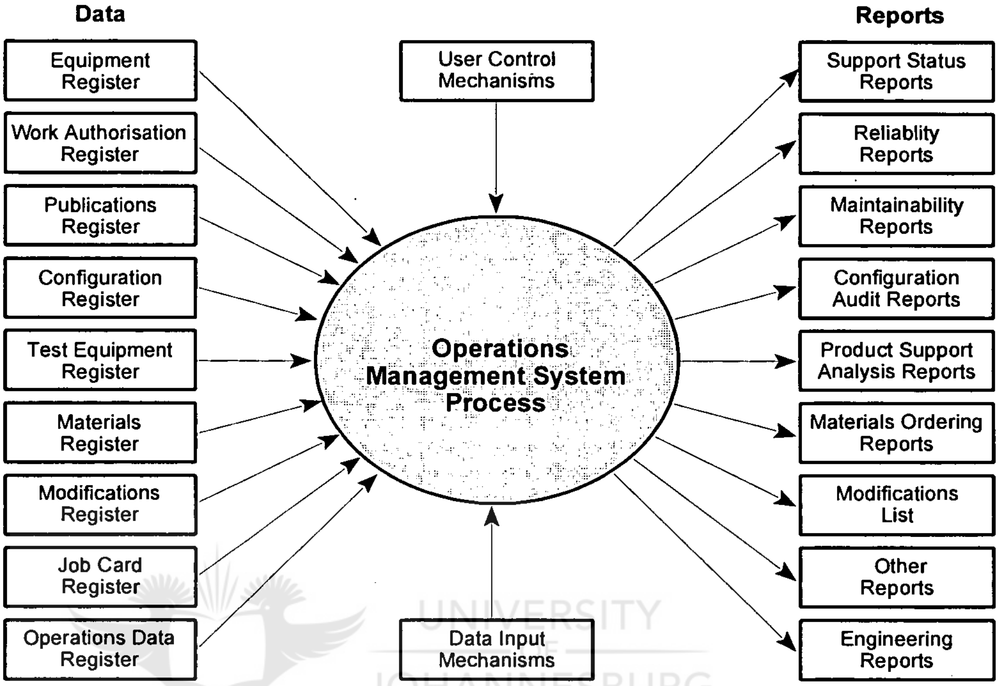


Figure 2.4.9: Basic operation management (OMS) function

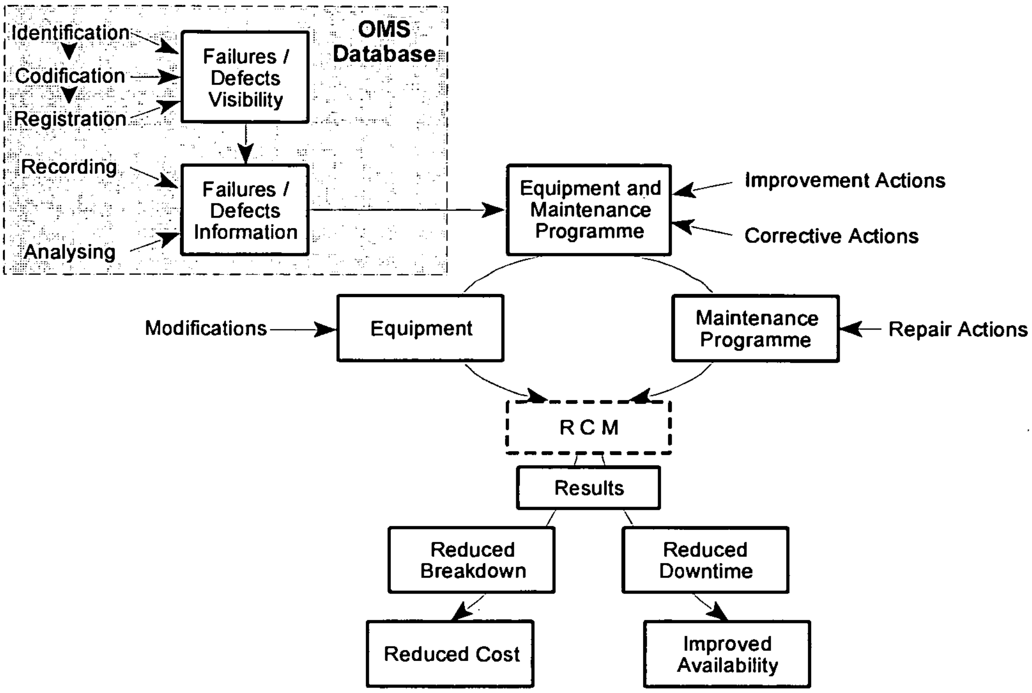


Figure 2.4.10: OMS as part of FRACAS

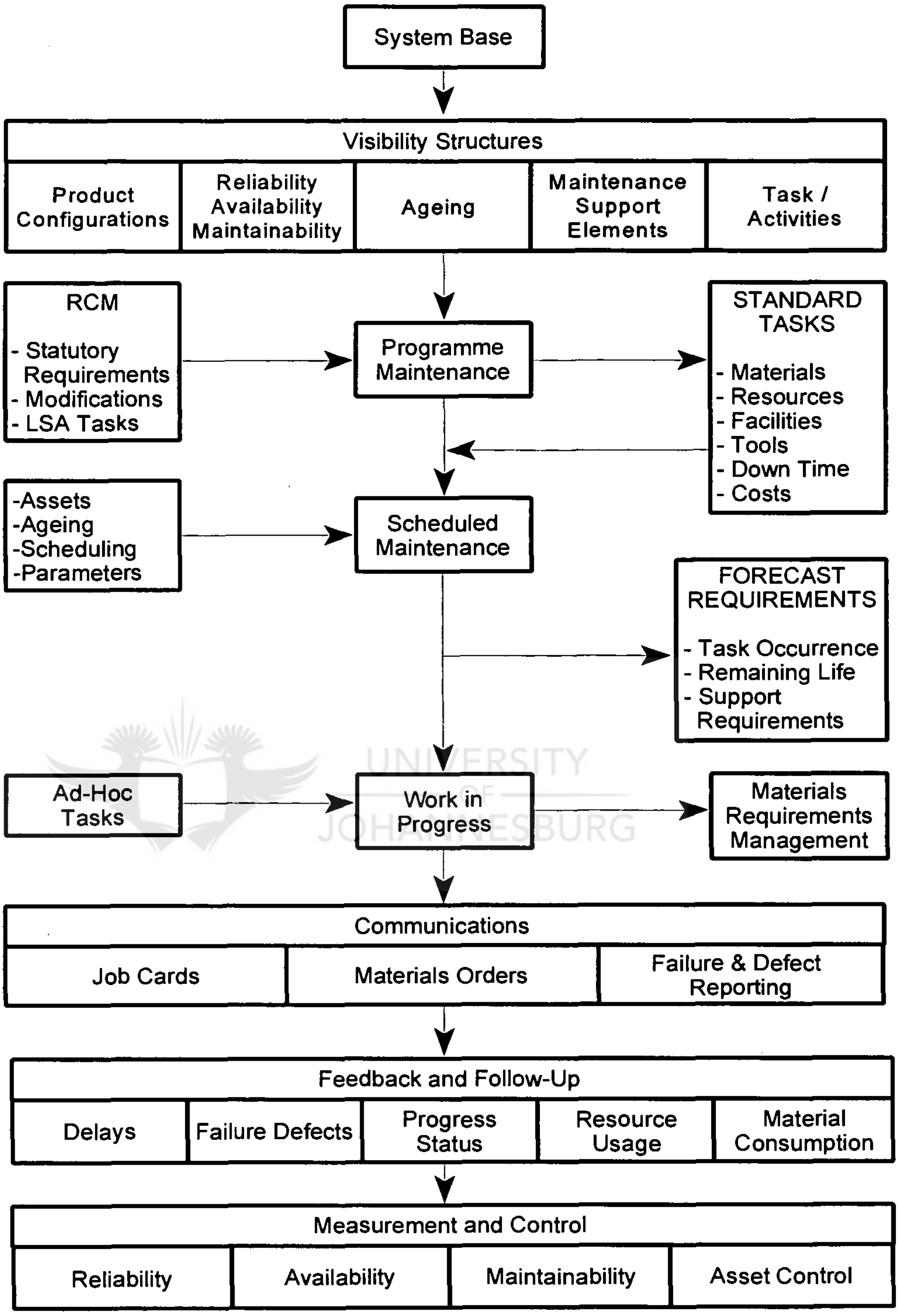


Figure 2.4.11: A typical OMS overview

The OMS is extremely important for reliability management of a system during the support phase. The OMS provides the visibility structures of failure and repair effectiveness trends. Failure trends can then be corrected by means of modifications. Halliday [3] states that at the centre of the reliability growth process, is the identification of failure mechanisms by testing and their elimination through design and hardware modification action.

The OMS is the only support management tool that allows effective closing of the management loop to enable the identification and quantification of problem areas and trends. This very important for effective reliability management in the support phase. Failure reporting and corrective action system should also be an integral part of the OMS in the support phase to facilitate system improvement as illustrated in figure 2.4.10.

The OMS must effectively identify, quantify and trend the effect of any fix that has been implemented.

ENGINEERING SUPPORT

In a complex system such as an aircraft avionics system, it is generally more practical to split engineering capability into system and design expertise since both capabilities can very seldom be vested in one person due to the specialised nature of each. A typical division of engineering support as well as the interfaces to the other support elements is shown in figure 2.4.12. The engineering support process in the overall support environment as well as the closing of the management loop, is shown in figure 2.4.13. A typical system improvement process is illustrated in figure 2.4.14.

SYSTEM EXPERTISE

System expertise is concerned with the interfaces of the system to the larger outside environment such as the impact of the INS performance on the overall aircraft avionics system. The system engineer is accountable for the performance and safety of the system and as such is the design authority. All changes to the system must be approved by the system engineer. The engineering change process (ECP) in the support phase is a very formal process since it implements changes to the system baseline. All stakeholders in the system baseline must form part of the ECP process. Figure 2.4.15 illustrates a typical engineering change and control process.

DESIGN EXPERTISE

The design expertise is concerned with the internal design details of the system. The design engineer is responsible for the design performance of the system and reports to the system engineer.

In the support environment both the system and design expertise is broken down into the capability: (a) to identify and quantify a technical system problem and (b) into developing a fix for the problem. In the case of an external procured system, the capability for (a) must be available internally whilst the capability for (b) would normally remain with the external supplier unless a technology transfer was part of the procurement strategy. The reason for this is that once a system is in the support phase, actual system problems must be separated from support environment induced problems since the external supplier has little or no control over the latter.

