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GENERATING PROJECT VALUE THROUGH DESIGN FOR RELIABILITY: ON THE DEVELOPMENT AND IMPLEMENTATION OF A POTENTIAL VALUE FRAMEWORK

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Abstract

The current trend to economically exploit deepwater hydrocarbon reserves is to reduce the capital expenditure; accomplished by deploying subsea equipment. The financial benefit afforded is offset by the risk of high operational costs associated with failure. Recognition of the life cycle cost implications of subsea reliability have led to the development of the reliability strategy. This strategy adopts a risk based approach to design for reliability where only analyses (and their subsequent recommended actions) perceived to add to whole project value are implemented. While life cycle costing has been developed to address through life cost, analyses are traditionally considered a source of cost accumulation rather than value creation.

This thesis proposes a potential reliability value decision making framework to assist in the design for reliability planning process. The framework draws on the existing concepts of life cycle costing to explicitly consider the through life value of investing in reliability analyses. Fundamental to the framework are the potential reliability value index and an associated value breakdown structure intended as central decision support for decentralised decision making.

Implementation of the framework is reliant on synergies within the project organization; including relationships between organizations and project functions. To enhance synergy between functions and dismantle some of the recognised barriers to implementing the reliability strategy an organizational structure, for projects, guided centrally by the reliability value framework is proposed. This structure requires the broadening of each project functions' skill set to enable the value added implementation of the strategy's activities. By widening the scope of application, the reliability analysis toolkit becomes the central guidance of the design process and awareness of the causes of unreliability and how they can be avoided increases. As this capability improves so the cost-efficiency with which reliability is managed in design (introduced as the reliability efficiency frontier) also increases.

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Contents

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Glossary of Terms

Where possible, this thesis retains the notation used by the original authors cited herein. As a result some notations assume different meaning throughout the document although meaning within a specific chapter is consistent.

Chapter 1

API	American Petroleum Institute
CAPEX	Capital Expenditure
E&P	Exploration and Production
EOQ	Economics of Quality
EOR	Economics of Reliability
ETA	Event Tree Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FTA	Fault Tree Analysis
LCC	Life cycle cost
OPEX	Operating Expenditure
RAM	Reliability Availability Maintainability

Chapter 2

API	American Petroleum Institute
CAPEX	Capital Expenditure
DNV	Det Norske Veritas
FEED	Front End Engineering Design

HR	Human Resource
LCC	Life cycle cost
NASA	National Aeronautics and Space Administration
OPEX	Operating Expenditure
PDCA	Plan Do Check Act
QA	Quality Assurance
QC	Quality Control
R&M	Reliability and Maintainability

Chapter 3

CAPEX	Capital Expenditure
CEO	Chief Executive Officer
LCC	Life cycle cost
OPEX	Operating Expenditure

Chapter 4

a	Operating time
ABC	Activity Based Costing
C_0	Fixed cost of the test facility
CAPEX	Capital Expenditure
C_{at}	Cost of Assurance testing
CBS	Cost Breakdown Structure
C_{DP}	Cost of deferred production
c_f	Cost of testing an individual item

$c_i(R_i)$	Cost of the i^{th} component
$\overline{C}_k$	Mean cost of k^{th} failure mode given failure
C_{LP}	Cost of lost production
C_P	Cost price as a function of reliability
C_{RL}	Repair labour cost
C_t	Expected net cash flow at the end of year t
C_W	Warranty cost
D	Global damage index
E&P	Exploration and Production
$E(C_t)$	Expected total cost of testing
F	Cost scaling factor
$f(\lambda)$	Cost price as a function of hazard rate
FEED	Front End Engineering Design
f_i	Feasibility of increasing the reliability of the i^{th} component
g	Cost shaping factor
$g(\lambda)$	Mean cost to repair as a function of the hazard rate
I_0	Initial investment
IRR	Internal Rate of Return
ITT	Invitation To Tender
K	Risk of Failure
k	Discount rate
$K(\lambda\text{-}x)$	Risk associated with the hazard rate, λ-x
$L(\lambda\text{-}x)$	Total loss after decreasing λ by x

LCC	Life cycle cost
LSC	Logistic Support Cost
$MTTF$	Mean Time To Failure
$MTTR$	Mean Time To Repair
n	Number of tests
N	Number of years
NPV	Net Present Value
$O_{F,i}$	Actual negative cash flow in the i^{th} year
$OPEX$	Operating Expenditure
PI	Profitability Index
P_P	Price of oil per barrel
P_R	Production rate
PV	Present Value
$Q(x)$	Investment required to reduce λ by x
R	Reliability
r	Risk free interest rate
R_i	Reliability of the i^{th} component
$R_{i,max}$	Maximum achievable reliability for the i^{th} component
$R_{i,min}$	Current reliability of the i^{th} component
R_m	Target reliability
ROV	Remotely Operated Vehicle
STC	Standard Technical Cost
t	Year
T_P	Time to restore normal production

t_w	Duration of the warranty period
V	Cost to repair a detected fault
$X(i)$	Detection time of the i^{th} fault
γ	Required confidence from testing
δ	Constant interest rate
λ	Hazard rate
λ_0	Hazard rate of an item with no specific design for reliability effort
λ_k	hazard rate of the k^{th} failure mode
τ	Test duration

Chapter 5

A	Availability
A_p	Production availability
CAPEX	Capital Expenditure
ETPLT	Equivalent Total Production Loss Time
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FTA	Fault Tree Analysis
LCC	Life Cycle Cost
MPTA	Maximum Production Time Available
MTTR	Mean Time To Repair
MUT	Mean Uptime
OPEX	Operating Expenditure
P	Probability

$P(X\|Y)$	Conditional Probability of event X given event Y has occurred
PAND	Priority AND
RAM	Reliability Availability Maintainability
RBD	Reliability Block Diagram
RPN	Risk Priority Number
t	Time
β	Characteristic shape parameter
η	Characteristic life parameter
λ	Hazard rate
Φ_a	Actual produced volume
Φ_p	Planned produced volume

Chapter 6

$C_{INCIDENT}$	Incident Cost
C_{LP}	Cost of lost production per unit time
C_{RL}	Repair labour cost per unit time
EOQ	Economics of Quality
FMEA	Failure Modes and Effects Analysis
HAZOP	Hazard and operability
HIPPS	High Integrity Pressure Protection System
MTTR	Mean Time To Repair
OPEX	Operating Expenditure
PAF	Prevention Appraisal Failure
U	Unavailability

β	Reliability index
μ_L	Mean operational stress
μ_S	Mean strength
σ_L	Standard deviation of the stress
σ_S	Standard deviations of the strength

Chapter 7

$\sigma_{\Delta CF(strategy)}$	Standard deviation of the change in cash flow
C	Cost
CAPEX	Capital Expenditure
C_{DM}	Cost of a single design modification
C_G	Cost of reliability growth programme
$C_{\lambda i}$	Cost per unit time of the assessment of the i^{th} failure type and
FMECA	Failure Modes and Effects Criticality Analysis
K	Cost to achieve the baseline functional performance P
K^*	Resultant Life cycle cost (excluding Q)
M	Number of design modifications
MTTF	Mean Time To Failure
OPEX	Operating Expenditure
OREDA	Offshore Reliability Data
P	Baseline functional performance
P^*	Functional performance as a result of investing Q
PI	Profitability Index
Q	Cost of investment in reliability

$\overline{Q}$	Mean investment cost
r	Discount rate
r	Discount Rate
R	Revenue forgone
RBD	Reliability Block Diagram
RVI	Reliability Value Index
t	Time
TTF	Time to failure
$t_{\lambda i}$	Time spent analysing the i^{th} failure mode
U	Random number uniformly distributed over the interval (0,1]
VBA	Visual Basic for Applications
α_i	Growth rate for the i^{th} hazard rate
β	Characteristic shape parameter
β_{RVI}	Safety margin for the reliability investment
$\gamma_{\lambda i}$	Detectability of the i^{th} failure mode
$\Delta\mathrm{CF}(strategy)$	Change in whole life cash flow as a function of the reliability strategy
$\overline{\Delta CF}(strategy)$	Mean change in cash flow as a result of investment
ΔC_{Fn}	Change in cash flow in the n^{th} year
η	Characteristic life parameter
λ	Hazard rate
λ_{0i}	Historical or original hazard rate of the i^{th} failure mode
λ_A	Systematic hazard rate attributed to the architecture change risk factor
λ_E	Systematic hazard rate attributed to the environment change risk

	factor
λ_{Gi}	Hazard rate of the i^{th} failure mode as a result of reliability growth
λ_O	Systematic hazard rate attributed to the organization change risk factor
λ_R	Target residual hazard rate
λ_T	Systematic hazard rate attributed to the technology change risk factor
σ_Q	Standard deviation of the reliability analysis investment
$\Phi(\bullet)$	Cumulative distribution function of the standard normal distribution

Chapter 8

b	Decline rate
bbl	Barrel
CAPEX	Capital Expenditure
ESP	Electric Submersible Pump
IRR	Internal Rate of Return
kbopd	Thousands of barrels of oil per day
LCC	Life Cycle Cost
M	Number of design modifications
MMbbls	Millions of barrels
MPP	Multiphase pump
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NPV	Net Present Value
OPEX	Operating Expenditure
P	Probability

PI	Profitability Index
Q	Cost of reliability investment
RR	Recoverable Reserves
RVI	Reliability Value Index
RVI	Reliability Value Index
STC	Standard Technical Cost
t	Time
WI	Water Injection
α	Fix efficiency coefficient
γ	Detection Rate
$\Delta CF(strategy)$	Change in whole life cash flow as a function of the reliability strategy
λ_0	Historical or original hazard rate of the failure mode
φ_{tp}	Topside processing capacity

Chapter 9

BAT	Best Available Technology
CAPEX	Capital Expenditure
FEED	Front End Engineering Design
FMEA	Fail Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FTA	Fault Tree Analysis
LCC	Life cycle cost
MTTF	Mean Time To Failure
OREDA	Offshore Reliability Data

Q	Cost of reliability investment
RAM	Reliability Availability Maintainability
RBD	Reliability Block Diagram
RVI	Reliability Value Index
Δcashflow	Cash flow as a result of investing Q

1. Introduction

Demand for oil and gas is driving exploration and production (E&P) companies to more remote and technically challenging environments. Exploration and production first ventured offshore in 1897 when a drilling derrick was placed on a pier reaching 250ft offshore. By 1961 the first subsea Christmas tree was installed and before the turn of the century the industry had achieved the milestone of completing 1000 subsea wells. This rapid growth of the subsea industry is due to both technological and economic drivers. As oil reserves are discovered in deeper waters, conventional technology solutions deployed in shallower waters become financially infeasible due to escalating capital expenditure (CAPEX). Deployment of subsea technology reduces the required size of topsides and their support structures (a significant CAPEX item), but the immediate financial benefit afforded by installing subsea equipment is offset by the potential cost of failure during operations.

Considering the trade-off between capital expenditure and operating expenditure (OPEX) is not new. The principles of life cycle costing were developed in the early 1960s, around the time the first subsea tree was installed. However, while the subsea industry embraces these concepts, CAPEX reduction is often the focus of life cycle costing; Hanrahan and Chitwood (2005) point out that any CAPEX item that can be deferred to incur a reasonable OPEX increase is favourable for project economics. At the same time, it is accepted that unreliability can unfavourably escalate OPEX (and whole life cycle costs) and that high reliability can be a source of enhance project value and competitive advantage. In recognition of this, the industry is recommending the best practises of technical risk management through its standardisation bodies. Subsequently, organizations are customising these practises to align them with existing project management policy.

Despite the introduction of technical risk management strategies the relationship between design for reliability effort, the achieved system reliability and life cycle cost is not fully appreciated. The reliability engineers' toolkit (reliability activities such as failure modes and effects analysis and system availability analysis) is too often reserved for ad hoc and belated implementation or compliance to contractual specification. Rather, they should influence design decisions through understanding what system reliability is required to satisfy a project's financial objectives.

Any investment of time and effort into design for reliability should be commensurate with the perceived level of risk within a project. The recommended practises applicable to the petroleum industry stipulate that design for reliability activities should only be performed if they add value to the project (ISO 20815, 2007; API RP17N, 2007). Aside from stating that the required effort increases with increased technical risk and providing rule of thumb implementation criteria, there is no guidance relating to how any design for reliability activity is qualified 'value added'. This research addresses the need for a rational methodology and appropriate tools to define the level of reliability that will meet corporate requirements and to provide evidence to decision makers, early in design decision making process, of the value of investing time and management effort in design for reliability activities during the design life cycle.

This thesis assumes four basic parts. Part one (chapters 2 and 3) introduces the underlying principles of technical risk management and addresses existing organizational constraints to the effective implementation of such a strategy. These chapters demonstrate the implicit links between the corporate objectives of an operator organization and the key processes that drive a reliability strategy, and highlight where barriers to implementing a pro-active value driven reliability strategy exist. Part two (chapters 4, 5 and 6) reviews the existing literature central to the construction of a decision making process that focuses on the value of reliability. These chapters explore the applications required to accurately model cost and reliability over a project lifecycle and their formulation within an economics of reliability model. Part three (chapters 7 and 8) constructs a 'potential reliability value framework' and demonstrates its application through a number of case studies. The framework incorporates key aspects of the technical risk management strategy (outlined in the industry's recommended practice) and acknowledges that the potential value added through design for reliability is influenced by the cost-efficiency with which the reliability toolkit is applied; this feature is introduced through the concept of a reliability efficiency frontier. Part four (chapter 9) extends the discussion of the case studies to explore how the framework can be incorporated to break down some of the barriers to strategy implementation and expand the reliability efficiency frontier. The thesis concludes that the potential value from the implementation of a technical risk management strategy is enhanced through encouraging decentralized application of the reliability toolkit and decision making driven by a centralized decision process.

Chapter 2 commences this study by introducing the fundamental aspects of technical risk management as presented in the upcoming recommended practice for the subsea industry. The approach is typified by the application of twelve key processes through a 'define, plan, implement, feedback' management loop. These key processes are understood as the management practices required to deliver reliability on projects and have their conceptual roots in design safety management. Core to the application of the technical risk management practice is defining and planning reliability management activities that add to overall project value. The definition of a scope of reliability work is a risk based decision. While it is not appropriate for standards or recommended practices to dictate those activities that are value added (as they cannot assume organizational risk preference), they lack guidance on how to define if activities are in fact value added or the effort required to adequately manage the perceived risk.

Chapter 3 explores the organizational barriers and constraints to the successful implementation of a reliability strategy. Literature reveals barriers to implementation, in the subsea industry, relating to the perception of the reliability disciple, a business focus on CAPEX and a lack of knowledge of failure causation. These barriers are symptomatic of the organizational structure. Traditionally, reliability is managed through a central function, isolated from the project. More recently decentralised reliability management has been suggested. This has the benefit of increasing the exposure of the reliability disciple to the rest of the organization but decentralised decision making can result in conflicts of interest. A central decision making framework is required to guide decentralised decision making.

Chapter 4 reviews the current literature relating to life cycle costing as a basis for such a decentralised decision making process. Fundamental to the application of life cycle costing is the definition of a decision metric and a cost breakdown structure. Metrics quantify and qualify the acceptance criteria for the decision making process while the cost breakdown structure defines the scope of the decision making process by identifying cost elements that differentiate the decision options. A reliability centred cost breakdown structure is proposed, which is used to model cost accumulation in either CAPEX or OPEX models and further defines these costs according to the project stage in which they are accumulated. The literature reveals that reliability centred CAPEX models tend to be reserved for product development instead of the project environment, addressing the ability to achieve target reliability at component level. Reliability centred OPEX models have received more attention in the literature. Combined, these models provide the basis of a life cycle cost model, but their application often focuses on differentiating existing options or reducing cost rather than identifying opportunities for and justifying value added reliability improvement in projects. More specifically, the LCC models are not used to support the value added application of the reliability toolkit or justify the amount of reliability effort required to manage the inherent technical risks to reliability improvement.

In order to justify the use of the reliability toolkit, decision makers need to understand the potential benefit that can result from its application. Chapter 5 investigates the strengths and weaknesses of technical risk and reliability assessment techniques and considers how they can support the life cycle costing process. Four techniques are identified as particularly applicable to this process; event tree analysis (ETA), failure modes and effects analysis (FMEA), fault tree analysis (FTA) and RAM (reliability availability and maintainability) analysis. RAM analysis naturally dovetails with the cost collection during the operational phase whilst the other techniques support decision making in the design and delivery phases. Combined with life cycle costing, these techniques can form the basis of a reliability centred life cycle costing framework designed to provide a centralised decision making criteria for assessing the value of reliability.

The final component of the decision making framework is the joint presentation of reliability and cost data, most readily achieved through analogy with so called economics of quality

(EOQ) models. Chapter 6 reviews the adoption EOQ models and their modification to economics of reliability (EOR). These types of model are the subject of much discussion regarding the optimum quality and, by analogy, reliability. The EOQ discussion is centred on whether or not the optimum quality exists at zero defects, but the same discussion is not immediately transferable to the field of reliability management as quality is neither necessary nor sufficient for reliability achievement. Despite this, economics of reliability models form the basis of a powerful decision making tool for managers who are more responsive to financial metrics. However, they are of less immediate use at project level as they do not reveal the direct value of implementing the reliability toolkit. This chapter concludes that for cost-beneficial investments in reliability a decision framework is required to identify the effort required at project level that supports the objectives of the economics of reliability model.

Chapter 7 constructs a potential reliability value framework that addresses the needs identified in the previous chapters. The potential reliability value framework is constructed around a potential reliability value index, which addresses both investment cost and functional performance of the value drivers identified in a value breakdown structure. This metric provides a central decision making criterion, which is applied to a model observing two distinct parts used to assess potential reliability centred CAPEX and OPEX. The OPEX model applies the reliability value index to more conventional concepts already present in the literature while the CAPEX model is based on the ability to rectify potential failure modes that have been detected from specific sources known to cause unreliability (as identified in the industry recommended practices API RP 17N and ISO 20815).

Chapter 8 applies the component parts of the potential value framework to a collection of case studies, based on a hypothetical oil field development, to demonstrate their use and indicate its benefits over conventional life cycle costing. The cases address the decisions of concept selection, optimum investment of reliability, the specification of a reliability budget and risk based planning of reliability activities. The first two case studies compare decision making using the reliability value index and more conventional life cycle costing and economics of reliability decision making criteria, while the other cases address decisions not readily evaluated with such metrics. The planning case study, importantly, introduces the concept of the reliability efficiency frontier, which acknowledges that the ability and efficiency with which organizations detect and rectify potential failure modes influences the decision to invest in design for reliability effort. This case demonstrates that reliability capability and maturity affect value generation from design for reliability effort and concludes that the same decision to invest in design for reliability varies between organizations.

Chapter 9 discusses the implementation of the potential reliability value framework and strategies to expand the reliability efficiency frontier. The thesis proposes that the most effective strategy is the decentralised implementation of the reliability value framework guided by a central decision making criterion, namely the reliability value index. Such an approach can be adopted at both organizational and project levels. Decentralised reliability management requires that all organization and project functions are cognisant of how their specific actions influence the value of reliability. While training can raise initial awareness of how reliability performance is affected by organizational or project decisions, relevant project functions must be involved with the appropriate applications of the reliability engineer's toolkit. This chapter concludes this thesis by recommending future scope for research with specific regard to introducing the supply chain into the decision scenario through financial incentivisation.

2. Reliability and Technical Risk Management in the Subsea Industry

2.1. Introduction

System reliability is becoming an increasingly important facet of any company's competitiveness. As such, reliability and maintainability (R&M) strategies should be considered part of the corporate strategy (Madu, 2005). This is especially true in the subsea oil and gas production industry as equipment failure can result in disproportionately long downtime compared to the dry (either topsides or land-based) equivalent. Prolonged periods of unexpected downtime can a have significant impact on project value. To manage such risks, the petroleum industry has provided guidance on reliability management strategies through various standardisation bodies. ISO 20815 (Petroleum, petrochemical and natural gas industries – Production assurance and reliability management) provides guidance for the wider petroleum industry while the forthcoming API recommended practice 17N (Recommended Practice subsea production system reliability & technical risk management) provides subsea specific guidance to reliability and technical risk management (API, 2007; ISO, 2007).

The API subsea strategy revolves around a four step reliability and technical risk management cycle as shown in Figure 2-1. Activities within these stages are implemented through a number of key processes understood to be essential in the competent management of reliability throughout a project life cycle. This chapter explains the fundamental aspects of the recommended practice and demonstrates how its underlying management processes support the corporate objectives of subsea operators. Section 2.2 details the primary activities associated with the management cycle and identifies the key processes that support the technical risk management strategy. Section 2.3 demonstrates how these key processes are implicitly linked to the corporate objectives of operator organizations and section 2.4 summarises and concludes the chapter.

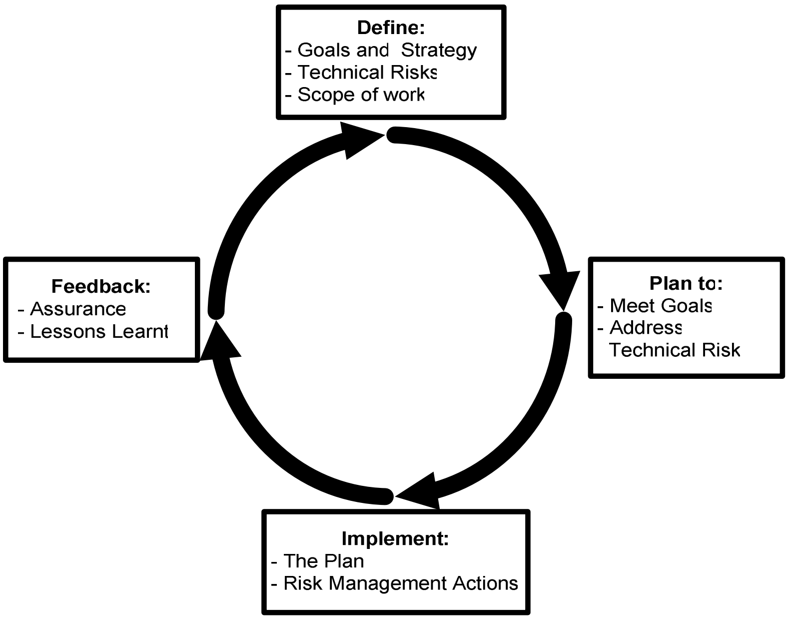

Figure 2-1: API RP 17N Reliability and technical risk management cycle (API RP 17N, 2007).

2.2. *Overview of the Strategy*

The forthcoming American Petroleum Institute Recommended Practice “subsea production system reliability & technical risk management” provides guidance on how subsea operator organizations manage risks to reliability achievement during field development projects. It is a subsea specific implementation of ISO 20815. The international standard mandates the implementation of a management tool to align design for reliability decisions to corporate objectives. The management tool is recommended to include the following (ISO 20815, 2007):

- systematic planning of production-assurance work within the scope of the programme;
- definition of optimization criteria;
- definition of performance objectives and requirements, if any;
- description of the production-assurance activities necessary to fulfil the objectives, how they are carried out, by whom and when;
- statements and considerations on interfaces of production assurance and reliability with other activities;
- methods for verification and validation; and
- a level of detail that facilitates easy updating and overall coordination.

API RP 17N (2007) interprets these recommendations within the management framework indicated in Figure 2-1. The management framework is guided by a four step feedback cycle of *Define*, *Plan*, *Implement*, and *Feedback*. The following details the purpose of each of these steps.

2.2.1. Define, Plan Implement and Feedback

The first step, *Define*, specifies the objectives of the project, identifies the risk to achieving the objectives and defines a scope of work to manage the risks identified. The objectives of a project are specified as either goals or requirements, which are differentiated by the level of evidence required to demonstrate conformance. A requirement is an essential product characteristic for which evidence of conformance is also necessary whereas goals are desirable characteristics for which evidence of conformance is either unobtainable or is not necessary (BS 5760-4, 2003). API RP 17N (2007) assesses risks to achieving these objectives through identifying change by using a process of technical risk categorisation. These changes are identified as deviations from previous projects based on five factors; reliability, technology, architecture, environment and organization.