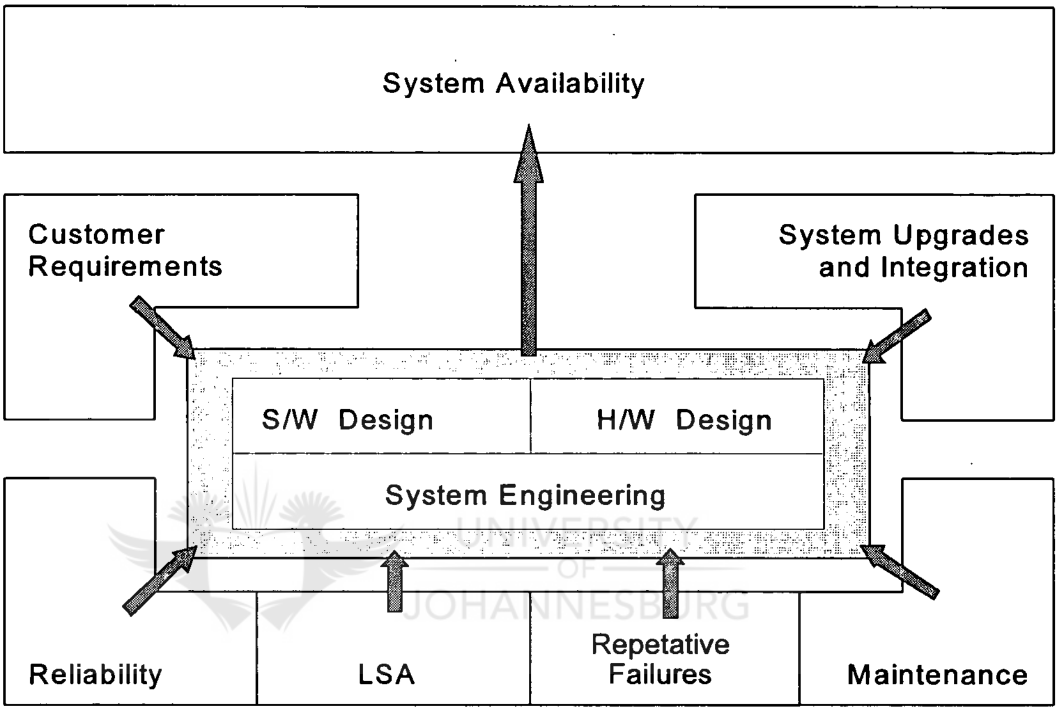


Figure 2.4.12: Engineering support interfaces

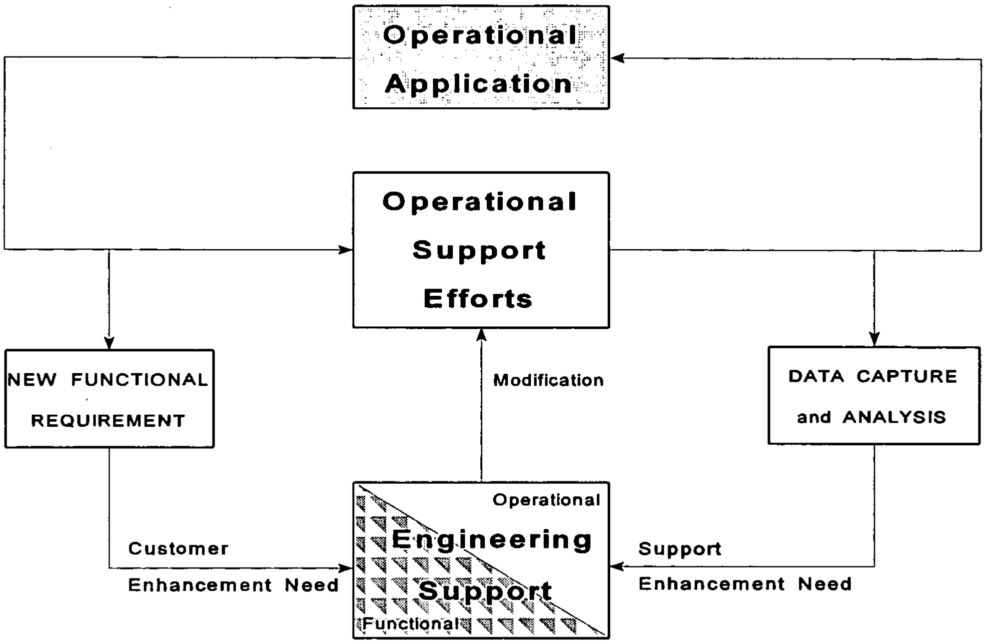


Figure 2.4.13: Engineering support process

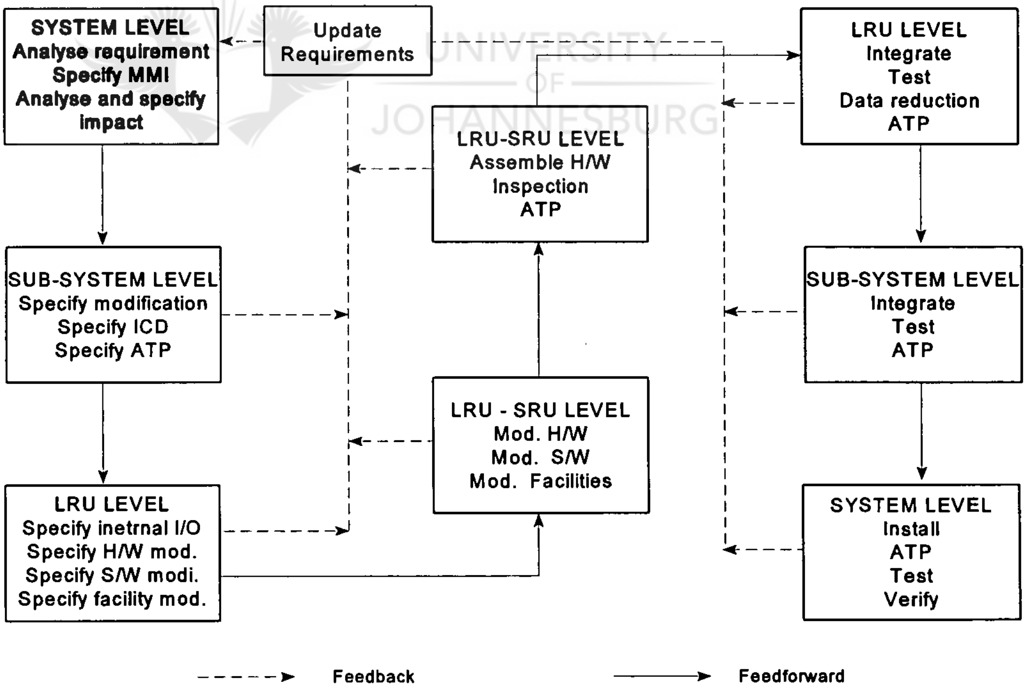


Figure 2.4.14: System improvement process

Engineering support capability can therefore be subdivided into:

- identification of a problem
- quantification of the problem
- development of a fix to eliminate recurrence of the problem.

The first two capabilities must be available internally where the system is deployed. The original system manufacturer as the design authority remains responsible for developing a fix unless a technology transfer has established a local design authority.

CONFIGURATION MANAGEMENT

The logistic element *Configuration Management* or baseline management keeps track of the physical modification and revision status of the system. All changes to the system must be via formal engineering changes, approved by the system engineer. It is imperative that during the support phase the configuration status of each operational system is known to ensure the correct application of each of the operational logistic elements to that particular system, for instance parts, drawings, test specifications, interface compatibility etc. This is generally indicated as part of the item label to facilitate maintenance actions.

Accuracy and completeness of configuration data is very important during the support phase in order to effectively manage system support and retrofit activities.

A deficiency in this logistic element during the repair process, may result in:

- supply and building of incorrect parts
- incorrect maintenance instructions
- incorrect test procedures
- the integration of incompatible subsystems.

These incorrect repair processes will impact negatively on repair times, system reliability and availability. Also the incidence of repeat failures will generally escalate under these circumstances.

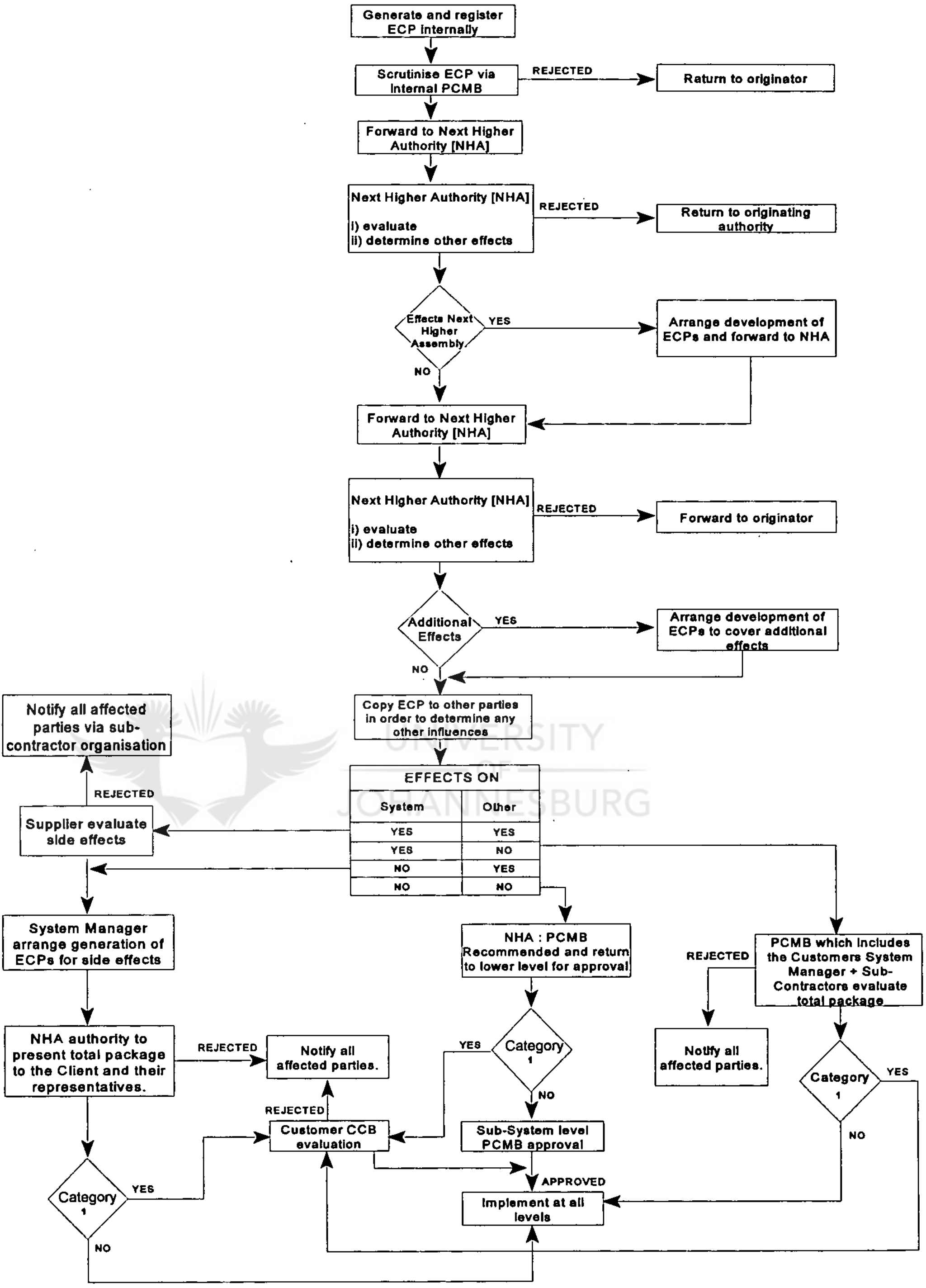


Figure 2.4.15: Engineering change proposal process

LOGISTIC ENGINEERING SUPPORT

System expertise, design expertise, and configuration management focus primarily on the system's technical integrity. The logistic engineering support elements focus on the logistic environment that supports the system

LOGISTIC SUPPORT ANALYSIS

During the system development, logistic support analysis process identifies all the support tasks. From these tasks, the different logistic elements are specified. Once in support , the support plan which was originally developed from the LSA process, (Mil-Std-1388 [64]), is regularly evaluated by means of a product support analysis process. The performance of the different logistic elements are during the PSA evaluated and adaptations implemented should it be required. The product support analysis process is illustrated in figure 2.4.16. Reliability centered maintenance (RCM) during the support phase, is a support system optimisation process by adapting the support policy and determining the most cost effective preventative maintenance actions and intervals to ensure system availability, (Blanchard, p252, [63]). The objective of RCM is to avoid unscheduled breakdowns of the system. In other words the RCM ensures that components with a limited life in a system are replaced just before they fail with the result that the operational system reliability is enhanced.

The support plan for the new support contract window (typically one year), is then updated. A multi-level support system logistic support analysis process is shown in figure 2.4.17. The FRACAS links the different levels of support. The analysed FRACA data is used to improve the effectiveness of the logistic elements. Figure 2.4.18 illustrates how for example the training process is optimised through the PSA process.

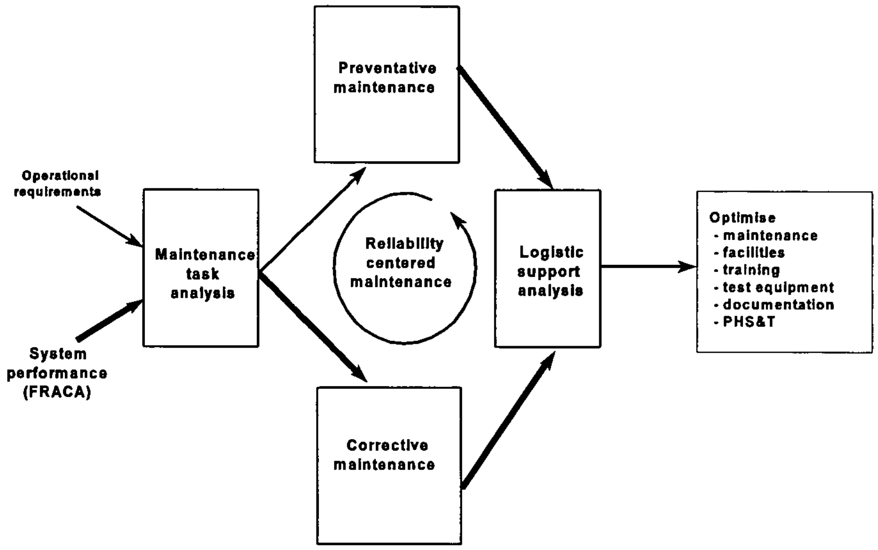


Figure 2.4.16: Product support analysis process

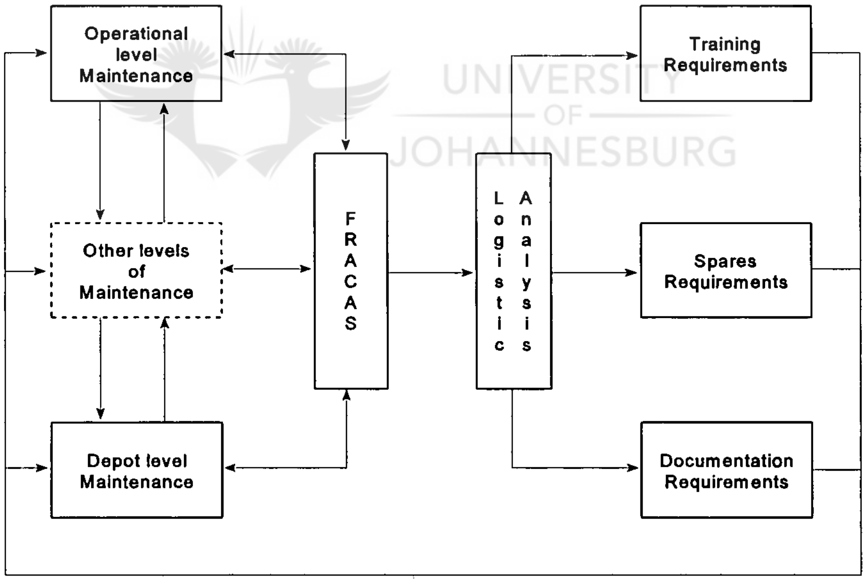


Figure 2.4.17: LSA process in the operational environment

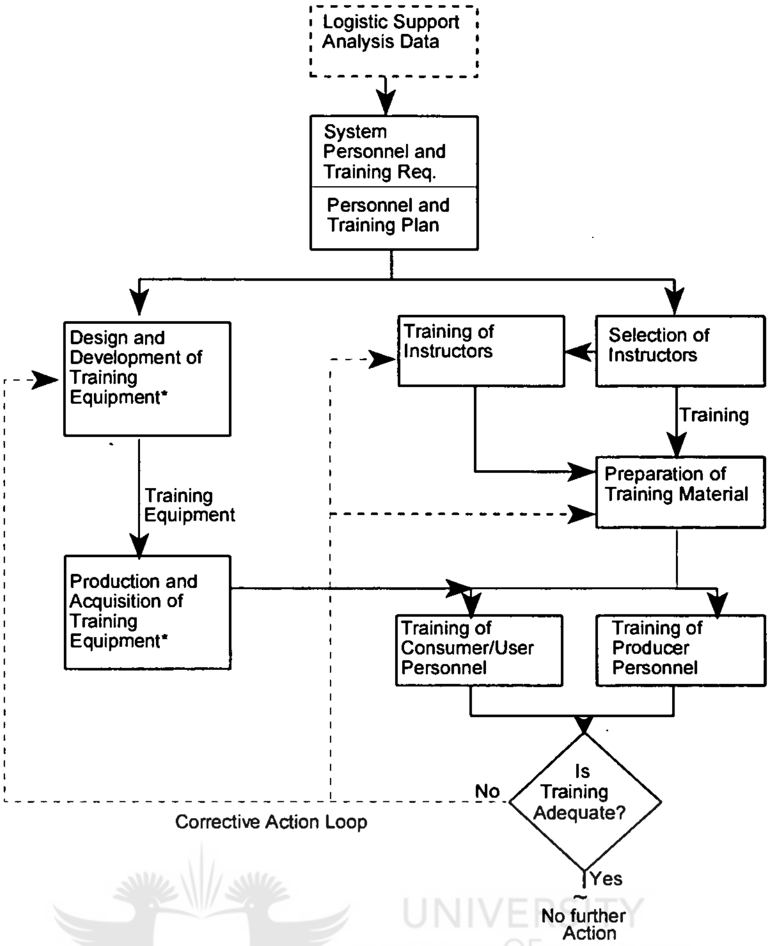


Figure 2.4.18: Training optimisation through the PSA process, (Blanchard [59])

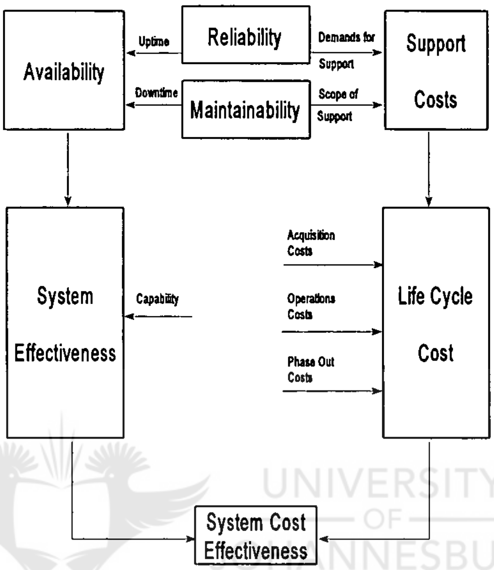
RELIABILITY AND MAINTAINABILITY

The actual operational reliability is determined from the FRACA data and quantified as mean time between failures (MTBF). The presentation of the data is normally on a moving window basis to ensure sufficient smoothing of the curve for trend analysis but not too long a window that will result in loss of trend sensitivity, (Malec [15]). During development, the cumulative failure rate is used, (Mil-Hdbk-189 [27]), to show the reliability growth trend. During the stable support phase, the failure rate stabilises towards a constant failure rate with the result that the cumulative failure trend tends to obscure small changes in failure rates. Figure 2.4.19 shows reliability and maintainability as an integral part of the integrated support system.