The reliability factor considers if historical reliability is sufficient to meet the project goals and requirements. The remaining factors can be considered as sources of risk to reliability achievement. The technology factor aims to identify where changes to the basic equipment have occurred or if new technology is required. Architecture addresses changes to system design and complexity. Environment identifies changes to the internal and external operating conditions. Organization considers changes to the project and organizational complexity and ability. Each factor is allocated a technical risk category based on a four point scale as indicated in Table 2-1. This ranking allows project engineers to prioritise the risks to reliability achievement.

Identifying a scope of work is the bridge between the *Define* and *Planning* stages. The scope of work defines the actions required to manage the changes/risks identified and achieve the project's objectives. To facilitate the application of technical risk management, the recommended practice defines a standard response to the changes observed during technical risk categorisation. Table 2-2 indicates that, for example, risk and reliability analysis is not necessary for low risk repeat projects as, by definition, it has been completed before.

Table 2-1: Technical risk category summary (modified from API RP 17N, 2007).

	Reliability	Technology	Architecture / Configuration	Environment	Organization
A (Very high)	**Reliability improvements (technology change)**: Significant improvements requiring change to technology.	**Novel technology or new design concepts**: Novel design or technology to be qualified during project.	**Novel application**: Architecture, layout or configuration has not been previously applied by supplier.	**New environment**: Pushing environmental boundaries such as, pressure or temp. Or a new geographic location.	**Whole new team**: New project team, working with new suppliers in a new location.
B (High)	**Reliability improvements (design change)**: Significant improvement requiring change to design but not technology.	**Major modifications**: Known technology with major changes to manufacturing process, materials, or upgrades. Non mature for extended operating environments	**Orientation and capacity changes**: Significant changes such as layout, size and orientation. Large scale, High complexity	**Significant environmental changes**: Extended and / or aggressive operating environment.	**Significant team changes**: New supplier or contractor; Changes in key personnel from previous project
C (Medium)	**Minor Reliability improvements**: Reliability Improvements requiring improved QA/QC.	**Minor modifications**: Same supplier providing a copy of previous equipment with minor modifications such as dimensions, tolerances or design life.	**Interface changes:** Interface changes, either with different equipment or control system. Small scale, low complexity.	**Similar environmental conditions:** Same as a previous project or no major environmental risks have been identified	**Minor team changes:** Minor changes in project team or supply chain
D (Low)	**Unchanged reliability:** Existing reliability and QA/QC is acceptable	**Field proven technology:** Same equipment of identical specification, manufactured at same location.	**Unchanged:** Identical to previous spec. No orientation, layout or interfaces modification	**Same environmental conditions:** Same as recent project	**Same team as previous:** Unchanged project team and supply chain.

As the technical risk categorisation process is based on uncertainty or changes rather than risk (defined as the product of consequence and probability of occurrence), the standard response defined may be superfluous or insufficient. In recognition of this fact the guidance indicates that all activities should add value to the project and be consistent with the project goals and strategy (API RP 17N, 2007). However, there is no guidance to support this decision making process aside specify that the technical risk management framework should be applied in conjunction with life cycle costing. The absence of more detailed guidance is due to the fact that standardisation bodies cannot presume the risk preference of organizations.

Table 2-2: Overview of the required activities based on technical risk and life cycle phase (API RP 17N, 2007).

Assurance Processes for Asset Development				**Life Cycle Phase**						
				Pre contract award		**Post contract award**				
Low Risk Projects	**Medium Risk Projects**	**High Risk Projects**	**Main Processes**	Feasibility	Concept Selection	FEED	Detailed Design & Manufacture	SIT Testing	Installation and Commissioning	Operation
	X	X	Definition of Availability Goals & Requirements	X	X	X	X			
X	X	X	Organizing and Planning for Availability	X	X	X	X	X	X	X
X	X	X	Design and Manufacture for Availability		X	X	X	X		
X	X	X	Reliability Assurance	X	X	X	X	X	X	X
	X	X	Risk and Reliability Analysis	X	X	X	X			
X	X	X	Verification and Validation	X	X	X	X	X	X	X
X	X	X	Project Risk Management	X	X	X	X	X	X	X
		X	Qualification and Testing		X	X	X	X		
X	X	X	Performance Data Tracking and Analysis					X	X	X
	X	X	Supply Chain Management			X	X	X	X	
X	X	X	Management of Change		X	X	X	X	X	X
X	X	X	Organizational learning	X	X	X	X	X	X	X

The *Plan* step attempts to translate the scope of work into an ordered set of deliverables, activities and or tasks designed to assess the risks identified during the assessment of technical risk. A plan should include sufficient detail such that the objectives of the scope of work can be satisfactorily achieved according to time and budgetary constraints, this detail can include (BS 6079-1, 2002):

1. task reference code;
2. summary description of the requirement;
3. name of the person accountable for completion of the task;
4. list of key deliverables;
5. timescales for the deliverables;
6. schedule of task dependencies and subsidiary tasks;
7. schedule of costs;
8. an assessment of risks associated with the task;
9. performance measurement and task completion criteria;
10. description of the work content of the task;
11. reporting requirements; and
12. name of task owners.

The *Implement* step is the actual doing stage, where the objectives of the scope of work are conducted according to the plan. Implementation of the activities should include validation and verification to ensure that the correct techniques have been applied (validation) and that they have been applied correctly (verification). During the implementation step, it is possible that either new risks are identified or it is recognised that known risks have been underestimated. In these cases, a secondary *Define, Plan, Implement* and *Feedback* may be applied during *Implement*, drawing analogy from Deming's PDCA cycle (Deming, 2000).

The final step, *Feedback*, closes out the reliability and technical risk management cycle for a given project phase. There are two component to the *Feedback* stage; assurance and lessons learnt. Reliability assurance is presented in the form of a reliability assurance document to decision makers. This document provides a critical examination of the information collected (during the *Implement* step) and indicates if the goals and requirements, set out in the *Define* step, have been or can be achieved. It is important, therefore, that the project decision makers understand how potential risks can affect system reliability achievement. Lessons learnt are the good and bad practices experienced during the project. These experiences are recorded for the future benefit of the organization by allowing project managers to better understand where risks to reliability achievement are introduced and improve the application of the technical risk management strategy.

2.2.2. Key technical risk management processes

The reliability and technical risk management cycle is applied through twelve key processes. These key processes are understood to be essential for the competent management of reliability achievement and where originally identified to assess organizational capability in design safety management (Sharp *et al.* 2002; Strutt *et al.* 2006). The key processes as defined by API RP 17N (2007) are:

1. Definition of Availability Goals & Requirements;
2. Organizing and Planning for Availability;
3. Design and Manufacture for Availability;
4. Reliability Assurance;
5. Risk and Reliability Analysis;
6. Verification and Validation;
7. Project Risk Management;
8. Qualification and Testing;
9. Performance Data Tracking and Analysis;
10. Supply Chain Management;

11. Management of Change;
12. Organizational learning.

These key processes are broadly grouped into core processes and supporting processes. The first four key processes embody the *Define, Plan Implement, Feedback* management cycle, while Risk and Reliability Analysis provides specialist support to many of the first four key processes. The remaining processes may be considered good management practice, which input to or receive output from the core key processes. Each key process is discussed further in the following section.

2.3. Relating Key Processes to Corporate Objectives

The key processes, listed above, were derived from those originally defined to assess organizational capability in design safety management (Sharp *et al*. 2002; Strutt *et al*. 2006). This section explores if, by analogy, the same key processes are necessary and sufficient for reliability achievement in subsea developments by discussing the implicit link between corporate objectives and key processes.

Observing a process similar to that of quality function deployment, a phased approach of relating key processes to corporate objectives is adopted. The first phase of the assessment is used to identify project requirements that can support the corporate objectives. As it is not proposed that technical risk and reliability management immediately satisfies all corporate requirements, some are excluded before considering how the strategy and its key processes link to the remaining project requirements.

2.3.1. Corporate objectives

The corporate objectives are taken to be the voice of the customer. Corporate objective have been compiled from numerous oil and gas operators' literature, identifying their basic business principles, values and corporate social responsibilities. Freely available information from the following corporations was reviewed to establish the oil and gas industry's core business principles and values[1]:

- BP (BP, 2007a);
- Chevron (Chevron, 2006);
- ConocoPhillips (ConocoPhillips, 2007);
- ExxonMobil (ExxonMobil, 2004);
- Anadarko (Anadarko, 2007);
- Royal Dutch Shell (Shell, 2005); and
- Total (Total, 2005).

Corporate objectives can be broadly categorised according to the following stakeholder focal points and are summarised in Table 2-3;

- **Shareholders**. The overriding objective is to provide competitive long term returns on investment and create value.
- **Employees**. Maximise the opportunity for success of their employees by providing training, respecting human risks and maintaining personnel health and safety.
- **Customers**. Gaining and retaining a market share through continually providing quality products at competitive prices to changing customer needs and preferences. One way to retain market share is to provide a reliable service. Although this may be

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[1] Corporate objects were also based on two pieces of Atkins Boreas work intentionally not cited here.

considered a solution to the gain/retain market share objective it is included here to provide an emphasis on reliability.

- **Environment**. Maintaining environmentally responsible operations.
- **Local communities**. Respect the local environment, laws, rules, regulations and cultures. Contributing to the economical and social development, through ethical business practices, of the local community is continually emphasised.
- **Business partners**. Generating long term and mutually beneficial relationships.

Table 2-3: Voice of the stakeholder.

Stakeholder focus	Voice of the stakeholder
Shareholder	Maximise shareholder value
Employee	Maintain personnel Health and Safety Maximise employee success opportunity
Customer	Gain/Retain Market Share Gain reputation amongst customers for reliable service
Environment	Maintain environmentally responsible operations
Community	Respect local laws/cultures Contribute to economic/social development
Business partners	Generate mutually beneficial business relationships

2.3.2. Relating Project Requirements to Corporate Objectives

The project requirements are attributes defined to satisfy the voice of the stakeholder. For each of the corporate objectives, at least one project attribute was defined to satisfy each voice of the stakeholder. Project attributes are defined to provide a solution neutral method of aligning the project objectives to the voice of the stakeholder. The relationships between corporate objectives and project attributes are discussed below.

Maximise shareholder value

Shareholder value can be defined as the financial returns afforded to the shareholder by the organization. These returns are generated either from dividend payouts or enhanced market share prices. Dividends afforded to the shareholder are determined from the net operating profit after tax and an estimation of the share prices can be determined from the ratio of the total business value of the company to the number of ordinary shares. As with dividend payout, the total business value is a function of net operating profit after tax. In order to provide dividends and increase share prices, the organization must optimise the profit margin. Share price is not entirely financial in its appraisal as although it is unlikely to fall below the ratio indicated above, the share price may be bolstered by operational practices, many of which are addressed below.

Maintain personnel Health and Safety

Offshore installations are hazardous environments and there have been a number of high profile incidents that have claimed many lives, which are severely damaging to an organization's reputation. In maintaining personnel health and safety the foremost requirement is to minimise health/safety risk exposure through the application of the relevant safety standards and legislation.

Maximise employee success opportunity

The management field of HR focuses on this specific corporate objective and is not the primary focus of this research. Maximising the success opportunity, in terms of career enhancement can be achieved through providing training and coaching.

Gain/Retain market share

As with maximising shareholder value, acquiring and retaining market share is not achieved by purely financial means. Here, gaining and retaining market share is considered in terms of perceived product value. It is important, therefore, to reliably provide quality products at low cost.

Reputation for reliable service

Gaining a reputation for a reliable service first requires that the company does have a reliable service (through maintaining high system availability), which can then be demonstrated. It also requires that the service is initially available on time.

Maintain environmentally responsible operations

A suitable project requirement for this corporate objective can be simply stated as reduce hydrocarbon release, both in terms of the frequency and volume of hydrocarbons released. Growing awareness of an organizations carbon footprint should also be considered.

Respect local laws/cultures

Oil exploitation is a global industry; operators are exposed it countless local laws and regulations. The field of corporate/local law is too broad for consideration and is therefore out of the scope of this study. For completeness, it is assumed that adhering to local standards, at least, satisfies respecting local laws.

Contribute to economic/social development

Recruitment of local labour/expertise or purchase of locally produced hardware can benefit the local economy. However, the interaction of company practice and macroeconomics is considered beyond the scope to this study.

Generate mutually beneficial business relationships

There may be two primary ‘business partners’ to consider in a field development project; the supply chain (service and hardware) and the joint-investors of project (field development projects are usually joint ventures). Operators therefore attempt to optimise their supply chain and should attempt to gain a reputation among other operators of being able to deliver, cost-effectively, high system availability.

Project requirements in response to the corporate objectives are summarised in Table 2-4. These requirements immediately satisfy the corporate objective from which they were defined. However, they also influence other corporate objectives; for example, shareholder value is affected by a company’s entire business practice, not just the ability to optimise its profit margin. A more detailed assessment, such as that achieved through the use of QFD, would demonstrate the strength of the solutions (in this case the project requirements) to the needs (corporate requirement) but is considered superfluous to this discussion providing the project objectives are defined.

Table 2-4: Project requirements based on defined to satisfy corporate objectives.

Corporate Objectives	Project Requirements
Maximise shareholder value	Optimise profit margin
Maintain personnel Health and Safety	Adhere to relevant safety standards
Maximise employee success opportunity	Provide training and coaching opportunities
Gain/Retain Market Share	Provide a cost effective goods/services
Gain reputation amongst customers for reliable service	High system availability Demonstrate repeatable reliability
Maintain environmentally responsible operations	Minimise carbon foot print Minimise spills
Respect local laws/cultures	Adhere to local standards
Contribute to economic/social development	Provide employment opportunities
Generate mutually beneficial business relationships	Optimise the supply chain Get project right first time, on time

The research objective addresses the need to understand the required reliability to meet corporate financial objectives and the effort necessary to achieve them. ISO 20815 (2007) and API RP 17N (2007) also state that design for reliability effort should only be invested if it adds value. To maintain this focus only the project requirements identified in Table 2-4 that are directly related to financial parameters and reliability achievement are considered in the second phase of the assessment, these are:

- Optimise profit margin;
- Provide a cost effective goods/services;
- High system availability;
- Demonstrate repeatable reliability;

- Optimise the supply chain; and
- Get project right first time, on time.

2.3.3. Relating Key Processes to Project Requirements

This section discusses how the key processes defined by API RP 17N (2007) and ISO 20815 (2007) help achieve the requirements generated in the previous section. The project requirements considered here are either financial in nature or relate to system reliability or availability performance. It seems unnecessary to discuss how the key processes relate to reliability or availability achievement as the primary purpose of the strategy, and its constituent activities, is to deliver system reliability. There is also a key process directly related to supply chain management. The remaining project requirements relate to the financial success of the project and the relation to the key processes is not as explicit. These are discussed further.

KP1: Definition of Availability Goals & Requirements

Defining goals and requirements initiates the application of technical risk management. It is the process of identifying needs and specifying acceptance criteria. Goals and requirements are differentiated by their acceptance criteria. Requirements are essential characteristics of a system to which the supplier has to provide evidence of conformance. A goal, however, is a desired feature, which the supplier either cannot or need not provide assurance (BS 5760-4, 2003).

Goals and requirements support the optimisation processes whereby operational performance is considered against an economic decision metric (ISO 20815, 2007). This allows decision makers to define the system availability required to meet the (economic) feasibility requirements. Defining an optimal availability requires that overemphasis on CAPEX (or maximum exposure) be avoided (ISO 20815, 2007) and as such requires that a life cycle costing activity be incorporated. API RP 17N (2007) phrases this as reliability value analysis, which directly incorporates reliability performance with life cycle costing (ISO 20815 employs life cycle costing as a separate activity within its optimisation process). The activity acknowledges that there is a trade-off between CAPEX and OPEX which is influenced by service life reliability and the cost necessary to achieve it. This enables project managers to align the reliability strategy with the financial objective of the project and the organization. Applying techniques, such as life cycle costing does have the potential to incorporate the value added from design for reliability effort, but there is no specific guidance on how this might be achieved and the petroleum industry's standard for life cycle costing does not explicitly address reliability analyses as cost elements. The application of reliability centred life cycle costing is addressed in detail in Chapter 4.

KP2: Organizing and Planning for Availability

Planning for availability schedules the technical risk management activities (identified during the *Define* stage) and allocates resource and expertise to each. Organizing for availability is the process of establishing the roles and responsibilities within the (subsea) project delivery team and defining the relationship between specialist reliability expertise and the rest of the project organization. Organizing for reliability is addressed further in Chapter 3.

It is necessary to define the level of effort based on the financial returns required from the project whilst considering the level of inherent risk within the project; over emphasis on reliability could cause delays to project schedules and drive project costs up (especially if these requirements are handed down to hardware suppliers, who would otherwise not implement such activities). Underestimating the design for reliability effort required can equally inflate operational costs due to failure in operation. ISO 20815 (2007) and API RP 17N (2007) use technical risk categorisation as a rule of thumb for applying the key processes, as defined in Table 2-2. However the specific activities are not addressed. The belief that reliability and technical risk management should be tailored to the specific risks is echoed in other reliability management strategies. Military Standard 785 (Department of Defense, 1988) states:

"Effective reliability programs must be tailored to fit the program needs and constraints, including life cycle *costs. This document [Mil Std 785B] is intentionally structured to discourage blanket application."*

Burns (1994) points out that there are no general rules to follow to deliver cost effective reliability and that each product should have a program that is appropriate to the technical risks associated with the product being developed. This appears to contradict the sentiments of ISO 20815 (2007) and API RP 17N (2007) somewhat (i.e. Table 2-2) although it is noted that depending on the risk (i.e. the combined effect of change or uncertainty as defined by the technical risk categorisation and consequences of failure) the key processes may or may not be value added. When considering *product* development the required reliability and technical risk management program may be specific to the product and its intended use. However, for *system design*, and specifically subsea production system design, many of the component parts are common between projects and cost of failure is usually significant (i.e. intervention vessel charges and lost or deferred production). Irrespective of this there could (and should) be a generic risk (or value) based framework to identify the design for reliability activities, which ISO 20815 (2007) and API RP 17N (2007) begins to address with their guidance and the application of life cycle costing. The traditional metric used during life cycle costing are not explicitly those defined to satisfy the corporate financial requirements although it is noted that these requirements are solution neutral; life cycle costing metrics could be adapted to suite the specific needs of a company. The international standard IEC 60300-3-3 (2004) does identify design engineering, including reliability, maintainability and environmental protection activities as typical cost generating activities but does not discuss these in terms of planning design for reliability effort. More importantly however, the petroleum industry's life cycle costing standards (ISO 15663-1, 2000; ISO 15663-2, 2001; ISO 15663-3,2001), while identifying that life cycle costing can be use for "*the alignment of engineering decisions with corporate and business objectives*" (ISO 15663-1, 2000) does not include reliability analyses as a cost element. That is, the industry does not employ life cycle costing as a planning tool for design for reliability and there is no evidence in the literature where life cycle costing justifies the use of reliability analyses. Chapter 4 explores the application of life cycle costing in greater detail.

KP3: Design and Manufacture for Availability

Design and manufacture for availability represents the link between design reliability and quality in manufacture. Design for reliability is the process of methodically identifying and removing system weaknesses until the required reliability is an inherent feature of the design. Manufacture for reliability is the application of concepts statistical process control and stress screening in order to ensure that the design reliability is achieved in operations.

There is a close relationship between the project requirements and the design and manufacture for availability key process. The engineering decisions that are made as part of design for reliability have the potential to achieve the performance objectives (both in terms of reliability performance and financial performance). Project design engineers are tasked with specifying the inherent characteristics of the system such that the project goals and requirements are achieved. Manufacture for reliability, then, is the process of ensuring that the inherent characteristics designed into the system are delivered in the final product, ensuring that the design reliability is not compromised through the introduction of latent faults.

KP4: Reliability Assurance

Reliability assurance is the process of demonstrating the extent to which the (goals and) requirements have been or can be achieved. The process, applied throughout the project, demonstrates that the risks identified have been adequately managed. This information is presented to project decision makers in the form of a reliability assurance document to assist in stage gate decisions. The reliability assurance document is created to generate confidence that the risks to reliability achievement have been identified and adequately managed such that the project objectives can be achieved.

KP5: Risk and Reliability Analysis

Risk and reliability analysis is the application of the reliability toolkit. These are the (systems) reliability analysis techniques used to assess the inherent reliability characteristics. This process is address in more detail in Chapter 5. Risk and reliability analyses tend to be considered as cost generating activities (IEC 60300-3-3, 2004) and may not therefore be considered in terms of achieving a project's financial requirements. Despite its label as a 'cost generating activity', the application of reliability analyses can be used to support the design for reliability decisions, setting the reliability goals and requirements and demonstrating that a design can achieve the project requirements. However, in the subsea oil and gas industry, the application of reliability analyses tends to focus on conformance to specification and is often applied too late in the design process to have any significant influence.

KP6: Verification and Validation

Verification and validation addresses the application of all the tools, techniques and processes implemented as part of the technical risk management strategy. Validation addresses if a tool, technique or process is the correct one for the intended result. Verification addresses if the tool, technique or process has been applied correctly. Verification and validation is an important aspect of reliability assurance and as such has similar links to the project objectives as the reliability assurance key process.

KP7: Project Risk Management

Project risk management ties in the technical risk management framework into the management of the field development project. It is an extension of both the reliability management plan and the qualification plan to consider how they might introduce potential budget or schedule risks and how they are managed. Likewise, it also considers how the project schedule and budget could introduce risks to reliability achievement. Project risk management practices, such as earned value analysis assess both time and budget performance against the scheduled consumption of resources, although it does not consider financial performance in operation.

KP8: Qualification and Testing

Qualification and testing is the process of advancing the maturity of technology. There are a number of assessment criteria for equipment qualification in the oil and gas industry; ISO 20815 (2007) uses the approach proposed by DNV RP A203 (DNV, 2001), which considers the level of operating experience in a known or new application area. API RP 17N (2007) adopts a technology readiness level approach, similar to that used by NASA (Shishko *et al.* 2004). Qualifying the reliability of new technology can incur significant cost and as such is not normally performed in the project environment. However, the results of such an activity can be a source of significant confidence with regard to reliability achievement in the intended use conditions.

KP9: Performance Data Tracking and Analysis

Data management considers the acquisition of reliability data. Its primary focus is collecting data in the field, which can be used to confirm reliability achievement in operations and support reliability analysis and decision making in future projects. The acquisition of valid data is vital to the design for reliability decision making process. The application of reliability analyses with poor quality or invalid data can undermine the confidence of reliability assurance and the decisions made during design for reliability.

KP10: Supply Chain Management

Supply chain management addresses the communication of the goals and requirements to potential suppliers and considers the ability of the supply chain to meet these requirements. The latter is achieved through the assessment of reliability capability maturity, which measures an organization's ability to influence and control reliability (Williams *et al.* 2003). In order for a project to achieve its objectives, it is important the supply chain is fully aligned to these requirements. The inherent reliability designed into a system can be undermined if the supply chain is not aware of, willing to meet or able to meet the reliability requirements. In many cases the effectiveness with which manufacture for reliability is implemented is dependent on the ability of certain organizations within the supply chain.

KP11: Management of Change

Management of change is introduced as a key process to ensure that changes introduced during the project do not adversely affect reliability achievement. The primary tool for management of change used in technical risk management is technical risk categorisation, which is used to identify differences between the current project and previous experience. Changes that are unknowingly introduced can have a significant impact on the project's ability to meet its objectives, especially if these changes are introduce with the intent to meet other objectives that may conflict with those of the project. This is especially true for changes that occur in the supply chain, which might not be visible to the operator and potentially lead to costly common cause failures.

KP12: Organizational Learning

The final key process is organizational learning. This is the process of continual improvement in terms of reliability performance but also in terms of the effectiveness with which the technical risk management strategy is applied. The main tool for achieving this is lessons learnt, which serves as an input to all other key processes. Organizational learning observes two main activities; lessons capture and lessons learnt review. The former is used to identify experiences (e.g. best practice, failures or near misses) on the current project that are considered noteworthy enough to be recorded for the benefit of future projects. As such this activity does not immediately satisfy the project objectives but does support the long term achievement of the corporate objectives. The second activity associated with organizational learning, does however, relate to the ways in which the project objectives might be achieved based on previous experience.