Logistic Support Planning

From the reliability and maintainability analysis, PSA evaluation and life-cycle costing analysis, revised logistic support strategies are planned.

This logistic engineering element plays an important role in reliability management during the support phase of a system. From the RAM analysis, revised support strategies can be devised that will ensure improved reliability, shorter repair times and subsequently improved system availability and lower life-cycle cost.



Reliability and Maintainability (R & M) are central to system cost-effectiveness, by affecting Availability and support costs.

Figure 2.4.19: Reliability and maintainability impact

Summary of the logistic support elements

Dividing the support system into logical support elements and then subsequently grouping these elements into groups, ensures that all aspects of support are addressed. The logistic elements also facilitate structuring of the support planning process. A deficiency in one element may impair the effectiveness of other logistic elements. A deficiency in one or more logistic elements implies that the system repair processes have deficiencies and will over a period of time degrade the system reliability.

2.5 OPERATIONAL SUPPORT MANAGEMENT

Operational support provides the basis for maintenance and maintenance infrastructure requirements for the system at all the levels of support. Figure 2.5.1 illustrates a typical multi-level support system, (Blanchard p106, [59]).

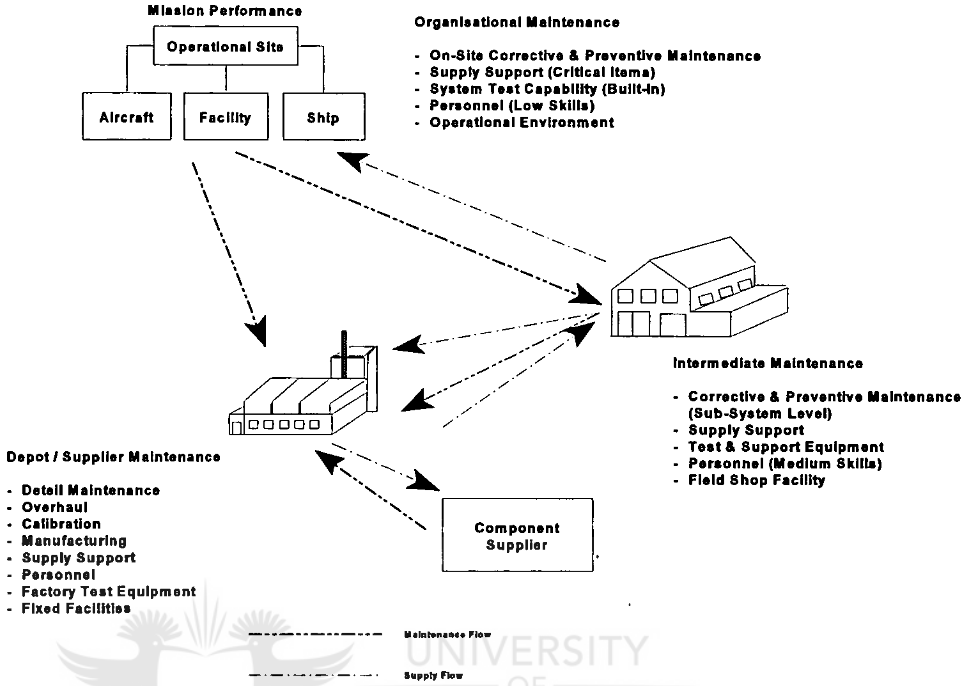


Figure 2.5.1: System operational maintenance flow, (Blanchard [59]).

The figure illustrates the general geographic separation of the operational site, the intermediate support site, the depot support site and the supplier of components. The modes of transport may vary from ship, air, rail and road. The system and its components must be able to withstand the environments of these transport modes. The packaging must be effective to isolate the system and its components from these transportation environments. This is normally not sufficient and in general handling instructions must also be provided.

The transportation times have a direct impact on system availability. This can only be compensated for by increasing the spares stock levels.

These different logistic sites are generally under different managements resulting in a number of interfaces and if not properly co-ordinated, may impair system reliability.

2.6 FAILURE REPORTING AND CORRECTIVE ACTION SYSTEM (FRACAS)

During the support phase the most cost effective FRACA vehicle is the job-card. The job-card by definition already contains a number of FRACA data fields. By expanding the job-card, it is possible to capture reliability data as well as maintainability data.

The job-card as the FRACA data vehicle

Unlike during the development and production phases where a dedicated FRACA data form is normally used whenever a non conforming item is encountered, in the support phase the logical and most efficient vehicle for FRACA data is the repair job-card. The main purpose of the job-card in any workshop is to manage work in process and to accumulate costs. These data fields already form the maintainability data of the FRACA system. A relatively minor extension of the job-card is required to also capture reliability FRACA data.

The reliability data fields contain the units of measure (operating units since last failure) whilst the maintainability data field contains the resources consumed (man-hours and spares) as well as the repair turn-around-time (TAT)

The maintainability data are all those data fields that are concerned with the repair action itself, such as time to repair and resources consumed.

The date and time fields, shows the current date and time when the failure was reported. The difference between this time and the previous repair job-card closing date and time provides the time between failure of this particular repair item. The difference between the opening and closing dates and times provide the repair time data. These fields are finally averaged over the whole operational inventory to provide a MTTF and MTTR figure for the particular repair-item.

In a multi-level support environment, the subassemblies sent away for repair must also be tracked. The tracking number, is a unique number that links the repair item through the deeper levels of repair to the original higher-level system from which it was replaced. The tracking numbers are linked through all the levels of support to provide a traceable audit trail.

Also by using the job-card as the data capturing instrument, has the advantage that all the data required is captured since the job-card is the universally accepted management tool by maintenance personnel.

However for an aggressive reliability growth programme, the job-card data may not be sufficient. In these instances, it is advisable to use an additional dedicated FRACA form for the duration of the reliability growth programme. An example of the form used for the reliability growth programme of the INS case study is provided in appendix E.

2.6.1 CORRECTIVE ACTIONS

Corrective actions during the support phase are those activities that result in the modifications of the system as well as adaptations of the logistic elements such as procedure changes, packaging changes, training adaptations, etc.

Figure 2.6.1 illustrates the interaction between configuration management, material management and maintenance management as part of operations management. System improvement is achieved through logistic and engineering management.

A typical multi-level failure reporting and corrective action support management system is illustrated in figure 2.6.2.

Figure 2.6.2 shows how the system improvement cycle encompasses the repair cycles in a multilevel support environment. The FRACAS links the two cycles together and drives the corrective action cycle. Coordination and verification for completeness of the failure data at the different levels of support is important. It must be possible to trace a system failure to a failed shop replaceable unit (SRU) and subsequent failed component failure through the support hierarchy in order to provide the exact cause of the system failure. The failure review board (FRB) in turn must establish the cause of the component failure.

Failure Review Board

A FRB is a technical meeting chaired by the system engineer assisted by the logistic and design engineers, (Rumble [22]). The main objective of the review board is to analyse failures and failure trends in order to determine the root cause of failures. The conclusion of the review could be that the cause of failure is:

- quality related
- normal wear-out of the component
- premature system component failure

The former is then referred to the quality manager to take remedial steps whilst the latter is referred to the FRB for further action. The FRB is generally part of the corporate total quality management (TQM), (Smith, [43]).

Corrective Actions Board

The corrective actions board (CAB) is a formal meeting involving the client and all stakeholders of the system. The main purpose of the CAB is to contract problem area investigations, fix development and oversee the fix test and evaluation as well as to oversee the subsequent implementation and retrofit programmes.

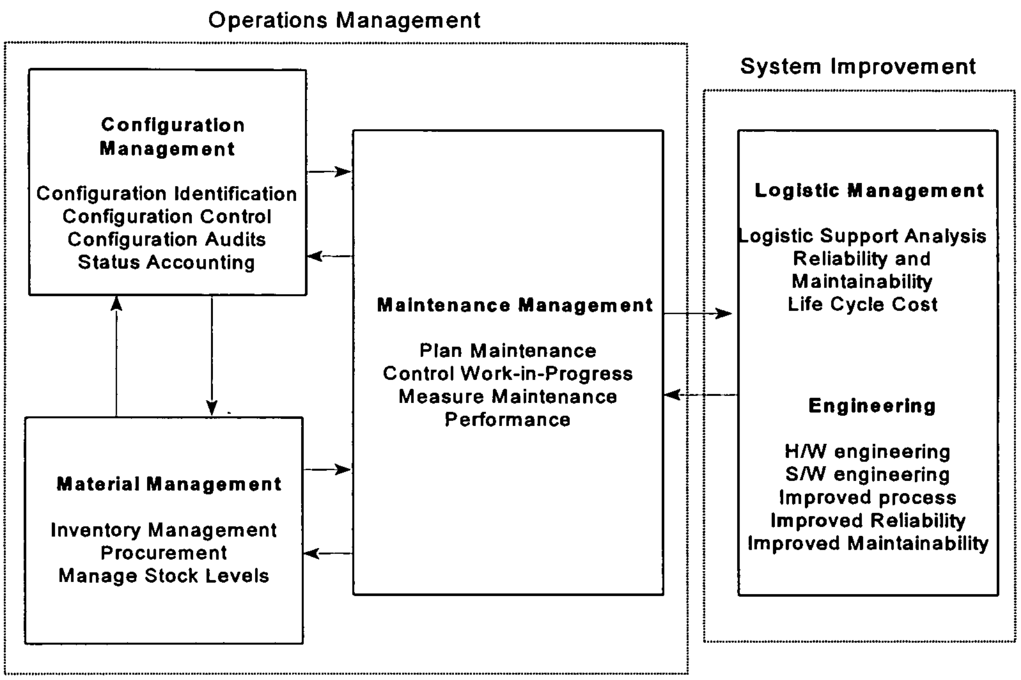


Figure 2.6.1: Operation and engineering management

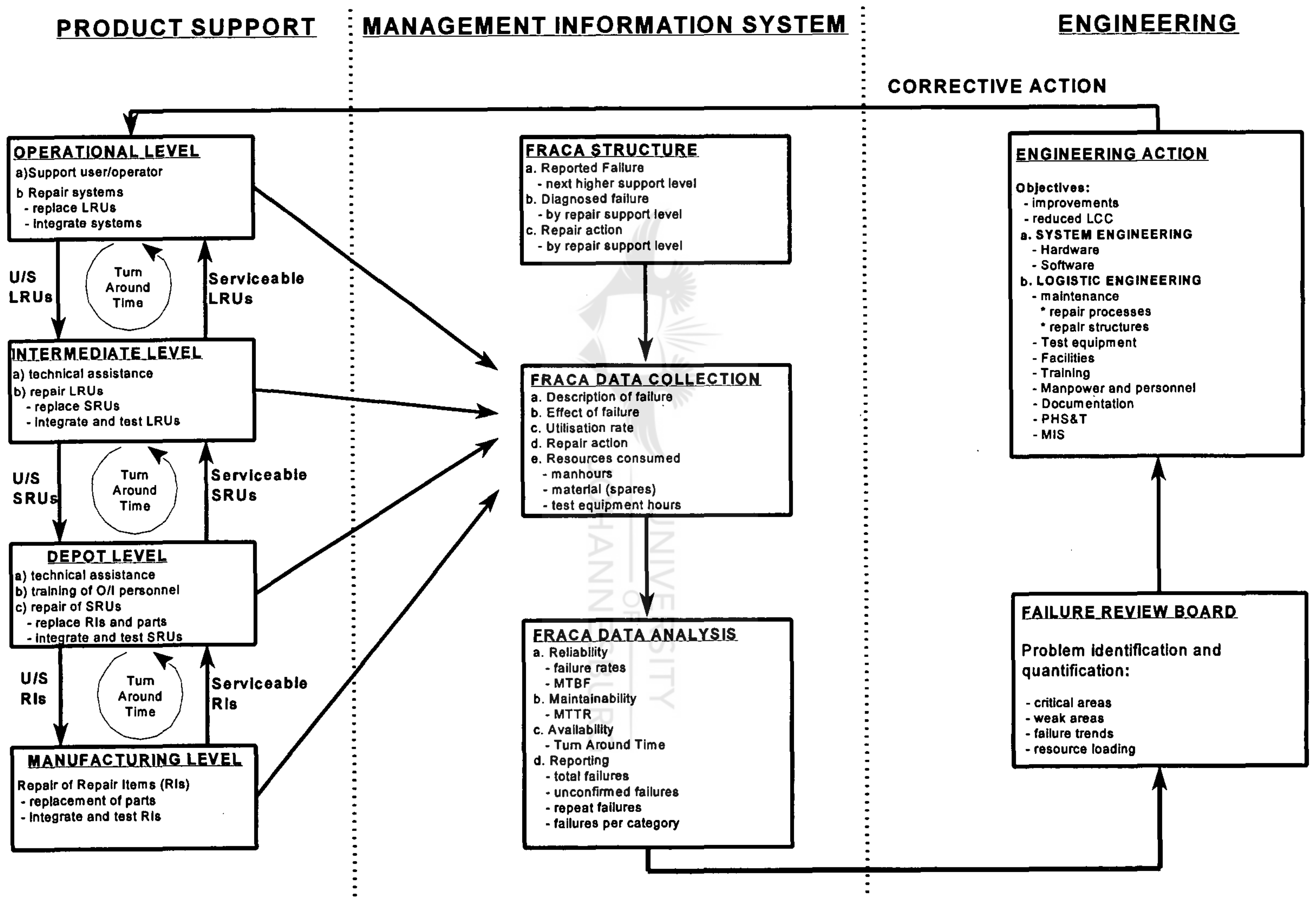


Figure 2.6.2: A multi-level Failure Reporting and Corrective Action System (FRACAS)

3. RELIABILITY GROWTH IN THE SUPPORT PHASE

The management during the support phase must also encompass the engineering logistic elements otherwise no system improvement by means of elimination of latent defects will be possible.