2.4. Chapter Summary

This chapter has provided an overview of the key aspects of the new wave of reliability and technical risk management standards and recommended practises that have been developed for the oil and gas industry and specifically the subsea industry (as is the case with API RP 17N). The strategy takes the key processes that originate from design safety management and structures them within a *Define*, *Plan*, *Implement* and *Feedback* cycle similar to that of a Deming (2000) PDCA (plan do check act) cycle observed in quality management.

The strategy is governed by the principle that design for reliability effort should be commensurate with the level of risk inherent within the project and that this effort should add to the overall project value. This sentiment is mirrored in standards that pre-date these newer publications but there appears to have been little progression in developing decision making criteria to support this objective. Concepts such as life cycle costing (LCC) have been proposed to facilitate such decision making. While the application of LCC has been used to support the decision as to what the optimum system reliability might be, there is no evidence that LCC has been used to plan the activities required to achieve the optimum reliability. This is especially the case when applying the reliability engineers toolkit (systems reliability analyses), which is normally considered a cost accumulating element of a life cycle costing model despite the reliance of the reliability and technical risk management strategy on the respective key process. In order for decision makers to understand the value of investing in such analyses it is necessary to define decision making criteria that enables them to identify when reliability analyses are value added. Chapter 4 provides a more detailed review of life cycle costing; before that however, issues relating to the implementation of reliability and technical risk management are explored to consider some of the more organizational needs of a decision making framework.

3. Reliability and Technical Risk Management Strategy Implementation

3.1. *Introduction*

Chapter 2 provided an overview of the reliability and technical risk management strategies being introduced across the oil and gas industry. The approach requires a value based approach to planning for reliability achievement that attempts to front load the design for reliability effort. The implementation of such a strategy requires a fundamental change to the way in which operators (and their supply chain) implement systems reliability analyses and design for reliability. Such a change invariably encounters resistance embodied as barriers to implementation. This chapter identifies these barriers and explores how a value based planning framework might be applied to accommodate some of these barriers.

3.2. *Barriers to implementation*

Identifying barriers to implementing a reliability strategy or culture has been the subject of some discussion in the literature (Roberts *et al.*, 2001; Brall, 2001; Busby and Strutt, 2001; Strutt *et al.*, 2007). Five barriers to the implementation of a reliability strategy have been identified:

1. Industrial perception of the reliability disciple;
2. Business focus on CAPEX;
3. Lack of knowledge of failure causation;
4. Power of the reliability tools; and

5. Organizational structure.

3.2.1. Industrial perception of the reliability discipline

Perhaps the greatest barrier to the implementation of a reliability strategy lies with the basic understanding of what reliability is. Many organizations believe that reliability is achieved through quality management (Roberts *et al.*, 2001) or that reliability and quality are synonymous (Levin and Kalal, 2003). There is however, an awkward relationship between quality and reliability as quality is not necessary for the achievement of target reliability and that reliability can mask poor quality (this is considered in greater detail in Chapter 6). However, there is synergy between the two practices and quality can support reliability improvement if targeted correctly.

By defining quality as conformance to specification (Crosby, 1979), quality can only help in the achievement of reliability only if it has been correctly specified. However, there is a perception that the function of reliability engineering is through measurement and analysis of reliability rather than achievement of improved reliability (Roberts *et al.*, 2001). The improvement of reliability is driven by the identification of goals and or requirements; if these reliability goals and requirement have not been specified correctly then the application of a quality management system only serves to guarantee poor reliability.

3.2.2. Business focus on CAPEX

The business model for the economic development of deepwater subsea installations tends to focus on CAPEX minimisation. The shorter the field life the more important a low CAPEX becomes (Chitwood *et al*. 2004) and deferment of CAPEX to incur a reasonable OPEX increase in the future should result in improved field economics (Hanraham and Chitwood, 2005). The underlying concept of (reliability centred) life cycle costing is in conflict with this basic goal of CAPEX minimisation; life cycle costing advocates an increase in CAPEX to observe a life cycle cost benefit. In addition, reliability investments are inherently risk based; decision makers are averse to a certain CAPEX increase against uncertain future income and OPEX reduction.

The CAPEX minimisation focus is supplemented with a desire to minimise the time to first oil; installations often stagger when production wells come on line in order to minimise the time taken to start generating revenue. However, there is a perception that the activities and analyses recommended in a reliability strategy increase the lead time of projects (Roberts *et al.* 2001). Furthermore, failures in operation are not viewed with the same priority than failures in the development stages as failure in operation do not obstruct the design process (Busby and Strutt, 2001).

3.2.3. Lack of knowledge of failure causation

Identifying the root cause of failure can only be achieved through the logical decomposition of information pertaining to a failure event. This requires transparent presentation of all failure related data throughout the supply chain. Root cause analysis, if performed incorrectly (or incompletely) can lead to the development of a blame culture (i.e. finger pointing at the first accountable person rather than understanding the organizational reasons for failure). Fear of such a blame culture and of damaged reputations has stifled the feedback of information through the supply chain (Roberts *et al.*, 2001) resulting in poor understanding of why failures occur and hence how to improve the reliability.

3.2.4. Power of support tools

Support tools can be considered on two levels; analysis tools such as those used to predict reliability and decision support tools which usually combine multiple criteria to optimise the trade-off between them.

Reliability prediction and analysis is both data intensive and potentially sensitive to model assumptions (in balancing the accuracy of the model and speed required to generate results). The data can take a long time to collect (Sandtorv *et al.*, 1996) and is mostly historical. Predictions based on historical performance might not be representative of the expected environmental conditions (for example, predictions of subsea performance in deepwater Gulf of Mexico should not be based on reliability performance of equipment installed in The North Sea) or indeed reflect any changes in reliability performance that might have occurred through the supply chain. Concerns over the quality of data have lead to a lack of trust in the analysis (i.e. garbage in, garbage out and or garbage in, gospel out), which is compounded by a belief that the recommendations from reliability analysis are often disjointed from what can be practically implemented.

Decision support that combines both reliability performance and economic appraisal is most readily achieved through the application of so call economics of 'X' models (see Chapter 6 for a more detailed review). These models, usually presented in graphical form, show the life cycle cost as a function of system characteristic, such as reliability or quality with the intent to identify the reliability (or quality) that minimises life cycle cost. Cost of quality models provide a means to gain the commitment from top management to initiate improvement strategies as managers are more responsive to financial metrics rather than defect rates (Hwang and Aspinwall, 1996) but are of less value at the project level. Plunkett and Dale (1988a) suggest that the economics of quality models were inaccurate despite a wealth of information. It follows then, that an economics of reliability model is not best suited to drive implementation at the project level and throughout the supply chain.

3.2.5. Organizational structure

The whole life cycle of a subsea field development project involves a number of organizations (operators, suppliers and contractors) over a range of disciplines or divisions (for example, project management, engineering design, financial management, quality control and assurance, reliability management, environmental and safety management). Barriers to the implementation of a reliability strategy, between the different organizations and disciplines are potentially vast. These barriers can result from conflicts of interest and poor relations between divisions (Rubenstein, 2001) and organizations. Rubenstein discussed these problems in terms of a single organization, but these issues are analogous to the makeup of a project organization observing interaction between operators, suppliers and contractors.

In an industry where supply is struggling to meet demand (Pridden, 2007) there is little incentive for suppliers to improve subsea hardware reliability and lower reliability equals more spares or replacement parts. Coupled with the operator's preoccupation with CAPEX minimisation there appears to be an accepted sub-optimum (assuming that without a reliability strategy the optimum reliability cost has not been achieved) which is in conflict with the LCC concept and potentially the wider corporate objectives of the supplier and or operator.

This acceptable sub-optimum is partly related to the poor relationship between the economics division and design management. Rubenstein (2001) suggests that the interaction between technology planning and financial planning is as follows; "*tell me what you want to do and we'll tell you when the time comes if we can afford it and it fits into our cash flow and investment planning*". Without a joined-up and forward thinking approach to design for reliability and project economics, the drive for continual improvement is surely stifled.

Figure 3-1 (Brall, 2001) indicates a typical hardware supplier organization that manages reliability through the employment of reliability specialists. Any and all reliability tasks are implemented through a reliability division. This organizational structure can be quite resource intensive and as such may not be sustainable by smaller companies (Brall, 2001). As reliability is sometimes considered a specialist field, the reliability expertise may also be outsourced to a separate organization. Whilst this can reduce cost, the problems associated with a central reliability management function might be magnified.

The barriers to implementation highlighted above (excluding the business focus on CAPEX) can be related to the organizational structure depicted in Figure 3-1. Here, the reliability function is subordinate to quality and not engineering. By adopting such a structure, the organization assumes reliability achievement is the responsibility of quality management, suggesting that reliability is a product of quality and does not necessarily allow fluent interaction with the product engineering and research and development. This could lead to the enhanced scepticism of reliability analyses. Such an organizational structure removes the responsibility of reliability achievement from the engineers and product developers. Reliability should be specified as a primary requirement of a function, especially when the equipment is located in remote conditions (e.g. deepwater subsea) where the cost of failure is significant. When reliability is not at the forefront of engineering decisions any data fed back to the reliability function may not reach the research and development group thus stifling the ability of an organization to improve the reliability of its equipment. Clearly many of these potential issues could be mitigated through investing in a larger reliability function with interaction across the remaining functions, but such an investment would prove costly (Brall *et al.*, 2007).

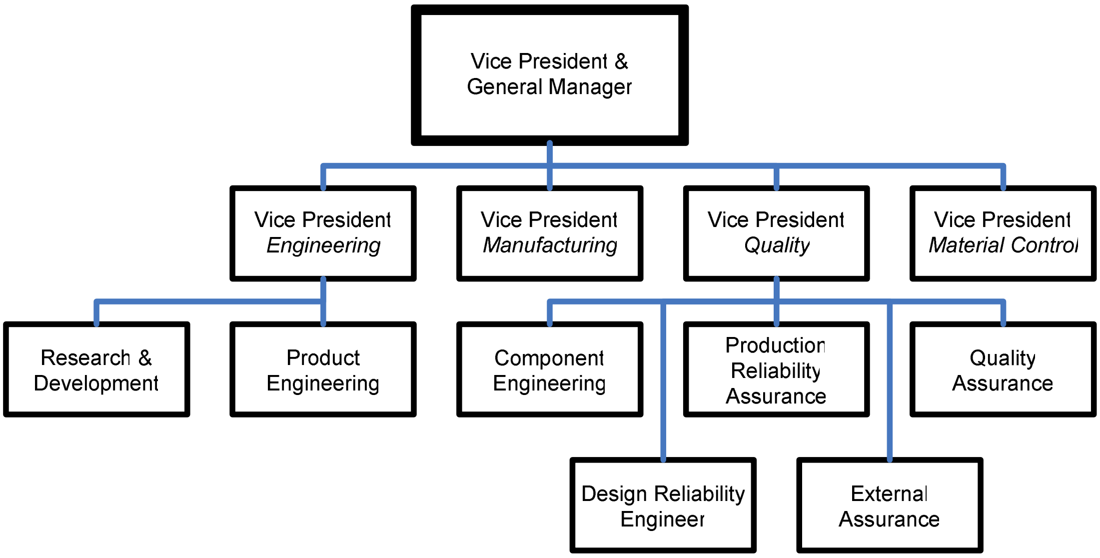

Figure 3-1: Traditional organizational structure for the implementation of a reliability strategy (Brall, 2001).

In contrast to the centralised approach to reliability management, Figure 3-2 (Brall, 2004) presents an integrated organizational structure for the implementation of a reliability strategy whereby the commitment to reliability is apparent throughout the organization and ownership of the reliability activity does not belong to a singular reliability division. Clearly, a separate reliability function still exists in this structure, presumably to support the other groups in the implementation of activities and to perform specific activities. However, by incorporating the reliability strategy into more (all) business functions (through basic training, for example) the resource requirement for reliability specialists within the company is reduced. While this has immediate appeal to smaller organizations that cannot afford the resources required to sustain a reliability division (such as that in Figure 3-1), there are clear benefits to larger organizations as well. Many of the barriers discussed can be related back to organizations adopting a central reliability function.

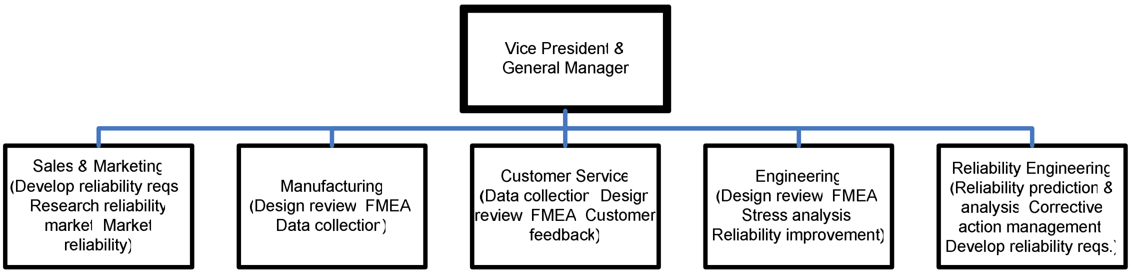

Figure 3-2: Non-traditional organizational structure for the implementation of a reliability strategy (Brall, 2004).

The activities described in Figure 3-2 reveal application of the risk and reliability analysis key process by the main functions of a firm. It should be noted that this organizational structure is not representative of an operator, but does indicate how an organization could apply the risk and reliability analysis key process. While reliability engineering still retains a separate (specialist) function it is no longer subordinate to quality management. The fact that quality has been removed should not be interpreted as unimportance of the function. Rather, this reliability centric organization presented appears to exclude the quality function deliberately to highlight the different treatment of reliability management.

Other key differences are that the definition of reliability requirements forms part of the sales and marketing division which recognises reliability as a source of competitive advantage. In addition data collection is shared across multiple functions potentially allowing for wider collection of data. With a wider source of data comes better understanding of the causes of failure and greater ability to improve the reliability, a responsibility that is shared across both the engineering and reliability engineering functions.

3.3. Chapter Summary

This chapter has addressed some of the barriers that might prevent an organization from implementing a reliability management strategy or establish a reliability culture. Most of these barriers can be attributed to an organizational structure observing a centralised reliability function. The literature has provided a model organizational structure for a supplier where responsibility for applying the reliability management key processes is shared across different functions within the organization. Decentralising the reliability function, while offering potential benefit through removing some of the barriers identified in this chapter, is not without its own potential problems. Decentralising a function such as reliability only works if all project functions assuming responsibility for reliability achievement are guided by the same objective. It is not enough to cite guiding principles such as minimise life cycle cost or maximise value as these can be a source of conflict with other functions or be to the detriment to the organization as a whole. Neither organizational model explicitly considers the interaction of the reliability division/function with financial management.

In order for project engineers to understand the potential value that can be generated from implementing design for reliability activities, such as those identified in Figure 3-2, they must be informed of what best suits their needs as well as those of the organization as a whole. This is true irrespective of the way in which an organization manages reliability, but it does appear that the decentralised approach offers greater benefits in the long term (with specific regard to the cost of sustaining a central reliability function). The provision of a value based planning tool for design for reliability cannot stand alone; it must interact with the organizational structure through guiding decentralised decision making with a central decision making criteria.

If the suppliers choose not to compete on reliability, then an operator could provide financial incentives in order to achieve the enhanced reliability goals. Incentive schemes can be reflected by a tournament game theory model (Lazear and Rosen, 1981) as a compensation scheme which pays out based on rank order rather than output level. Rank order tournaments are often applied in discussion regarding incentives for sales teams and salaries for directors and CEOs. The argument for the latter is that large salaries afforded to directors and CEOs is compensation for the effort invested in the company prior to becoming director/CEO rather than in expectation of enhanced output once promoted. Tournaments have also been applied to supplier selection, Deng and Elmaghraby (2005) modelled the supplier selection process of a firm given a period with which the firm observed the quality of a product concurrently supplied by two vendors. A similar approach to reliability management could be adopted where suppliers are selected and rewarded based on their efforts to improve reliability performance and assurance. There is, however, no relevant literature regarding the use of rank order tournaments to support reliability based supplier selection.

There are three potential solutions proposed to facilitate the implementation of a reliability and technical risk management strategy and establish a reliability culture. The first is a decision making framework that supports decision makers in the defining the effort (specifically, application of the reliability engineers toolkit) required to managed the inherent risks that exist in a project and add value to the project. Chapter 2 identified that whilst life cycle costing does include reliability analyses as a cost element, it is not used to identify which techniques should be applied and when they should be applied. The second solution is through adopting a decentralised reliability function; while this has the benefit of removing some of the barriers to implementation discussed in this chapter it does introduce possible conflicts of interest between functions. This can be managed through allowing decentralised decision making guided by a central decision making criteria. Any kind of planning tool or decision making framework should have this objective; to support decision making at corporate and project level. The economics of reliability tools, while capable of supporting management with decisions regarding the optimum reliability are lacking at the project level. The final solution proposed is through providing financial incentives to a supply chain that might otherwise choose not to improve reliability. When considering a subsea development project, the suppliers (both hardware and service suppliers) could be considered part of the organizational structure. In doing so, the decentralised approach to reliability management is expanded to these individual organizations. A decision framework for investing in design for reliability effort would therefore have to include these incentives to the supply chain as part of the central decision making criteria. This final requirement, while clearly important, is considered a refinement or addition to the basic need of a planning tool that supports decision making at project and corporate levels with regard to defining the level of reliability effort (specifically implementation of the reliability toolkit). The following part of this research (Chapters 4, 5 and 6) explores the literature to identify existing knowledge and techniques to support the attainment of this research objective. The subject of providing financial incentives is revisited in the final part (Chapter 9) as a source of further research in the field.

4. Life Cycle Costing

4.1. Introduction

The major activities observed during a project may be characterised into a number of project life cycle stages. Figure 4-1 (modified from Jahn *et al*., 2001) indicates a typical project life cycle for an oil field development. Many of the earlier (design) project stages revolve around a set of decision making processes to manage project risk and provide confidence that the project can deliver value to the organization. Iterative assessment against decision making criteria establishes a stage-gate project management structure whereby the project team may decide to proceed to the next project stage, continue development at the current stage or abandon the project. As a risk management strategy the stage-gate approach provides the opportunity to abandon, or re-assess, the project at the minimum accumulated cost. The number of iterations around this decision making process, therefore, depends on the scale of the project and the risk perception of the project organization.

The operational stage observes a number of different phases, mainly attributed to the production rate of the system (Figure 4-2). During the early life, there is often a production ramp up phase, where more production capacity is brought on-line. The gradual introduction of extra production capacity enables the facility to start generating revenue, and hence repaying the capital expenditure, as soon possible. After the ramp-up phase the project observes a period of constant production known as the production plateau, which is followed by the production decline. One objective of the operational stage is to manage and control the operating expenditure (OPEX). The reliability of the system, revealed during operations, can represent a significant risk to the planned OPEX control. For subsea systems, failure of equipment can result in prolonged down time as spare parts are located and support vessels mobilised. During this time the system may be incapable of producing at full capacity and generating the expected revenue, increasing the total cost of failure.

Implied by Figure 4-2, the total cost of failure is dependent on when a failure occurs. Not only does the time value of money mean that expenditure today is greater than the same expenditure in the future, but the system's production function also varies with time and hence the lost or deferred revenue also varies with time. Early life failures have a higher present cost in terms maintenance but also extend the payback period, resulting in increased interest repayment. Although wear-out failures have a lower present cost in terms of maintenance cost they can ultimately determine the economic life of the field, which is the point at which the OPEX exceeds the revenue generated. The costs associated with operations can overshadow the procurement costs for a system depending on the consequences of failure (Goble and Tucker, 1993).

Life cycle costing was developed by the US Department of Defence to increase the effectiveness of government procurement (Shields and Young, 1991) in recognition of the fact that up to 75% of the total cost was attributable to operations and support (Gupta, 1983). However, Figure 4-3 (Berliner and Brimson, 1988) suggests that commitment of cost occurs prior to procurement, during the design stage. The increasing recognition of the life cycle cost implications has triggered the development of a variety of Design for 'X' methodologies, which, despite not necessarily using cost as the assessment criterion, were shown to reduce cost (Asiedu and Gu, 1998).

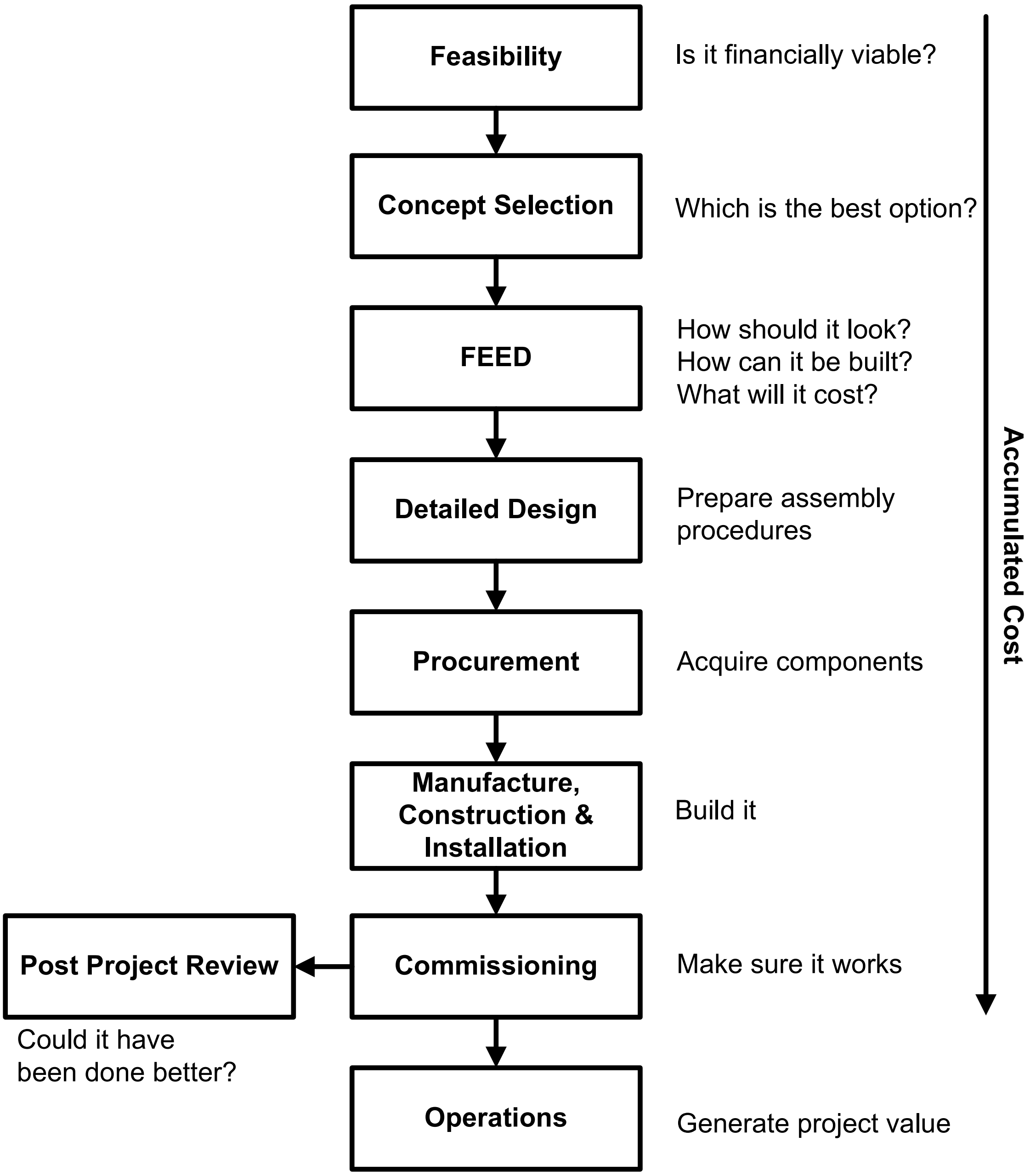

Figure 4-1: Generic project life cycle stages for subsea production system (Jahn *et al*., 2001).