The improvement process also includes the improvement and refinement of the operational support processes in addition to the actual system improvement.

Evaluation

During the development phase, only the design and quality related aspects that impacted on the reliability inherent to the system (design maturity), were addressed. Once in the production phase, the production environment and production processes also impact on the achieved reliability.

In the support phase, the achieved reliability is further impaired through the impact of the real operational environment as well as the effectiveness of the logistic elements as illustrated in figure 1.1.3, par 1.1, Part III of this research work.

Generally in the avionics support environment 12 logistic elements are defined to ensure total support. This implies that if system availability is not to expectations, a large number of factors or combination of factors may be the possible cause. The problem becomes highly complex which can generally not be resolved simplistically. It is this complexity and external influences which in essence are the main differences between reliability growth during the development phase and support phase.

The problem is generally further complicated as a result of ineffective failures (NFF and RF) in the support system. The analogy in this case is to add noise into the closed management loop obscuring the actual causes for the poor performance of the system.

Extensive literature searches could not find more research information on reliability growth in the support phase. Wong [48], identifies the escalation and subsequent recovery in failure rate early in the support phase of complex electronic systems. His discussion for the reasons for this escalation in failure rate is focussed on the system itself. Wong [39] shows how environmental stress screening (ESS), can be applied to achieve and demonstrate reliability growth. The support system influence has been excluded in Wong's discussions.

3.1 RECOMMENDED APPROACH

The following are broad guidelines for turning a system's reliability around in the support phase.

The fundamental difference between reliability growth during the support phase and the development phase is that the rate of growth is more difficult to manage. The reliability growth process in the support phase is dependent on operational usage of the system and time taken to retrofit the system inventory after each fix during the system improvement process. This dependency on operational usage is to a certain extent compensated for in that the accumulative usage is now extended to the total system operational fleet which generally provides a large amount of statistical data in a relatively short time span. This is demonstrated in the case study in part IV, figures 8.1 and 8.2.

Closing the management loop

Experience has shown that whenever system reliability problems in the support phase are being experienced such as poor availability, escalating life-cycle cost and an escalating failure rate, the management loop is open resulting in support management to be ineffective. This is more prevalent in multi-level support organisations because of the individual support level management structures. It is not sufficient to have closed loop management at the individual support levels, the overall corrective action loop must also be closed as illustrated in figure 2.6.2. The effect of an open loop support system is demonstrated in the case study in part IV. All failures must be actively managed and the *root cause* of each failure must be found. Although it might appear beneficial in the short term to correct the symptoms, for long term recovery, it is essential that the root cause for the poor performance be identified and eliminated by means of corrective actions, (Seusy [8]).

One of the real practical problems for managing reliability growth in a multi-level support environment is that generally the different levels of support are the responsibility of different organisations (figure 2.5.1) each with different value systems. The case study in part IV shows how an escalating failure rate benefited the depot level support contractor. The contracting models must be reviewed to provide a financial incentive to all participants in the support structure to facilitate reliability growth, (Koon [5]).

The reliability growth programme ideally should be managed by the user from the operational level with the support of independent consultants and system experts. It is also possible for the user to contract the original supplier as the main support contractor and make him responsible for system availability (full maintenance contract).

Although the contracting model for the intermediate support level as the main contractor appears to be simpler, it is not advisable to implement such a contracting model. The reason for this is that generally the intermediate level support lacks both the operational and detail system expertise of the other two organisations.

In the support phase any fix for a latent defect that has been developed, must be retrofitted to the whole system inventory. This includes all operational as well as spare systems. Depending on the seriousness of the defect, the fleet may be grounded and recalled for retrofit or the fleet may be retrofitted over a period of time when systems are due for repair and the retrofit implemented as part of the repair process. In the latter case, the operational management system must tag the serial numbers of the systems not yet retrofitted and generate a retrofit job-card together with the repair job-card in order to keep configuration status and traceability.

Once a root cause has been identified and quantified, it is quite acceptable from a practicality point of view to circumvent the cause rather than fix the root cause for example a change in software may overcome a deficiency in hardware.

It can however not be overstressed that in order to be successful in the system reliability turn-around, the root causes must be established first prior to designing/devising a fix.

Remove the noise inside the management loop

System control theory shows that noise inside a control loop, impairs control loop performance. Appendix A figure A.1, Havinga, illustrates the error propagation in a typical INS control loop to form the basis for INS system performance evaluation. A support management loop is no different in this regard hence the next logical step is to eliminate all unproductive failures such as no fault found (NFF) and repeat failures(RF). This is achieved by ensuring that the support system loop is closed and a FRACAS, FRB and CAB is in place and meticulously managed. Even in highly complex systems the NFF/RF component of failure reports should be less than a few percent of the total. It is essential that this be achieved before the next step is attempted. This is generally the one action that has shown the most improvement in the short term availability of a system as demonstrated in the case study part IV, tables 7.1.1 and 7.1.2.

The test specifications and test limits in a multi-level support environment can also give rise to a high level of NFF/RF incidences. If the test specifications and tolerances are the same at the different support levels, small variations in calibration accuracies of the test equipment may give rise to NFFs and RFs when the repair-item is retested at the next support level.

It may also be necessary to introduce special tests, in particular limited ESS tests, that better emulate the operational environment to ensure that all reported failures can be reproduced and repaired, (Koon [5]). Limited ESS tests after the repair action may also prove to be beneficial to assure the quality of the repair and prevent repeat failures.

Another major cause for unproductive failures is the lack of system knowledge by the support personnel. Training and training effectiveness must be evaluated in these instances.

Test Analyse and Fix process (TAAF)

Once the unproductive failures have to a large extent been eliminated it is possible to start analysing and by a process of elimination, zoom in to the major causes for the poor performance.

The fact that all logistic elements are present, is not sufficient to guarantee good system operational performance. Even minor deficiencies in one or more of the logistic elements can result in a dramatic drop in system availability as demonstrated in the case study in part IV.

The completeness and effectiveness of all logistic elements must be evaluated and analysed. As demonstrated in the case study, all the logistic elements were present but one was not complete (system/design expertise). There must be sufficient local system and design capability to identify and quantify any system problems. It is not sufficient to report to the external supplier that a system is not performing to expectations without detail information of what precisely the system is not doing after the impact of the logistic elements, over which the external supplier has little or no control, has been eliminated.

Once the impact of all the logistic elements have been addressed and any deficiencies corrected, will the support team, by means of the logistic elements *system and design expertise*, be sufficiently knowledgeable to identify and quantify the actual root causes of the system's technical deficiencies.

At this stage it is possible to conduct a regular structured and orderly corrective action board (CAB) with the external supplier to ensure that all defects are addressed and that proposed fixes are properly evaluated and implemented. The process at this stage is identical to the TAAF process during the development phase, (Patterson [11]).

4. CONCLUSION AND RECOMMENDATIONS

In order to achieve a successful reliability turn around in the support phase of a system, comprehensive knowledge and insight into each applicable logistic element is required to enable separation of the logistic support environmental factors from the actual system latent defects.

The constant failure rate region (bottom of the bath-tub hazard function) can only be realised provided the system support infrastructure has been completely established and system support effectively managed.

The 'roller coaster' effect described by Wong [48], is in all probability as a result of ineffective support management and support resources early in the system's support phase. Effective support management can only be realised in a tight closed loop support management system utilising all the support resources effectively.

Effective support management will also reduce the support cost which generally is a substantial portion of the total system life-cycle cost, (Blanchard, p66, [59]).

The importance of the closed-loop system management in a multi-level support environment where not only the repair loops but also the corrective action loop must be closed, will be demonstrated in the case study in part IV.

In summary, the recommended approach is:

- get total management commitment and close the management loop over the different levels of support (FRACAS, FRB and CAB)
- establish the root cause of every system failure
- implement a TAAF policy
- remove any noise (RF, NTF and NFF) inside the management loop by eliminating these ineffective repair actions
- ensure that the system operational environment is within the system specification
- remove latent design defects from the system
- correct deficiencies in the logistic elements.

PART IV

CASE STUDY

MULTI PURPOSE LONG RANGE AIRCRAFT ACQUISITION

1. BACKGROUND AND PROBLEM STATEMENT

A medium sized airline operator, identified a need for four long range multi-purpose jet aircraft to complement its current aircraft fleet, for the expansion of its cargo business.

The airline operator, already has a substantial established aircraft support infrastructure capable of performing first and second line servicing of all its existing aircraft inclusive of avionics systems. The airline operator's existing support infrastructure has sufficient spare capacity to accommodate the planned additional four aircraft.

In order to save on support infrastructure establishment costs and subsequent under utilisation of these facilities, the airline operator management viewed it prudent to standardise as far as possible on maintenance significant items. The avionics suite of the new aircraft fleet, was a prime candidate for such a cost saving standardisation exercise.

The inertial navigation system (INS), was for safety reasons on the new aircraft duplicated providing fully independent dual redundancy navigation data to the flight control computer. The inertial measurement unit (IMU) used by the airline operator on its existing aircraft fleet is a 3 gimbal platform, gyro stabilised unit providing acceleration inputs to a flight computer for navigation. The IMU is the most expensive unit in the avionics suite of the aircraft. Also the IMU has the lowest inherent reliability and required the most expensive and specialised support infrastructure. The IMU used by the airline operator could be supported by the local industry, reducing repair turn around time. In addition, considerable savings in spares inventory holding costs could be realised if the same IMU could be used on the new aircraft.

A systems engineering feasibility study revealed that it was possible to use the IMU as used by the operator on its other aircraft but that a newly developed flight control computer (FCC) with associated navigation software would be required. The required better navigational accuracy could be achieved by dual horizontal axis alignments, mapping calibrations and the implementation of Kallman filter algorithms in software to reduce the inertial platform alignment errors of the IMU.

Although this placed a substantial computational load on the flight control computer (FCC), the development cost of the FCC and associated software more than compensated for the costs of establishing a new logistic infrastructure for the support of another type of IMU. In view of the small volume of expected repair work, this new infrastructure would also be very under utilised.

Financially the proposal looked attractive to the client, hence four used, refurbished, re-equipped four engined jet air freighters were ordered to be delivered after an initial FCC development period at three monthly intervals. The overseas main contractor, appointed an overseas subcontractor for the development and delivery of the navigation systems using the airline operator's standard type of IMU. This subcontractor was also the supplier and design authority of the client's existing IMU inventory. This subcontractor was also responsible for the integration of the INS into the avionics suite of the aircraft.

The establishment of the additional logistic infrastructure was part of the procurement programme. This included extensive airline operator flight crew and maintenance personnel training, test equipment, spares as well as operating and maintenance manuals. The logistic infrastructure establishment programme, was completed prior to the delivery of the first aircraft.

An aggressive reliability growth programme was adopted by the aircraft supplier's subcontractor during the development of the FCC and the unit was fully qualified and certified on delivery for integration onto the aircraft by the aircraft supplier.

On delivery, the aircraft and all its subsystems, performed to expectations. The navigation system performance and availability was good. It was however anticipated and accepted by all parties that in view of the small volume development of the FCC and to be still cost effective, that a certain amount of reliability growth had to be achieved in the support phase and as such was part of the INS warranty.

To this effect, the avionics subcontractor kept a small technical team in place at his facility to perform design authority (DA) functions as well as technical assistance during the warranty period.

Mission abort criteria as dictated by the Director of Civil Aviation, (DCA) safety rules, are as follows:

(i) before take-off, both systems must pass the start-up tests and inertial platform pre-flight alignments.

(ii) in-flight if both systems were to fail.

Once in flight should an INS failure occur, it is not possible to re-initialise the system since the heading and attitude information of the inertial axis reference system stabilised by the gyros, would be lost.

The DCA rules allowed continuation of the flight if one system failed after take-off during flight, since the aircraft was also equipped with Global Position Satellite navigation (GPS) and magnetic sensor units as a secondary navigation capability.

Each aircraft, on delivery, was immediately commissioned into operational use. Initially, the INS performance and reliability was acceptable. However soon after the aircraft was commissioned into service, the availability instead of improving as anticipated by the reliability growth programme, started to drop dramatically, so much so that mission abort and flight cancellations became daily occurrences. This trend also caused an abnormal demand for spares resulting in out of stock situations and unserviceable aircraft.

The problem was further exacerbated by the abnormal consumption of IMU spares impacting on the availability of the other aircraft types in the fleet.

The failure rate per 100 flights are reflected in table 1.1:

Six month Period	Number of failures per 100 flights
year 1 - first half	12.3
year 1 - second half	14.0
year 2 - first half	29.9
year 2 - second half	49.2
year 3 - first half	41.9

Table 1.1: Deterioration in INS reliability

This rapid and unexpected decline in availability so soon after the introduction of the new air freight service, had enormous business and cost implications to the airline operator. Figure 1.1 shows the INS hazard function indicating the expected region and the apparent failure rate region.

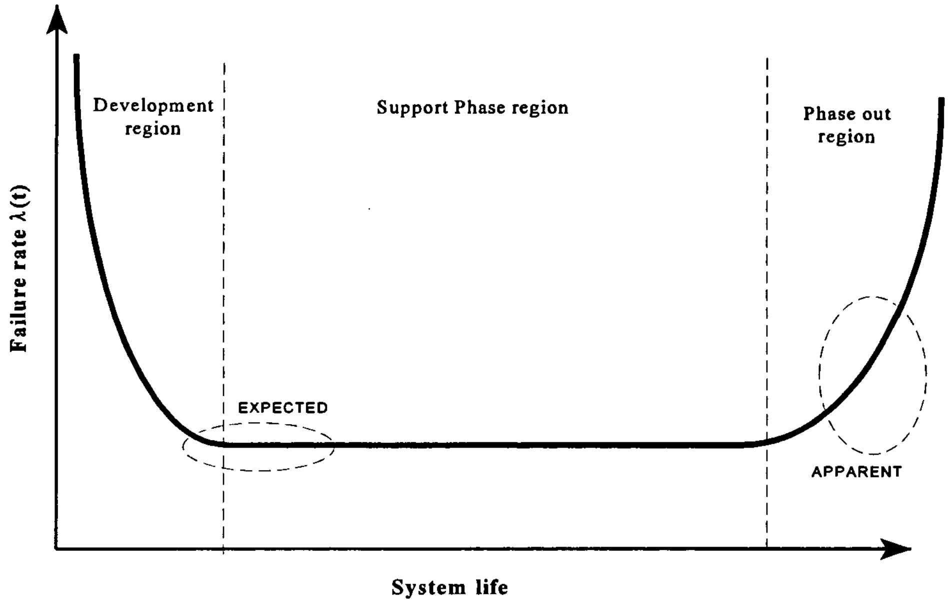


Figure 1.1: The INS expected and apparent failure rate regions

The airline operator management reacting on feedback from the flight crews (pilots, navigators and flight engineers) started to place undue pressure on the maintenance personnel who in turn placed the blame on the aircraft supplier and avionics subcontractor. This resulted in very strained relations between the different stakeholders and communications generally degenerated to formally minuted information via the project manager.