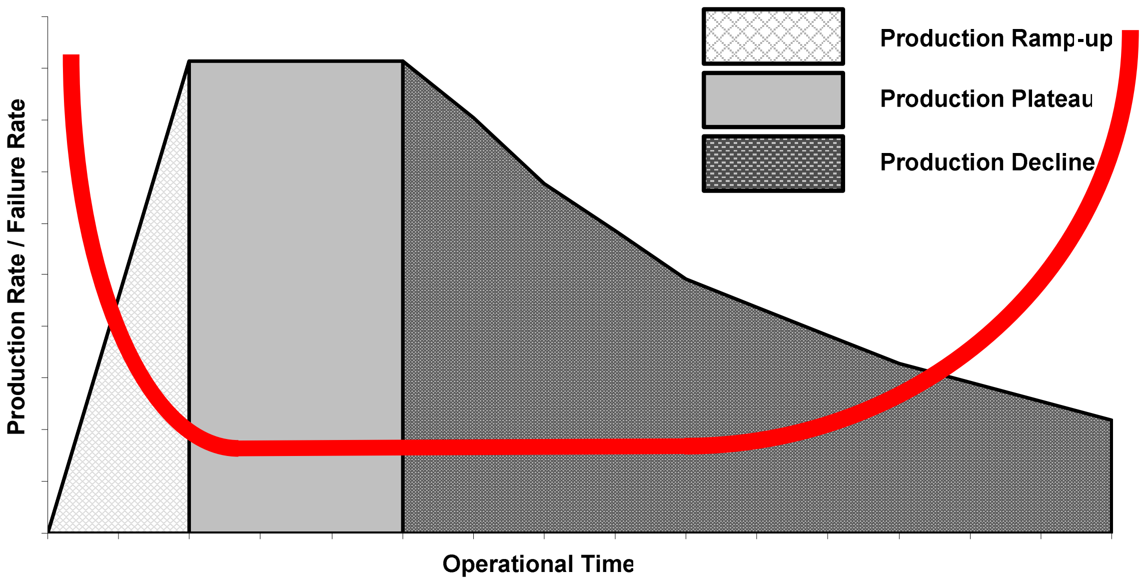

Figure 4-2: Generic production rate phases observed during the operational stage with system bathtub curve.

In order to support the premise that a higher initial investment in reliability can result in lower life cycle cost, decision makers rely on the acquisition of accurate data and the availability of valid decision support tools and techniques. As a technique, life cycle costing provides a methodical approach to the analysis of the costs incurred throughout the project life cycle and support life cycle cost minimisation decisions during the project development stages. The field of reliability engineering and technical risk management is also supported by a variety of techniques that can help support reliability based decisions during the design process. It is the combination of these techniques, however, that can support risk based decision making in design whereby corporate and project value is maximized.

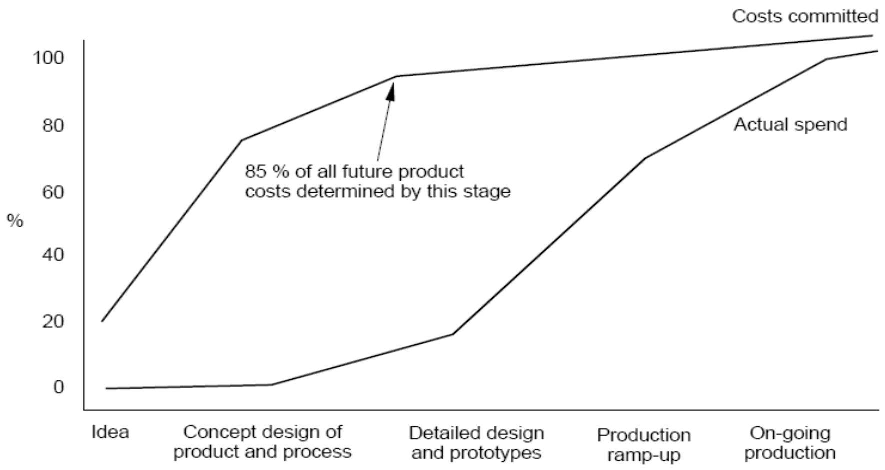

Figure 4-3: Cost commitment and actual spend over project life cycle (Berliner and Brimson, 1988).

Life cycle costing is the economic analysis of the total cost of acquisition, ownership and disposal of a product (IEC 60300-3-3, 2004). It is concerned with assessing competing options and establishing the option that best meets business objectives, which differentiates it from economic investment appraisal (ISO 15663-1, 2000). Life cycle costing follows a life cycle engineering approach whereby the entire life cycle is considered and treated in each stage of the product's life cycle (Keys, 1990). As such life cycle costing can be implemented in any or all project stages to support the decisions indicated below (Blanchard, 1979; IEC 60300-3-3, 2004; ISO 15663-1, 2000):

- Allocation of funds;
- Alternative design layout;
- Alternative disposal or recycling;
- Alternative maintenance strategies;
- Alternative management policies;
- Alternative procurement strategies;
- Alternative product distribution;

- Alternative production strategies;
- Alternative test strategies;
- Equipment type;
- Financial planning;
- Identification of cost drivers;
- Identify cost improvement options; and
- System modifications.

The application of life cycle costing to the assessment of reliability seems natural given the relationship of reliability to the operational cost. Indeed, Asiedu and Gu (1998) rightly point out that reliable and easily serviced products lead to maximum availability and customer satisfaction. The authors' indicate, however, that this is justification for improvements in maintainability and maintenance resource minimisation rather than planning design for reliability effort. Two international standards, ISO 15663 'Petroleum and natural gas industries – life cycle costing' and IEC 60300-3-3 'Dependability management – Part 3-3: Application guide – Life cycle costing', indicate relationship between life cycle cost, reliability and reliability analyses (ISO, 2000; ISO, 2001; IEC, 2004). ISO 15663-2 (2001) suggest the use of reliability analyses as a "*basis for establishing the cost of sustaining a function over its lifetime*". IEC 60300-3-3 (2004) discusses the consideration of dependability as a combination of reliability, maintainability and maintenance support and states that "*higher initial costs may result in improved reliability* and or *maintainability, and thus improved availability with resultant lower operating and maintenance costs."* Again, neither of these standards considers the use of life cycle costing for planning reliability analyses.

The fundamental objective of life cycle costing techniques is to determine and compare the (relevant) total cost incurred by the product or project throughout its whole life cycle. This is achieved by logically breaking down the costs into smaller constituent parts and formulating them within a model. A life cycle costing model is intended to mimic, with suitable accuracy, the behaviour of how costs are accumulated throughout the product or project life cycle. In doing so, not only can the model support the decision as to which option observes the lower life cycle cost but also identifies where the majority of cost is being accumulated, which in turn may provided a focal point for continual cost reduction. However, this chapter is intended to review the current literature and consider existing practice that could be used to create a value based planning tool for reliability analyses.

4.2. Cost breakdown structure

Life cycle cost is made up of the costs to the manufacturer, user and society (Asiedu and Gu, 1998). These costs are often classified into one of three major cost drivers, namely; cost of acquisition, cost of operation and the cost of disposal. Major cost drivers are logically decomposed further into individual cost elements, in doing so this cost decomposition (referred to as the cost breakdown structure, or CBS) defines the scope of the decision making process by identifying the smallest constituent parts of the cost drivers that differentiate the decision options. As a project progresses through its life cycle, the cost breakdown structure expands to reflect the increasing detail and understanding of the system.

A generic cost breakdown structure for an E&P project is presented in Figure 4-4 (modified from IEC 60300-3-3, 2004), which indicates the cost drivers defined in the industry as the cost of acquisition (capital expenditure or CAPEX) and the cost of operation (operational expenditure or OPEX). While the cost of disposal/decommissioning offers a significant input to the overall life cycle cost it has not been included in this review in order to concentrate on the reliability and maintainability aspects of the OPEX/CAPEX trade-off.

In terms of a planning tool for reliability analyses, the cost breakdown structure highlights the necessary cost elements to be considered. Cost elements within the CAPEX cost driver include the introduction, identification and mitigation of faults or potential failure modes. The related cost elements in the OPEX cost driver are the reactive costs of failure in operation, including spare part acquisition and interventions costs.

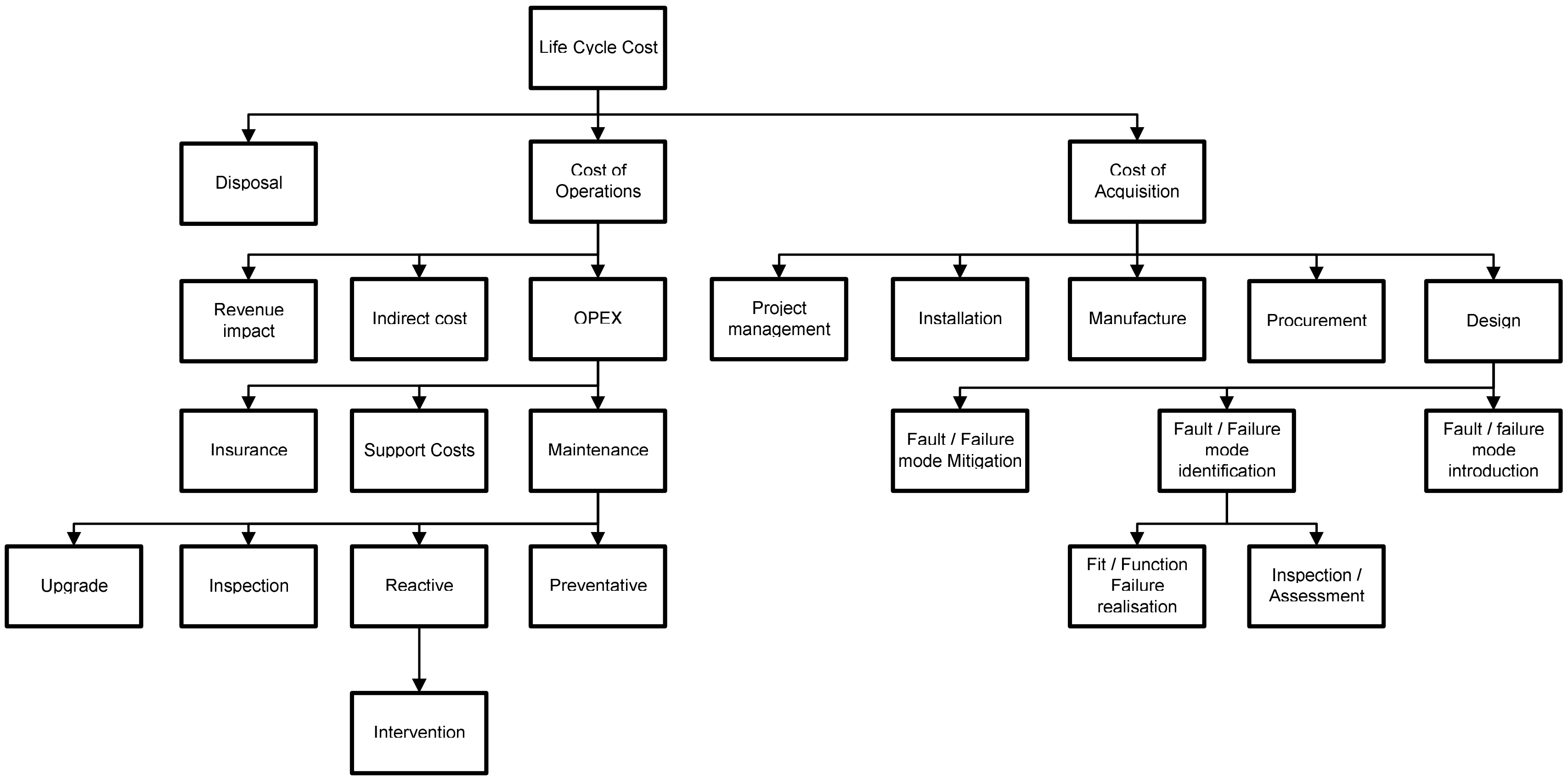

Figure 4-4: Example cost breakdown structure (modified from IEC 60300-3-3, 2004).

Note: Installation, Procurement and Manufacture all exhibit the same cost elements as defined for Design.

4.3. Cost estimation

Each cost element in a life cycle costing model is defined because its behaviour differentiates the competing options. It is important therefore that the cost element is accurately estimated by a method appropriate to the behaviour of the cost element. The definition of cost elements and their accurate estimation allows the designer to understand why a project accumulates the costs it does.

4.3.1. Estimate accuracy and uncertainty

Cost estimates need to be both accurate and within tolerable bounds of uncertainty. Accuracy refers to the precision with which the estimate reflects the reality while tolerable uncertainty defines an acceptable deviation (i.e. horizontal deviation on Figure 4-5) about the mean estimate.