The collapse of effective communications between the parties resulted in further degradation of the INS system availability. The aircraft supplier assumed that the avionics subcontractor was at fault since it was his system that was at the centre of the problem. The avionics subcontractor's technical team on site visits, could not find any deficiencies related to their product.

The author was contracted as an independent avionics systems and logistic engineering consultant to assess the situation and recommend remedial action.

The approach to the problem, methodology and techniques used and proven in this case study is the subject of this research work.

2. SYSTEM DESCRIPTION

Dual Inertial Navigation Systems (INS) are used on the airline operator's air freighter fleet. The INS provides navigation data to the autopilot, flight guidance computer, cockpit instrumentation and other mission equipment. Altitude and position updates from the altimeter and GPS are used to assist the inertial navigation system. The INS is duplicated in a dual hot standby mode on each aircraft.

Except for the two control display units (CDU) which were installed in the cockpit in front of the navigator position, the other line replaceable units (LRU) were installed in the instrument bay underneath the cockpit.

The IMUs were mounted next to one another on special aligned mounting trays. Cooling air to the IMUs, was supplied by means of a separate fan and air distribution pipes.

The two FCCs were mounted in the instrument rack together with all the other radio and electronic equipment on the upper two shelves one above the other.

The two PDUs, because of their size and weight, were mounted on the floor to the right of the instrument rack.

2.1 TECHNICAL DESCRIPTION

Inertial Navigation System

The INS comprises an Inertial Measurement Unit (IMU), Flight Control Computer (FCC), Control Display Unit (CDU) and Power Distribution Unit (PDU).

To improve navigational accuracy, the IMU is mapped to the FCC during integration.

The INS is rated to operate in the following environment:

–	maximum continuous operating temperature		71 deg C
–	maximum Storage temperature		95 deg C
–	maximum operating altitude		21500 m
–	vibration	- sine wave	20g, 5Hz to 2Khz
–		- random	12g, 20Hz to 2Khz
–	mechanical shock		11ms, half sine, 15g
–	humidity	- operating	95% @ 30 deg C
		- storage	97% @ 65 deg C
–	salt spray		5% NaCl

The geographic layout of the INS in the overall aircraft avionics suite is shown in figure 2.1.1.

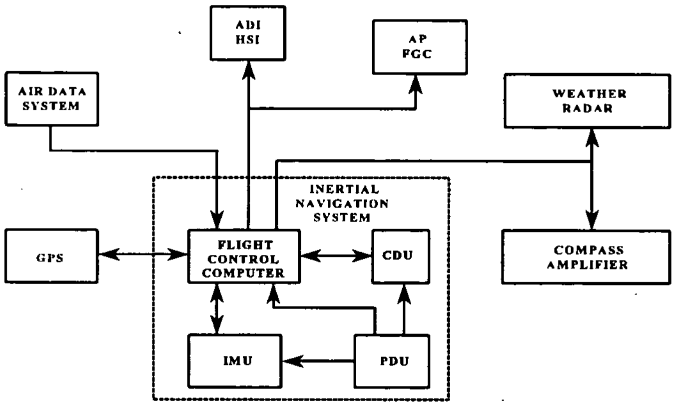


Figure 2.1.1: Geographic layout of the INS

The INS interconnection to the rest of the aircraft avionics units is shown in figure 2.1.2.

Inertial Measurement Unit

The IMU, by means of gyros and accelerometers present bearing and acceleration data to the navigation software to produce attitude information for the cockpit instrumentation and autopilot.

The IMU consists of a stable platform, control electronics, communications electronics and power supplies. The inertial stable platform is the reference by which attitude and bearing changes are measured. Communications between the IMU and FCC are via a dual redundant high speed synchronous communications bus. Data passes to the computer via the IMU Control card. The IMU control electronics operate the platform by applying torque to the gyros and gimbals to provide an earth referenced inertial system. Alignment takes place in both the X- and Y-axes to improve accuracy.

The IMU must provide a basic navigational accuracy over an eight hour period. The INS navigational software improves performance by:

- executing an extended alignment process in both horizontal axes as well as the vertical axis (X-, Y- and Z axes).
- mapping the bias parameters per axis in the IMU memory to improve control precision and accuracy.
- controlling the IMU functions in a closed loop with the computer.

The IMU requires both 28 Volt DC and 115 Volt 400 Hz 3 phase AC power.

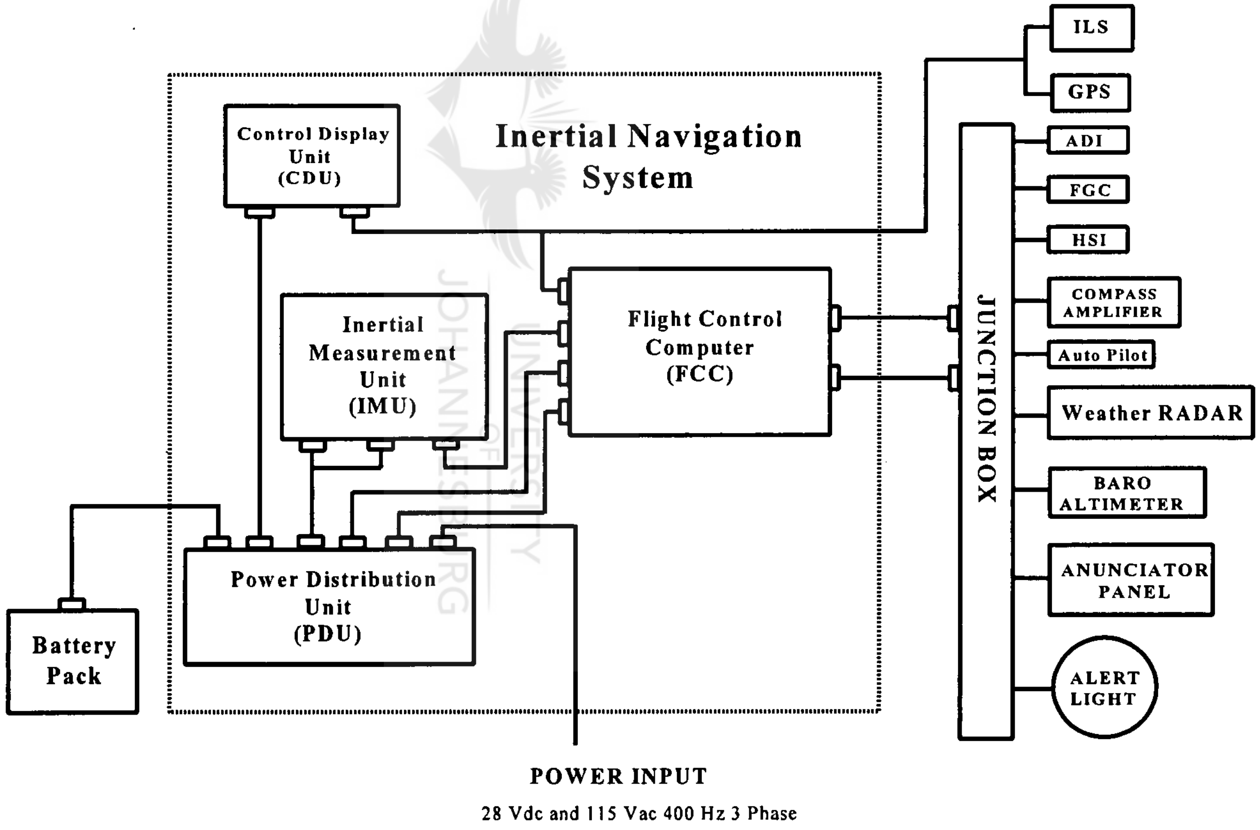


Figure 2.1.2: INS interfaces to the aircraft avionics suite

Flight Control Computer (FCC)

The FCC accepts signals from Instrument Landing System (ILS), Auto Pilot, Horizontal Situation Indicator (HSI) and Altitude Direction Indicator (ADI). The IMU acceleration signals are integrated into velocity data and position data. The GPS is integrated into the navigation algorithms and accuracy enhanced by means of Kallman filter data reduction techniques implemented in software.

The central processing unit of the FCC uses bit-slice- and floating point processors. The embedded software is in non volatile EPROM memory and data in RAM. The FCC configuration consists of a processor -, floating point -, memory and interface cards. A power supply unit converts the aircraft 28 volt DC to the internal electronic supply voltages.

The FCC PC boards are full Euro size with integral heat sinking for heat dissipation to the outside peripheral of each board. The different PC boards are sandwiched together to form the computer case together with the front panel and rear Power supply unit.

The following dedicated interfaces are available on the FCC:

(i) Autopilot Card

The autopilot card (APC) function of the FCC is to generate signals for the auto pilot system as well as ALERT signal to the cockpit lamp and auto pilot alarm.

(ii) Synchro to digital Card

The synchro to digital card (SDC) converts phase angles in either synchro or resolver formats as well as analogue signals to digital format.

(iii) Analogue Control Card

The analogue control card (ACC) acts primarily as buffer amplifying pitch and roll signals to external units. The ACC also provides the COMP (computer) and ATT (attitude) flags.

(iv) Interface Management Card

The interface management card (IMC) provides the interface for data to and from the CDU. The IMC also provides the 25 ms interrupt signal for software timing.

The FCC power consumption is approximately 200 watts and mass approximately 22 kg.

No internal forced air cooling is provided.

Control Display Unit

The CDU is the operator interface with the INS via a keypad and numeric display. Operational modes, and test modes can be selected. All functions are displayed on a numerical display panel.

The CDU display panel and ergonomic layout is shown in figure 2.1.3.

After switch-on the system goes into alignment and after warm-up, the heading is optimised where upon it automatically goes into the navigation mode.

The test mode activates the BITE. Selected addresses in memory can be accessed by means of the *P-In* and *P-Out* functions for diagnostic and test purposes.

The communication with the CPU is by means of a high speed asynchronous serial data link.

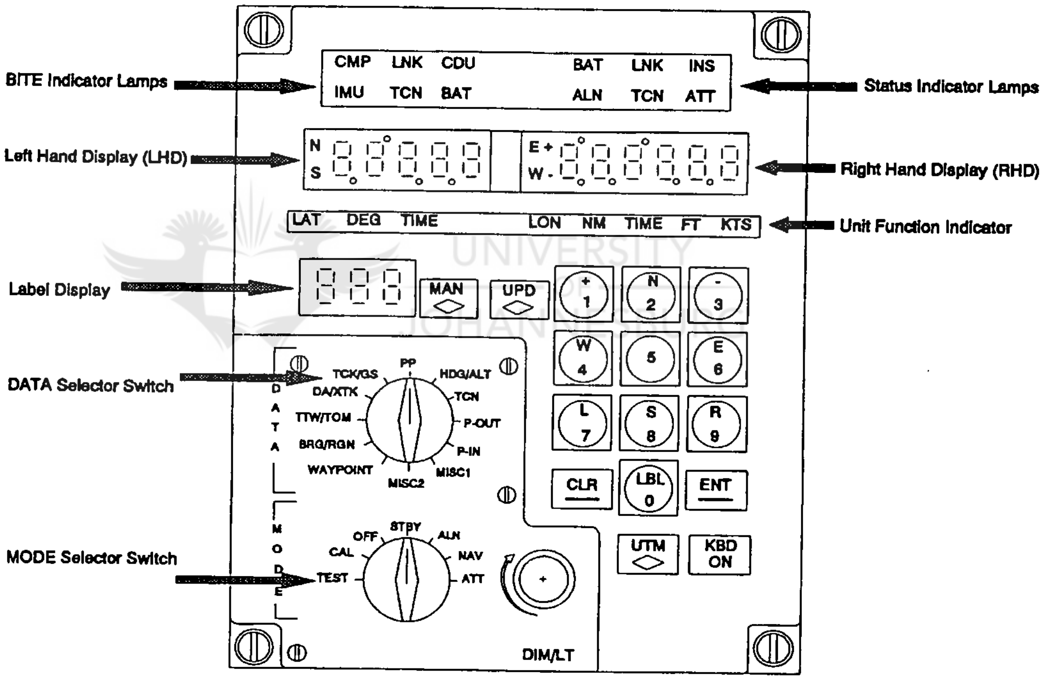


Figure 2.1.3: Control display unit (CDU) front panel

Power Distribution Unit

The power distribution unit (PDU) filters and distributes both DC and AC electrical power from the aircraft to the IMU, FCC and CDU. An internal backup battery is provided to provide temporary protection against power brown-outs. The PDU switches to an internal back-up battery should the aircraft 28 volt supply drop below 22.5 volt. The PDU prevents voltage spikes from the aircraft power from damaging the INS line replaceable units (LRU).

The PDU maximum input power requirements are:

- 115 volt 3 phase 400 Hz AC @ 8 amp/phase
- 28 volt DC at 15 amp.

3. LOGISTIC ENVIRONMENT

LOGISTIC SUPPORT

Maintenance

Maintenance is performed at the following support levels:

(i) Operational level

The maintenance at the operational level (O-Level) is performed by the ground crew without any special test equipment. System BITE identifies faulty line replaceable units (LRU) and repair is effected by replacement of faulty LRUs. IMU mapping parameters must be manually entered into the FCC should an IMU or FCC be replaced. The INS LRUs are the IMU, FCC, CDU and PDU.

(ii) Intermediate Level

At the intermediate support level, repair of LRUs are effected by changing faulty shop replaceable units (SRU), re-calibration and acceptance testing of the repaired LRU. Repaired LRUs are returned to the operational level store. Faulty SRUs are returned to depot level for repair. SRUs are the individual INS LRU PC boards and subassemblies.

(iii) Depot Level

At the depot level, PCB cards are repaired, calibrated and returned to the I-level store.

(iv) Manufacturing Level

At the manufacturing level (M-Level), the IMU inertial platform, gyros and accelerometers are repaired, refurbished and calibrated in specialised facilities by local industry under contract. Serviceable platforms are returned to the I-level store.

4. ANALYSIS OF THE PROBLEM

Symptoms

Operational Level Support

All malfunctions, failures and problems are recorded by the flight crew during each flight. These are then handed to the maintenance planning and control (MPC) centre who generate job-cards and schedule the work for the maintenance personnel.

The maintenance personnel must attend to the problem and once fixed, sign off the job-card. Once all job-cards have been signed off, the aircraft can again be declared serviceable for the next flight.

Operational level repair of the avionics suite, consists of changing malfunctioning LRUs with serviceable ones until the system passes the integration acceptance tests.

The operational personnel were unsure of which LRU caused which type of failure and to a large extent were doing repairs by trial and error. Quality Assurance (QA) rules prevented the return of any LRU as serviceable to the store once it has been withdrawn and installed on the aircraft. These units had to be returned to the intermediate level for verification of their serviceability.

The operational personnel also found that very often they could not reproduce a failure that had occurred during flight but out of sheer desperation changed units even though these might not be the cause for the actual reported failure.

This resulted in frequent out of stock situations in the operational level store of serviceable LRUs which impacted negatively on aircraft availability.

Intermediate Level Support

Personnel at the intermediate support level on receiving faulty LRUs diagnosed the failures by starting the appropriate acceptance test procedures for the applicable LRU. If the LRU proved to be faulty, it would fail on a specific test in the acceptance test procedure sequence. The maintenance personnel would then proceed to diagnose and identify the faulty SRU and exchange this item for a serviceable one obtained from the intermediate level store.

As with the operational personnel, it was found that the intermediate support technicians were to a large extent unsure of which SRU was at fault and resorted to a guess and try approach until the faulty LRU passed the complete acceptance test.

A large number of LRUs after acceptance testing, were found to have no fault at all and were returned back as serviceable to the operational level store.

Depot Level Support

Depot level and the intermediate level was established in the same workshop and the same personnel supporting the intermediate level avionics LRUs were used to support the avionics electronic cards at depot level. Replacement of PCB components was done by a specialist soldering section. The IMU inertial platform SRUs, however were returned to manufacturing level for repair and refurbishment

Manufacturing Level Support

Manufacturing Level support is performed by industry in specialist facilities. The maintenance plan dictated that only IMU SRUs should be returned to manufacturing level and only under exceptional circumstances should the complete IMU be returned.

In view of the large number of unconfirmed failures and inability of the intermediate level maintenance technicians to isolate the problematic SRUs, returning of complete IMUs to manufacturing level became the norm rather the exception. The Manufacturing Level contractor was paid per repair activity.

Summary of the symptoms

The work load became abnormally high as a result of the large number of no fault found (NFF) incidents. Intermediate level maintenance personnel assumed that the operational level maintenance personnel were not doing their jobs properly resulting in strained relations and further breakdown of communications.

The high level of unproductive repair activities impacted adversely on the maintenance budget and the system became prohibitively expensive to support.

False data as a result of the exceptional large number of unproductive failures and maintenance activities, cluttered the real problem causes. There was no formal structured FRACA system in place. Failure analysis, in order to determine the root problem causes and decide on the best corrective action, was virtually not possible as a result of the false data and unproductive repair activities.

5. SYSTEM PERFORMANCE

System performance is assessed as the combination of availability, reliability and operability of the navigation systems.

LRU	SHU	Total Failures	Repairs	NFF
Flight Control Computer		**16**	**4**	**10**
	Processor card	2	1	1
	Floating Point card	0	0	0
	Memory card	0	0	0
	Auto Pilot card	1	1	0
	Synchro-To-Digital card	2	1	1
	Analogue Control card	1	0	1
	Interface management card	0	0	0
	Power Supply Unit	2	1	1
Control Display Unit		**6**	**1**	**5**
	Front Panel	0	0	0
	Processor Card	2	1	1
	Power supply Unit	1	0	1
Power Distribution Unit		**2**	**1**	**1**
	Control Card	1	0	1
	Control Assembly	1	1	0
	Backup Battery	0	0	0
Inertial Measurement Unit		**12**	**5**	**7**
	Inertial Platform	4	3	1
	Control card	0	0	0
	Synchro-To-Digital Card	2	1	1
	Servo card	0	0	0
	AC-DC Power Supply	1	1	0
	DC-DC Power Supply	1	0	1

Table 5.1: INS and SRU failure trends prior to corrective actions

Failure Data Analysis

No formal FRACAS was in place to accurately identify and quantify the problem areas. Analysis of the aircraft log book and repair job-cards over the past six months period revealed the failure trends shown in table 5.1.

Availability

The navigation system hardware failures on the aircraft are covered by replacing a faulty LRU with a serviceable unit from the operational level store. A shortage of LRUs will prevent the repair of an unserviceable INS and will result in an unserviceable aircraft. The number of serviceable LRUs in the operational level store is the degree of availability of INS maintenance significant items that will ensure that any failing LRU in an INS can be rapidly replaced. LRUs are returned to the operational level store after repair at the I-, D- and M-level facilities. Availability is therefore also dependent on reliability and repair facility turn-around times (maintainability).

The minimum monthly spares stockholding over the same six months period is shown in table 5.2.

Month	FCC	CDU	PDU	IMU
1	1	1	1	1
2	0	0	1	1
3	0	1	1	0
4	0	1	1	0
5	0	0	1	0
6	0	1	1	0

Table 5.2: Minimum spares stockholding

6. ENGINEERING INVESTIGATIONS

General

Site inspections were conducted at the different levels of support with the prime objective to confirm the symptoms and to obtain more detailed specific information.

Operational Level

The flight crew presented a clear overview of their pre-flight and in-flight activities and tasks. These activities were verified against the manuals. No deviations were found. The flight crew also gave a concise account of the type of problems, frequency and under which circumstances these were most likely to occur.

The most prominent failure was the 'CDU Flashing Decimal' (CDU-FD) since all communications from the CDU to the FCC was then lost. The CDU-FD was most likely to occur towards the end of the inertial alignment process with the aircraft on the apron prior to engine start and take-off procedures. The engines were switched off during alignment to reduce vibrations to ensure an accurate north-find inertial alignment for improved navigational accuracy. Once in flight, the incidences of the CDU-FD were low and other failures were more likely to occur. The CDU-FD failure resulted in a take-off delay, INS system alignment retry and generally ended in a flight abort when the failure keeps recurring. This failure was more prominent during the summer months than during the winter months.

The operational level maintenance personnel on receiving a job-card from the maintenance planning and control (MPC) section, would initiate the avionics system acceptance test procedure in order to confirm and diagnose the reported failure. The CDU-FD failure would generally recur towards the end of testing whilst the aircraft was on the apron. With the aircraft back in the hanger, few incidences of CDU-FD were recorded. During these diagnostic tests, the aircraft was powered from a mobile power source.

On evaluation against the manuals on how the maintenance personnel went about the diagnostic tests and LRU replacement, it was found that the maintenance technicians:

(i) had a very limited knowledge of the basic functionality of each LRU of the INS and how these fitted and interacted with the larger avionics system.

(ii) were wearing protective gloves not mentioned in the maintenance manuals when removing a FCC from the instrument bay. Further investigation revealed that the FCCs were too hot to handle with bare hands immediately after switch-off. Pressure of work did not allow a cool down period prior to handling. The two FCCs are mounted in rack positions one above the other. The upper FCC always appeared hotter than the FCC in the lower position.

(iii) IMU testing was done by trial and error after having eliminated all other possible failures.

Intermediate Level

Faulty LRUs returned to I-Level are tested in a test bench which in essence consists of a 'hot mock-up' of all the INS LRUs, instrumentation and a test computer. Particularly the CDU-FD failure could not be reproduced on the intermediate level test bench. The intermediate level repair laboratory is air conditioned and forced air cooling is supplied to the INS test bench and the unit under test (UUT).

The apparent hot FCC problem experienced on the aircraft, was not experienced on the test bench, even after extended testing.

IMU repair by means of replacement of SRUs was problematic. Very often the same type of SRU had to be replaced a number of times before the IMU would pass all the acceptance tests. Those SRUs that could not be repaired were returned to manufacturing level for repair.

Test equipment was found to be serviceable and calibration dates valid. Documentation errors and deficiencies found by the intermediate level maintenance personnel were recorded but not followed up.

Since depot level electronic PCB repairs was performed by a special soldering section in the same facility, this was also evaluated. All repair activities were in accordance with the prescribed procedures. Minor faults were found on the FLUKE cards tester.

Manufacturing Level

Investigation at the local industry repair facility revealed that very often complete IMUs instead of only the inertial platforms were received for repair.

In the majority of cases the original IMU failure could not be confirmed but other unrelated failures were found and repaired prior to return to the intermediate level store.

Difficulty was also experienced at this support level in confirming IMU failures as well as effecting repairs. It was found that in a number of cases the inertial platforms and electronic cards, after having passed their individual tests, could not be integrated successfully and a 'mix-and-match' technique had to be adopted.

Overseas Aircraft Supplier and INS subcontractor

Consultative discussions were also held with the overseas aircraft supplier and the INS subcontractor. The main problem appeared to be lack of detailed quantitative information to enable development of corrective actions. Engineering investigation teams send by the main contractor could not localise and pin point the problems. The cost of keeping permanent engineering capability at the local airline operator's facility was too high to be practical.

Failure Analysis

Since there was no formal FRACAS in place collecting all the relevant failure data made quantitative failure analysis impossible. Site inspections revealed that the availability problem had a number of facets. Each facet interacted with the others making problem area pinpointing and diagnostics difficult.

Early on in the exploratory investigations, it became clear that the problem was not only of a technical nature but also that the support management and the effectiveness of logistic elements played a major role. The latter to a large extent explained why the attempts by the overseas supplier were not successful since their prime focus was only on technical aspects of the INS for which they were contracted.

Initial qualitative analysis identified the following main support problem areas:

- no formal FRACAS
- excessive number of unproductive failures at all the levels of support
- excessive FCC temperatures
- deficiencies in training
- test equipment deficiencies
- deficiencies in test specifications
- documentation deficiencies.

6.1 CORRECTIVE REMEDIAL ACTIONS

As a first priority a comprehensive support management measurement system was implemented, collecting FRACA data in sufficient detail to facilitate quantitative analysis of problem areas and effectiveness of corrective actions.

The defined FRACA data fields ensured that both reliability as well as maintainability data was to be captured. To this effect, the job-cards at all levels of support were extended to incorporate the following data fields:

- description of failure
- effect of failure
- diagnosed failure
- repair action
- utilisation rate
- resources consumed
  - man-hour
  - material (spares)
  - test equipment and facility hours
  - physical repair time
  - administrative delay times.

Also for the duration of the programme, particularly to address the high number of no fault found (NFF) incidences, the special FRACA form provided in appendix E, was introduced.

Initially weekly FRB meetings were held. This was reduced to fortnightly review meetings once the initial reliability improvement was achieved.

The operational level store stock level was also reported at the FRB meetings in order to identify the availability bottle necks.

With the support performance measuring system in place quantitative analysis of failure data and measurements of corrective steps was possible.

The Pareto principle was applied to the failure data and setting of corrective action priorities.

The reliability growth programme entailed evaluation of external environmental factors followed by detailed evaluation of the performance of the appropriate support logistic elements.

Environmental factors

The computer was the only LRU in the INS that appeared to be operating at an excessive temperature. Initially irreversibly thermally induced damage to the computer was suspected to be the primary cause of the poor INS reliability.

Investigation of the instrument bay on the aircraft revealed that little cooling air flowed over the two FCCs. An air flow modification by the aircraft supplier improved the flow of cooling air considerably as shown in table 6.1.1.

	No- Cooling - Aircraft on Ground	No Cooling - Aircraft flying	With cooling - Aircraft on Ground
Probe 1 (inside the casing of computer)	80°C after 3:30 hours	76°C after 4:00 hours	75° after 4:00 hours
Probe 2 (close to computer above PDU)	33°C after 4:00 hours	50°C after 3:00 hours	40°C after 4:00 hours
Component temperature on SRU	from 80 to 100°C	from 80 to 100°C	from 70 to 82°C

Table 6.1.1: Temperature profile of the FCC

The forced air cooling modification has been installed in all four aircraft using the new INS.

Analysis of the component reliability was made by a comparison of the results of the parts-stress Analysis as per Mil-Hdbk, 217F, section 3.4 [61] of a sample of the components that operated at the highest temperatures compared to the same sample operating at normal temperatures. At elevated temperatures (100°C), the predicted component failure rate was approximately double that of the failure rate at 70°C.

It was suspected that permanent irreversible component reliability degradation to some of the FCCs have taken place as a result of exposures for long periods to high environmental temperatures. To identify these degraded items, an additional long term environmental test lasting 50 hours at 80°C was performed at the intermediate support level after the integration test. Latent faults in SRUs were successfully diagnosed while testing the FCCs at an elevated temperature.

These FCCs when re-installed onto the aircraft revealed a fairly consistent operational MTBF of 207 flight hours.

Despite the fact that FCC repair turn around time was considerably increased, after an initial drop, availability improved to over 98%.

The single corrective action by improving the air flow over the FCCs had already made a substantial improvement in system reliability and was the main reason for the very good initial β reliability growth value of 0.12 as reflected in table 7.1.2.

7. LOGISTIC ELEMENT PERFORMANCE ANALYSIS

During the support phase, achieved system reliability is influenced by the remainder latent design defects as well as deficiencies in the logistic support elements.

A test analyse and fix (TAAF) policy, (Patterson [11]), was followed on all the logistic elements. Design changes or modifications to the operational equipment were followed-up by retrofit actions of the entire system inventory. These retrofit activities are the major difference between a TAAF approach during the development phase and that during the support phase.

7.1 ENGINEERING SUPPORT

The primary goal of the engineering support was to improve availability of the INS by improving the operational reliability.

Original situation

The airline operator did not make provision during the aircraft acquisition for local INS system and design expertise. Reliability degraded over a period of approximately 18 months to almost 50 failures per 100 flights.

Fault diagnosis at the operational and intermediate support levels in many instances did not correlate, identifying a need for improved diagnostic test capability and maintenance personnel skills training at all levels of support.

Current situation

Initial engineering effort was directed at:

- establishment of local system expertise
- assessment of system status as well as of the support system
- correction of system and support system deficiencies.

System and Design expertise

Initial system expertise was established by the appointment of an engineer who ultimately would be responsible for the local system and design expertise and be able to identify and quantify problem areas.

After an initial training period starting with self study of all the documentation and circuit diagrams augmented by overseas training at the INS supplier's facility, the local system engineer's main tasks were:

- chair the FRB and direct technical investigative action
- prepare technical reports for the overseas INS supplier
- evaluate modifications received from the overseas INS supplier
- prepare retrofit instructions and manage their implementation
- training of maintenance personnel
- updating of documentation.

The backlog of the original equipment manufacturer (OEM) approved engineering changes were retrofitted to ensure that all configuration items were at the same baseline.

A total of 107 engineering changes to the INS, INS software, test software and logistic infrastructure were approved and implemented during the recovery period.

Configuration management

A detailed physical configuration audit was performed on all the configuration items (systems, LRUs, SRUs and spares) in the inventory inclusive of all test equipment. The following data was captured:

- configuration item name
- serial number
- hardware modification status
- software/firmware revision status
- location
  - installed - higher level configuration item serial number
  - store - location and bin number
  - repair depot -job-card number
- status
  - serviceable
  - unserviceable.

All maintenance and training documentation were also audited and revision status recorded.

The major shortcomings in the documentation were:

- inaccuracies in some diagrams
- inadequate diagnostic and maintenance guides
- incomplete INS acceptance test procedure
- inadequate system operation guides
- no specific maintenance master reference index (MRI) collating and grouping all the maintenance and training documentation.

All changes after the audit were tightly controlled by means of an engineering change process.

The failure rate improvement per 100 flights since the start of the reliability growth programme in the second half of year 3, are reflected in table 7.1.1.

Six month Period	Number of failures per 100 flights
year 3- second half	37.4
year 4 - first half	10.0
year 4 - second half	4.0
year 5 - first half	3.8
year 5 - second half	4.2
year 6 - first half	3.4
year 6 - second half	3.9

Table 7.1.1: Improvement in INS reliability

Using the Duane growth model, Blanchard, p265, [63]:

$$\log(\lambda_c) = \log(\lambda_s) - \beta \log(T) \tag{7.1}$$

λ_c is the end cumulative failure rate
λ_s is the start cumulative failure rate
β is the slope of the growth curve
T is the unit of measure for the test period

The cumulative failures and flights are reflected in table 7.1.2.

The reliability growth rate after the initial rapid improvement followed a constant slope as predicted by Duane [14]. A β value of 0.17 represents a very aggressive reliability growth rate. This growth rate is to be expected since the unreliability factors were being addressed on both the system and logistic infrastructure level. Also the system had already been through a development reliability growth phase.

Six month Period	Cumulative flights	Cumulative number of failures per 100 flights	β
year 2 - second half	100	49.2	
year 3 - first half	200	91.1	0.12
year 3- second half	300	128.5	0.17
year 4 - first half	400	138.5	0.17
year 4 - second half	500	142.5	0.17
year 5 - first half	600	146.3	0.17
year 5 - second half	700	150.5	0.17
year 6 - first half	800	153.9	0.17
year 6 - second half	900	157.8	0.17

Table 7.1.2: Reliability growth

Maintainability has been improved through the introduction of a comprehensive FRACAS and closed loop management of the repair time and logistic delays. At each level of support, the following activities resulted in a substantial improvement of repair turn around times:

- revision of maintenance procedures
- review of test specifications and procedures
- introduction of quicker diagnostic tests
- review of the maintenance documentation
- resolving of FCC/IMU integration problems
- training of maintenance personnel.

Logistic Support Analysis

Although a detailed LSA was initially envisaged, it was subsequently found not to be cost effective since the hardware and most of the support infrastructure had already been in operational use for a period of time. Instead effort was placed into extracting adequate data from the maintenance history records to form the history FRACA data base in order to facilitate RAM analysis.

A life-cycle costing model was developed for the system using the LCC software package EDCAS, primarily to track recurring support cost factors during the reliability growth programme, in order to optimise system maintenance and spares holding at the different levels of support.

The following targets were set and assumptions made for the LCC model:

- operational availability . . . . > 95%
- mean time to repair at operational level . . . . < 4 hours
- overall INS MTBF . . . . > 130 hours
- system life cycle . . . . 5 years
  (for analysis purposes only)
- only operational support have been modelled, engineering support has been excluded for the study.
- confidence level of operational data . . . . > 80%
  (mainly as a result of limited data)

Effect of unproductive failures have been excluded from the model since these were aggressively addressed at the start of the reliability growth programme and resulted in the first major step improvement in availability.

Logistic Support Planning

The combination of reliability, availability and maintainability as well as logistic support analysis facilitated improved support planning. A number of changes and adaptations to the operational logistic support elements procedures were introduced under engineering change control. A faster diagnostic aid has been introduced at intermediate and depot levels of support through the introduction of a static navigation test (Schuler test). To reduce the work load on the IMU calibration and INS integration test benches, a special test bench was developed and built to perform a long static navigation test. A short technical description of the Schuler test is provided in appendix A.

The application of the Schuler static navigation test, enabled the introduction of INS inertial sensor performance evaluation within 90 minutes of test time versus the normal up to 40 hours of calibration time. In order to provide a measure of typical long mission navigation performance as well as to eradicate any latent defects in the INS, this test was extended to 8 hours provided the first 90 minutes was within acceptable limits. The test bench was completely automatic and PC driven to enable the tests to be performed over night.

The long navigation test was followed by a 50 hour environmental screen test at 80°C. This test was discarded once all temperature degraded components in the FCC had been eradicated in order to preserve operational system life.

7.2 OPERATIONAL LOGISTICS

The engineering support logistic elements are only applicable to that level of support that has the capability and expertise to control the overall support process and system baseline which for this case study was the depot support level. At this level all 12 logistic elements illustrated in figure 2.4.1, Part III, are applicable.

The operational logistic support elements are concerned with the day-to-day system repair activities. These logistic elements are applicable and unique to each individual level of support. At these support levels only the 6 operational logistic elements are applicable.

Infrastructure and Facilities

At the operational support level, the overheating of particularly the FCC during extended testing using ground power to the aircraft was overcome by providing a mobile cooling unit with a flexible duct to provide cooling air to the aircraft instrument bay.

At the intermediate support level, it was found that the workshop 115 Volt, 400 Hz, 3 phase AC supply (motor alternator set) was not within specification and resulted in sporadic IMU calibration and INS integration test failures. This was particularly problematic during the newly introduced long navigation and environmental tests. The power demand was low and therefore it was practical and cost effective to overcome this deficiency by upgrading the test benches with individual internal solid state 115 Volt, 400 Hz, 3 phase AC regulated supplies.

Personnel and Training

During the initial support investigation period, the initial skill levels and training received by all maintenance personnel was assessed and evaluated. It was generally found that the time period from having received specialised training to the introduction into service of the INS was too long, mainly as a result of project completion delays by the overseas supplier.

A retraining programme as well as a 6 monthly competency certification was introduced for the maintenance personnel at the different support levels.

To be cost effective the retraining was done locally by the local system engineer with the support of specialists from the overseas supplier. This approach also proved to be very effective for establishing adequate local engineering expertise for continuation support of the INS system.

The training programme was augmented by hands-on training.

Maintenance and Technical Support

The local system engineer was normally stationed at depot level but was on-call by any of the other support level technicians to provide technical assistance. The local system engineer had direct access to the overseas supplier for support.

Technical Publications

All errors in the documentation found during the normal course of maintenance was recorded. This was augmented by a detailed documentation audit conducted by the local system engineer. Interim changes were managed by means of numbered service bulletins which generally remained in effect until superceded by later service bulletins or a new publication of the appropriate manual pages.

Material and Supply Management

To prevent a depletion of IMU spares for the other aircraft types in the fleet, 4 IMUs were allocated to the new aircraft for support purposes. This resulted in one spare IMU for every 2 operational IMUs since each aircraft was equipped with 2 IMUs.

The Mil-Hdbk-217F, reference [61], reliability predictions were used to determine the reduced electronic component reliability under extended temperatures of particularly the FCC. The stock level of these components were temporarily increased in line with the operational usage and expected reduced reliability.

Operating Management System

A temporary limited operational management system was introduced using a general data base software package until such time that the client has commissioned his planned integrated business management system.

Data between the different levels of support was transferred on magnetic media to a common data base at depot level on a weekly basis.

The job-cards were enhanced to incorporate all the FRACA data fields.

The operational management system was serial number driven and would immediate trigger the last time the specific item was in for repair and what the diagnosis and repair action was. This facilitated corrective steps in particularly repeat (RF) and unconfirmed (NFF) failures.

8. CONCLUSION AND RECOMMENDATION

The turn-around in reliability of the INS system was achieved by comprehensive logistic support management utilising all the logistic elements.

The management of the multi-level support system was complicated by the fact that each individual level of support had its own management structure and value system which was not always the optimum for the total system reliability recovery effort. Through regular feedback and workshop sessions involving all the players, integrated team work was successfully established.

The recovery has now been sustained for more than 3 years and the system appears to be in a constant failure rate phase as shown in figure 8.1.

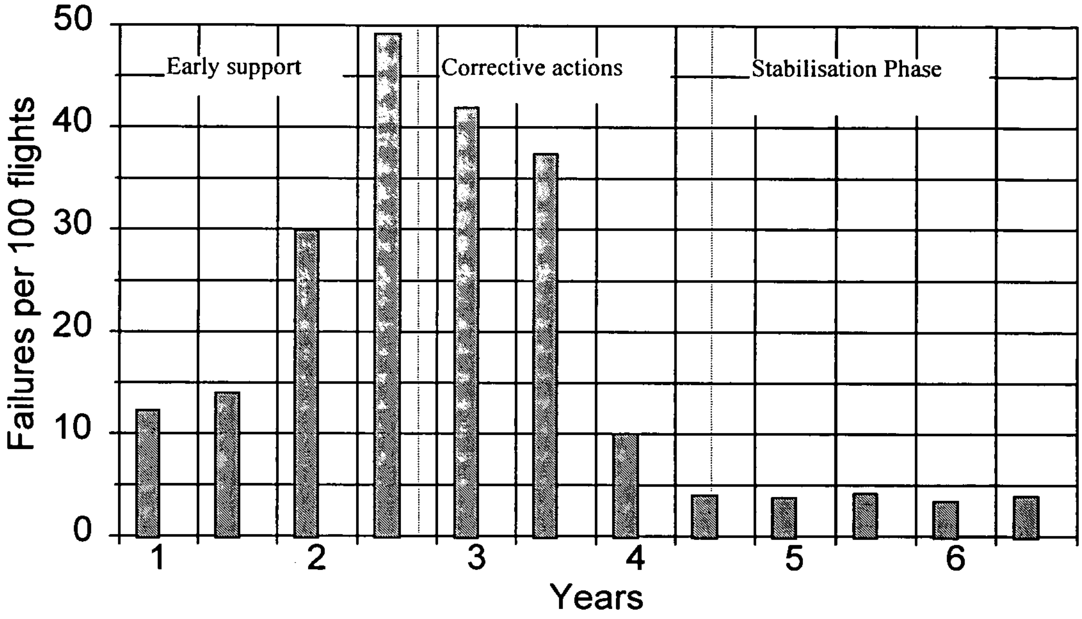


Figure 8.1: Reliability growth during the support phase

Table 7.1.2 shows that the reliability growth still appears to follow the Duane [14] reliability growth postulate. The data to verify this fact however is insufficient to come to a general conclusion. From practical experience there is no reason to believe that the relationship between cumulative failures and operational time would not follow a Weibull process.

The growth trend however was found to be very good in comparison with what is normally achieved during the development phase as shown in figure 8.2. This may in part be due to the very aggressive growth programme adopted, but more likely as a result of the large number of operational hours and subsequent failures that can be achieved over a relatively short time with the whole INS fleet in actual operation.

This does not imply that reliability growth could as a norm be performed in the operational environment for the following reasons:

- negative initial product reliability perception by the client - (Malec [15]).
- all actions are under the direct auspices of the client and mistakes can not be afforded
- retrofit actions are very expensive, time consuming and disruptive to system fleet availability
- it is not always easy to achieve total management commitment at all the levels of support in practice.

This case study also supports Wong's findings that reliability of complex electronic systems do not follow a constant failure rate during the support phase, (Wong [39] and [48]). A constant failure rate of these systems can only be achieved by sound support management involving all the logistic support elements.

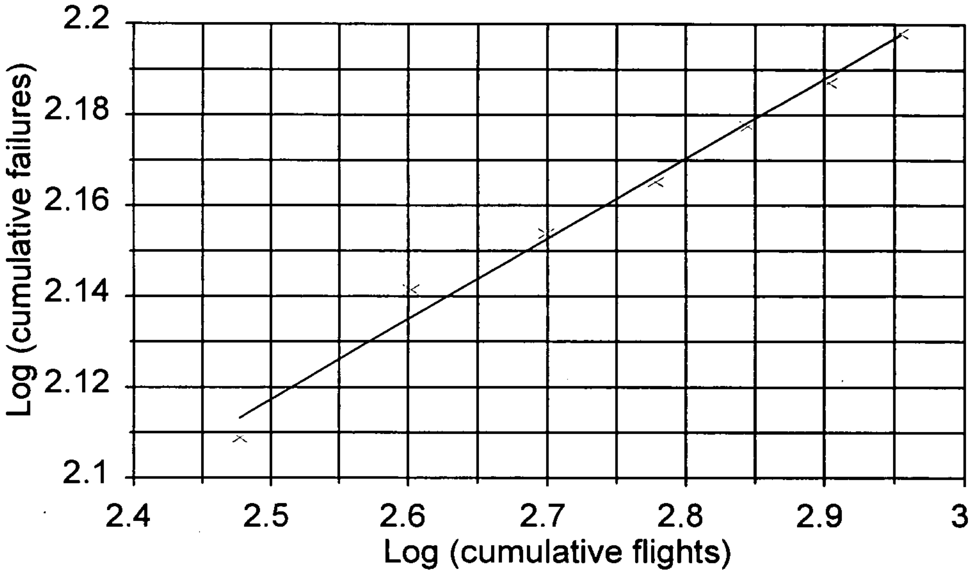


Figure 8.2: Reliability growth trend

The airline operator during the acquisition process overlooked the importance for local engineering support and mistakenly assumed that overseas engineering support by the OEM would be adequate. The case study has illustrated that during the support phase the interaction of all the logistic support elements and impact on the operational system reliability performance is so intertwined that overseas engineering support alone can not ensure an optimally performing system.

For complex systems that are to be supported by a multi-level support infrastructure, it is recommended that adequate local logistic and system engineering support be established for optimal and cost effective system performance.

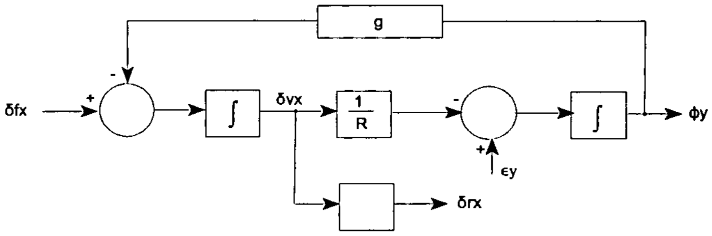
APPENDIX A

STATIC NAVIGATION OR SCHULER TEST

If a navigation system is kept stationary in a fixed position and orientation, it must navigate against the earth's rotation around its axis. The system must calculate the correct gyro torques to compensate for this transport rate.

An earth stationary navigation system must maintain its current coordinates. This means that any velocity output by the navigation system is a velocity error, and the position drift away from the initial position is a position error.

Figure A.1, shows a simplified error propagation along the X-axis of INS velocities and position as a function of time.



δfx = x axis accelerometer error
δvx = x axis velocity error
ϵy = y axis gyro drift
δrx = x axis position error
ϕy = y axis mislevel angle
R = nominal radius of the earth (6.378×10^6 m)
g = gravity (9.81 m/s^2)

Figure A.1: X-axis INS error propagation

Y-axis gyro drift and mis level angle is caused by gimbal precession

A similar error propagation model can be set-up for the y-axis.

The solutions of the X- and Y-axis velocity and position differential equations contain imaginary roots. The position errors will drift as a function of time with a sinusoidal frequency superimposed upon them. The natural frequency of oscillation is given by:

$$T = 2\pi\sqrt{R/g}$$

$$= 84.44 \text{ minutes}$$

From the error analysis it can be deduced that a constant gyro drift will cause a constant velocity offset as well a sinusoidal oscillation at the Schuler frequency.

Integrating the constant velocity error results in a position drift at a constant ramp drift with an oscillatory Schuler frequency superimposed upon it.

The accelerometer errors will cause an oscillatory velocity error at the Schuler frequency with a zero mean offset. The peak-to-peak deviation of the velocity error curve is as a result of accelerometer bias.

From the above it can be concluded that the static navigation test can after a period of 85 minutes give a clear indication of the gyro and accelerometer performance of an inertial navigation system. Experience has shown that it is quite feasible to perform this test on the aircraft, recording the results say every 5 minutes provided the movement and vibrations are curtailed.

Reference: M.C. Havinga Januarie 1992

AFLEIDING VAN ENKELE INERSIëLE NAVIGASIEMODELLE EN 'N STUDIE VAN DIE MEEGAANDE FOUTVERGELYKINGS

Referaat ter vervulling van die graad M.Ing aan die Universiteit van Pretoria.

APPENDIX B

ABBREVIATIONS

Δ - Delta (difference)
AC - Alternating Current
ACC - Analoque Control Card
ADI - Attitude Direction Indicator
ADM - Advanced Demonstration Model
AMSAA - United States of America Army Materiel Systems Analysis Activity
APC - Auto Pilot Card
ATP - Acceptance Test procedure
BIT - Built In Test
BITE - Built In Test Equipment
CAB - Corrective Actions Board
CDU - Control Display Unit
CDU-FD - Control Display Unit - Flashing Decimal
CIP - Component Improvement programme
DA - Design Authority
DC - Direct Current
DCA - Director of Civil Aviation
DOD - Department of Defence (United States of America)
EPROM - Electrically Programmable Memory
ESD - Electro Static Discharge
ESS - Environmental Stress Screening
FCC - Flight Control Computer
FCNR – Fault Confirmed, Not Related
FMECA - Failure Mode, Effects and Criticality Analysis
FRACA - Failure Reporting and Corrective Action
FRACAS - Failure Analysis and Corrective Action System
FRB - Failure Review Board
FTA - Fault Tree Analysis
GE - General Electric
GPS - Global Position Satellite
H/W - Hardware
Hdbk - Handbook
HSI - Horizontal Situation Indicator
IBM - International Business Machines
ILS - Instrument Landing System
ILS - Integrated Logistic Support
IMC - Interface Management card
IMU - Inertial Measurement Unit
INS - Inertial Navigation System
LCC - Life-Cycle Cost
Log - Logarithm
Log - Logistics
LRU - Line Replaceable Unit
LSA - Logistic Support Analysis
M(t) - Mean Cumulative Number of Failures
M(t) - Mean Cumulative Number of Failures
M-Level - Manufacturing Level

Mil - Military
MIS – Management Information System
MMHD - Maintenance and Modification History Document
Mod - Modification
MPC - Maintenance Planning and Control
MRI - Master Reference Index
MSI - Maintenance Significant Item
MTBF - Mean Time Between Failure
MTBM – Mean Time Between Maintenance
MTBMA - Mean Time Between Maintenance Actions
MTTF - Mean Time To Failure
MTTR - Mean Time To Repair
NFF - No Fault Found
NHPP - Non homogeneous Poisson process
NTF - No Trouble Found
O&M – Operations and Maintenance
OEM - Original Equipment Manufacturer
OMS - Operation Management System
PAIRS - Product Assurance Inspection Reporting
PAIRS – Product Assurance Inspection Reporting
PATS - Product Assurance Test System
PATS - Product Assurance Test System
PC - Printed Circuit
PCB - Printed Circuit Board
PDU - Power Distribution Unit
PPM - Pilot Production Model (Pre-Production Model)
PRAT - Product Reliability Acceptance Test
PRAT - Product Reliability Acceptance Test
QA - Quality Assurance
R&M - Reliability and Maintainability
RAM - Reliability Availability Maintainability
RAM/LOG - Reliability Availability Maintainability/Logistic
RAM - Random Access Memory
RCA - Radio Corporation of America
RCM - Reliability Centered Maintenance
RDGT - Reliability Growth Development Test
RF - Repeat Failures
RGT - Reliability Growth Testing
ROCOF - Rate of Occurrence of Failures
S/W - Software
SDC - Synchro to Digital Card
SRA - System Reliability Analysis
SRU - Shop Replaceable Unit
Std - Standard
TAAF - Test Analyse and Fix
TAT - Turn Around Time
TQM - Total Quality Management
UK - United Kingdom
USA - United States of America
USAF - United States of America Air force
UUT - Unit Under Test

APPENDIX C: RELIABILITY DEFINITIONS

1. DEFINITIONS

The definitions are taken directly from the literature referenced and no attempt to re-phrase or adapt the grammar has been attempted. Where no reference has been provided, the definition is provided in the author's own words.

1.1 ACHIEVED RELIABILITY (measured)

The reliability achieved by the design during the test phases of the program using FRACA data.

1.2 ALLOCATED RELIABILITY

A top-down reliability allocation for the different subsystems, derived from the overall system's reliability budget. This reliability is a contracted reliability figure and is used in development specifications.

1.3 AVAILABILITY

Availability or the measure of the degree a system is in the operable and committable state at the start of a mission when the mission is called for at an unknown random point in time, (Blanchard, p18, [59]).

Availability is the fraction, ratio, or percentage of time that the systems are physically able to perform (Lamb, p6 [60]).

Availability is the probability that an item will be available when required, or as the portion of total time that the item is available for use (O'Connor, p127, [50]).

Availability represents the likelihood of having the product in a useable state (Pecht, p1, [58]).

From the above it can be construed that availability is the combination of the reliability and maintainability probability functions.

1.4 CLOSED LOOP FAILURE REPORTING SYSTEM

A controlled system assuring that all failures and faults are reported, analysed (engineering or laboratory analysis), positive corrective actions are identified to prevent recurrence and that the adequacy of implemented action is verified by tests (Mil-Std-2155, p2, [28]).

1.5 DESIGN MATURITY

Design maturity is achieved after a calender time when the reliability of the system has reached its growth potential, (Healy [10]).

1.6 FAILURE

The termination of the ability of an item to perform a required function (Healy [10]).

An event in which an item does not perform one or more of its required functions within the specified limits under specified conditions. (Mil-Std-2155, p2, [28])

1.7 FAILURE ANALYSIS

The logical, systematic examination of an item to identify and analyse the consequences of potential and real failures (Healy [10]).

A determination of failure cause performed by the use of logical reasoning from examination of data, symptoms, available physical evidence and laboratory analysis results (Mil-Std-2155, p2, [28]).

1.8 FAILURE ANALYSIS AND CORRECTIVE ACTION SYSTEM (FRACAS)

A formal closed-loop system established to identify and track failure events, determine corrective actions and track the effectiveness of incorporated corrective actions (Healy [10]).

1.9 FAILURE CAUSE

The circumstances that induce or activates a failure mechanism; e.g. defective soldering, design weakness, assembly techniques, software error, etc. (Mil-Std-2155, p2 [28]).

1.10 FAILURE REVIEW BOARD

A group consisting of representatives from appropriate contractor organisations with the level of responsibility and authority to assure failure causes are identified and corrective actions are effected (Mil-Std-2155, p2 [28]).

1.11 FAULT

A degradation in performance due to failure of parts, detuning, misalignment, maladjustment, and so forth (Mil-Std-2155, p2 [28]).

1.12 HAZARD RATE

For non-repairable item, the conditional probability of failing in an arbitrarily small interval of time beginning at time ***t*** given that the item has survived to ***t*** divided by the length of the interval (Healy [10]).

1.13 INHERENT RELIABILITY

The reliability after all failure modes which are cost-effective to correct has been seen and corrected (Healy [10]).

The sum of the intrinsic reliability under typical operational stress conditions of all the components of the system, assuming a mature design.
(Mil-Hdbk-217F [61]).

1.14 MEAN TIME BETWEEN FAILURE (MTBF)

A basic measure of reliability for repairable items: The mean number of life units during which all parts of the item performs withing their specified limits, during a particular measurement interval under stated conditions [Mil-Std-721C].

For a stated period of time in the life of a system, the length of the stated period of time divided by the expected number of failures during the stated time
(Healy [10]).

(i) INHERENT MTBF

The instantaneous MTBF, after all failure modes that are cost-effective to correct have been seen and corrected. (Healy [10]).

(ii) INITIAL MTBF

The instantaneous MTBF for a system at the beginning of a reliability growth testing (Healy [10]).

(iii) INSTANTANEOUS MTBF

For an arbitrarily small time interval in the life of a system. The length of the stated time interval divided by the expected number of failures during the stated time. The final instantaneous MTBF is the instantaneous MTBF at the end of all reliability testing (Healy [10]).

(iv) OBSERVED MTBF

For a stated period in the life of a system, the mean value of the length of time between consecutive failures computed as the ratio of the length of the stated of time to the observed number of failures during the stated time (Healy [10]).

1.15 MEAN TIME BETWEEN MAINTENANCE (MTBM)

A measure of system reliability taking into account maintenance policy. The total number of life units expended by a given time, divided by the total number of maintenance events (scheduled and unscheduled) due to that item [Mil-Std-721C].

1.16 MEAN TIME BETWEEN MAINTENANCE ACTIONS (MTBMA)

A measure of the system reliability parameter related to demand for maintenance manpower: The total number of system life units, divided by the total number of maintenance actions (preventive and corrective) during a stated period of time [Mil-Std-721C].

Is the mean or average time between ***all*** maintenance actions (preventive and corrective), (Blanchard, p46, [59]).

1.17 MEAN TIME TO REPAIR (MTTR)

A basic measure of maintainability: The sum of corrective maintenance times at any specific level of repair, divided by the total number of failures within an item repaired at the level, during a particular interval under stated conditions [Mil-Std-721C].

Geometric mean time to repair (Blanchard, p16 [59]).

1.18 NO FAULT FOUND (NFF)

An NFF is a repair item diagnosed at one level of repair as unserviceable, when send to the next level of repair where after extensive diagnostic tests and checks, no fault could be found and returned in its original state to higher level support organisation.

1.19 RATE OF OCCURRENCE OF FAILURES (ROCOF)

The rate of change of the expected cumulative number of failures for a repairable system. The ROCOF is often called the intensity function (Healy [10]).

1.20 RELIABILITY GROWTH

The positive improvement in a reliability parameter over a period of time due to changes in product design or the manufacturing process (Mil-Hdbk-189 [27] p3, Healy [10]).

1.21 RELIABILITY GROWTH MANAGEMENT

The systematic planning for reliability achievement as a function of time and other resources, and controlling the ongoing rate of achievement by reallocation of resources based on comparisons between planned and assessed reliability values (Mil-Hdbk-189, p3 [27]).

1.22 RELIABILITY PREDICTION

An estimate of the reliability of a system based on reliability models which use information on the system architecture, the parts composing the system, test data, and field data (Healy [10]).

1.23 REPAIRABLE SYSTEM

A system which, after failure to perform at least one of its required functions, can be restored to performing all of its required functions (by any method except replacement of the entire system) (Healy [10]).

1.24 REPEAT FAILURE (RF)

A RF is a repair item that has been repaired and put back into service only to have the same failure recur after having been into service for less than 10% of the expected MTBF.

1.25 SYSTEM

Whenever the word *system* is used, the meaning must be construed in the broader sense namely a product, a subsystem, a production plant, a utility supplier such as a power station, data network supplier or telephone exchange.

1.26 LINE REPLACEABLE UNIT (LRU)

A unit designated to be removed upon failure from a larger entity (equipment, system) in the operational environment, [66].

1.27 SHOP REPLACEABLE UNIT (SRU)

An item that is designated to be removed or replaced upon failure from a higher level assembly in the shop (intermediate or depot maintenance activity) and is to be tested as a separate entity. Also referred to as a shop replaceable entity [66].

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[67] System Support Group,
Kentron, a Division of Denel,
P.O. Box 7412, Centurion 0046,
Republic of South Africa.

APPENDIX E: INS FRACA FORM

D-LEVEL INSTRUCTION

The D-Level technician must complete the D-Level section on the FRACA form, for any No Fault Found (NFF) on the LRUs or SRUs received for repair from I-Level.

The Depot Manager shall be notified of any NFF's. On completion of the FRACA form the Depot Manager shall sign the form. It is the responsibility of the Depot Manager to allocate a FRACA tracking number and control the flow and status of this form.

On completion of this form a copy shall be kept in the Maintenance and Modification History Document (MMHD) and the original form shall accompany the LRU/SRU diagnosed as NFF to I-Level.

The Depot Manager shall on return of this form, from I-Level, decide if an investigation is required or if the FRACA can be closed. If the LRU/SRU still fails the same test at I-Level, an investigation must be launched. If I-Level could not reconfirm the fault, close the FRACA form.

A copy of this form must be distributed to the FRB and CAB.

I-LEVEL INSTRUCTION

The I-Level technician must reconfirm the failure as reported to D-Level.

The I-Level technician must complete the I-Level section of the FRACA form for any No Fault Found (NFF) LRUs and SRUs received back from D-Level.

This form shall be completed, signed and returned to the D-Level Depot Manager.

FRACA FORM

FRACA Tracking No:____

FRACA Date:_/_/_Time: _h_

O-level Tracking No:____

LRU/SRU Desc. :___S/N: ___

I-level Tracking No:____

LRU/SRU Desc. :___S/N: ___

D-level Job-card No:_____

D-level Action on MSI with NFF

D-level Date/Time Received:_/_/_Time: _h_
D-level activities in sequence:____
D-level Recommended Action:____
D-level Technician:
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___
Depot Manager:
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___**(To be completed by D-level)**

I-level Action on MSI with NFF

I-level Date/Time Received:_/_/_Time: _h_Reconfirmed Failure at I-level (Y/N) ___
I-level activities in sequence:____
I-level Technician:
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___
I-Level Manager
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___
(To be completed by I-level)

Investigation Team Action on FRACA

Investigation Start Date/Time :_/_/_Time: _h_
Confirmed I-level Findings: (Y/N)________________
Investigation Action:____
Recommendation:____
Action to be Performed:____
CAB Required (Y/N):___Investigation Complete Date/Time: _/_/_Time: _h_
Investigation performed by:
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___
Name:_____No.:_____Rank: _Date: _/_/_Sign: ___
(To be completed by D-level)

Depot Manager:

Name:_____No.:_____Rank: _Date: _/_/_Sign: ___

FRACA Closing Date:_/_/_Time: _h_