The Freiman curve (Figure 4-5, modified from Daschblach and Apgar, 1988) describes the relationship between the estimated project costs and the actual project expenditure. The three main areas on the graph relate to the under-estimated costs, accurate cost estimates and over-estimated costs.

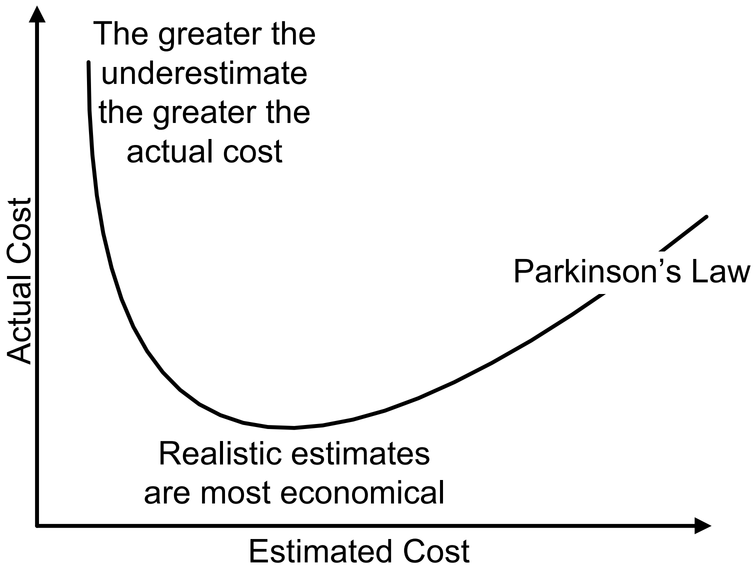

Figure 4-5: Freiman curve (Daschblach and Apgar, 1988).

While low cost bids may win contracts or satisfy a preference for CAPEX minimisation, under-estimated project often observe the highest project costs. Projects that under-estimate on cost are initially planned and resourced to that budget. However, the under-estimate is soon realised as unachievable and the project requires rescheduling, incurring extra financial losses and schedule delays (Daschblach and Apgar, 1988).

Projects that over-estimate on cost tend to observe Parkinson's Law, which states that work or cost expands into the time or budget available (Parkinson, 1957). Without sufficient budgetary policing, the over-estimate becomes a self fulfilling prophesy (Daschblach and Apgar, 1988).

Realistic estimates consider the necessary detail to deliver the project without over compensating on the required float or contingency. In doing so, project management is kept aware of any excessive resource consumption (Daschblach and Apgar, 1988), whilst retaining flexibility in the project.

As a product progresses from conceptual design through to detailed design, the number of cost elements should increase in line with the increased understanding of the product. This increased definition of the product and its cost elements also leads to a more comprehensive cost estimate and reduced uncertainty. The cost estimating methodology may also tend towards a more detailed technique as the understanding of the costs element behaviour also increases.

Creese and Moore (1990) indicate that cost estimate accuracy increases significantly from conceptual design to detailed design (Table 4-1) as the system becomes better defined and more accurate cost estimation techniques are deployed. These figures suggest that there is a tendency for projects to overestimate on cost. This may be in response to the fact that, according to the Freiman curve, underestimated costs can lead to the highest project cost.

Table 4-1: Cost estimate accuracy (Creese and Moore, 1990).

Design phase	Cost estimate accuracy
Concept design	-30% to +50%
Preliminary design (FEED)	-15% to +30%
Detailed design	-5% to +15%

According to Figure 4-6 (modified from Jahn *et al.*, 2001) cost estimate accuracy for oil field development projects increases from 35% estimate during project initiation to 15% estimate in definition (FEED) and ultimately cost commitment and control in detailed design. The values cited suggest that either cost estimators for field development projects are more accurate or (more likely) that the techniques have become more accurate over time as more relevant information has been collected. Figure 4-6 also implies that the decision to progress a field development project is sensitive to the uncertainty of the cost estimates; that is projects may be rejected if the uncertainty surrounding the project cost is too great.

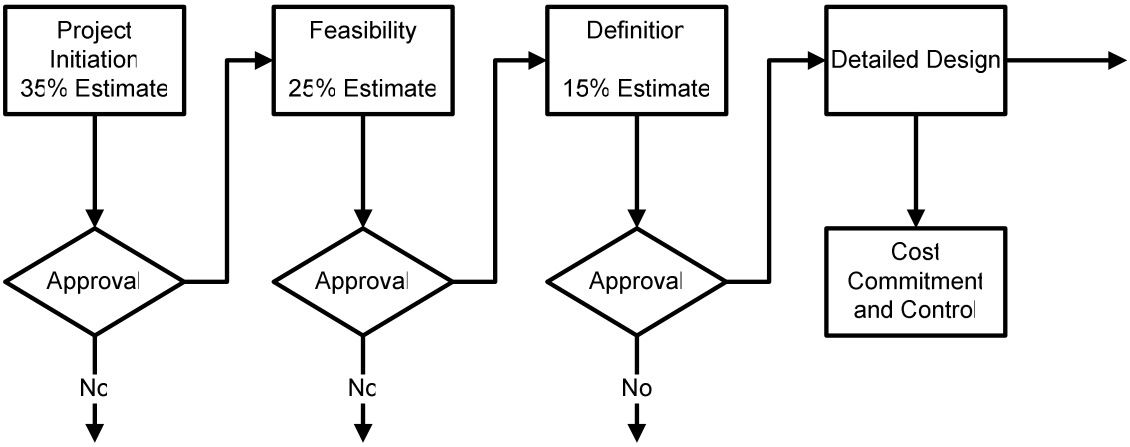

Figure 4-6: Cost estimate uncertainty through the design life cycle (Jahn *et al.*, 2001).

4.3.2. Cost estimate methods

Depending on the available information regarding the behaviour of the cost element and required accuracy, the cost element may be estimated through a variety cost estimating methodologies. These can be generalised in to three categories:

- Parametric cost estimating;
- Cost estimates by analogy; and
- Detailed costs estimates.

Parametric cost estimation relies on the determination of functions that explain the relation between cost and some other measurable characteristic of the item (Dean, 1995). A parametric approach requires significant historical data to establish the statistical relationships that drive the functions. However, once the relations have been established, the method can quickly produce estimates. Parametric estimations may have a tendency for over-estimating the cost but are made more accurate over time as more information regarding the statistical relationship is acquired (Daschblach and Apgar, 1988). Parametric cost estimates have proven to be successful for costing assemblies of components (Creese and Moore, 1990), suggesting that their application may be best deployed during FEED before the absolute detail of the design is finalised. The reliance on historical data, however, means that this method is not suitable for estimating the cost of new technology.

Analogous costing relies on costing the difference between the intended product and a similar product whose cost has already been observed. The technique is dependent on the ability to identify the differences between the two products and judge the cost of the difference noted (Asiedu and Gu, 1998).

Detailed modelling of cost provides the most accurate estimate of the cost at the expense of the time taken to generate the estimate. The technique uses direct costing of materials, labour rates, machine time, et cetera with subsequent allocation of the overheads. The approach can be complemented by activity based costing (ABC) in its allocation of overheads. The method is best deployed for sustained repeat production of items rather than complex, one off systems (Asiedu and Gu, 1998).

4.4. Life cycle *cost drivers*

Life cycle cost is composed of three major cost drivers, the cost of acquisition, cost of operation and the cost of disposal. These cost drivers are decomposed into cost elements that differentiate the options. With the exception of the cost of disposal, each of the major cost drivers can be differentiated according to the reliability effort in design (cost of acquisition) and the resultant reliability performance in operation (cost of operation).

4.4.1. CAPEX cost elements

ISO 15663 part 1 (2000) defines CAPEX as the money required to procure, install and commission a capital asset. The cost of acquisition (CAPEX) is often the most visible part of the life cycle cost (IEC 60300-3-3, 2004) despite not necessarily being the largest cost driver. This visibility often makes it central to the decision making process. Indeed, Hanrahan and Chitwood (2005) point out that the largest parts of the CAPEX breakdown often offer the greatest scope for cost reduction and that any CAPEX cost that can be delayed usually improves field economics. The fact that CAPEX is not usually incurred as a lump sum means that the greatest amount of debt observed by the project (known as the maximum exposure) is often not equal to the total cost of acquisition. Cost elements within the CAPEX cost driver that relate to the application of reliability analyses are the costs to introduce, identify and mitigate a fault or potential failure mode.

The cost breakdown structure of the CAPEX should suit the objectives of the analysis (IEC 60300-3-3, 2004). As the objective of this research is to provide a value based planning tool for reliability analyses, the cost breakdown structure has been defined (Figure 4-4) to reflect the major project realisation phases that influence cost and reliability (and hence the cost of operations). Each major project realisation stage influences the introduction, identification and mitigation of faults or potential failure modes.

IEC Standard 60050(191) (1990) defines a fault as the state of an item characterised by the inability to perform a required function (excluding during preventative maintenance or due to a lack of external resources). Faults can, but need not, be the result of a failure, which is the event that brings about the cessation of an item's ability to perform its required function. The term fault is used herein to describe an item that is incapable of performing its intended function but *not* as a result of a failure event. Items that are incapable of performing its intended function as a result of a failure are referred to as being in the failed state. Faults can be introduced at any time during the product or project life cycle and can be defined according to the origin or cause of the fault (Table 4-2).

Table 4-2: IEC 60050(191):1990 'Quality Vocabulary part 3.2' definitions of faults that (can) originate in the project realisation phase**.**

Fault Name	Fault Description
Mishandling fault	Fault cause by incorrect handling or lack of care of the item.
Design fault	Fault due to the inadequate design of the item.
Manufacturing fault	Fault due to non-conformity during manufacture to the design of the item or to its specified manufacturing process.

Functional failure modes ultimately correlate back to their intended function (Tumer and Stone, 2003). This may be expanded to state that all failure modes ultimately correlate back to an intended requirement. If a failure mode is defined as the manner in which an item fails

(IEC 60812, 2006) then a potential failure mode is the way in which an item *can* fail. All functions and requirement therefore have at least one potential failure mode, whether it occurs or not is dependent on the design management system and the conditions of use.

An item with a fault, by definition, is incapable of performing its required function. Faults are identified therefore when the function is requested either via an acceptance test or in service demand. Faults can be revealed either as ‘functional faults’ or ‘fit faults’; functional faults are those that cannot provide the required function whereas fit faults are those that are directly concerned with the specified design space for the system. Interference between sub-systems or parts will occur when they occupy the same co-ordinates in the design space and, as such, will not fit (Thomke and Fujimoto, 2000). Items with potential failure modes, by definition, have not yet failed. Therefore potential failure modes can be identified by reviewing the requirements set upon the item. As the existence of a potential failure mode is a function of defining a requirement, its existence is largely unavoidable. Potential failure modes can be revealed as a result of a failure event, in which case the item is in the failed state and is no longer to able to perform its function. This may occur either during operations or testing.

Potential failure modes can only be removed if the associated requirement is also removed. As this is not always possible, the probability of failure or consequence of failure has to be managed instead. For the purposes of this research, only ‘potential failure mode management’ is considered. This is achieved through the managing the cause of the failure mode either through redesign at the system level (e.g. introducing redundancy) at the component level (e.g. at the failure mechanism level) or at the organizational level (e.g. improving internal procedures). Items that either have a fault or are in the failed state require either repair or replacement. Depending on the cause of the fault or failure simple replacement/repair may not rectify the problem. For example, common cause failures may affect all similar components. Systematic faults or failures directly relate to specific causes and can only be eliminated by modification to the design or manufacturing process; corrective action does not necessarily eliminate the cause (IEC 60050(191), 1990).

During the design process potential failure modes are both created and managed. However, the timing and efficacy of the management events has a profound effect on the efficiency of the design, both in terms of the speed at which a reliable component or system can be brought to operation and the field life reliability. Inefficient design protocol may lead to a delay to the inception of the system to operation, which when considering the oil and gas industry represents a costly delay to first oil. Figure 4-7 (Booker *et al.* 2001) indicates the timing at which faults with cost implications are both generated and eliminated; 75% of the faults are generated in the development and planning stages whilst 80% are eliminated during the final testing and operational stages.

The financial consequences of failure increases as the time between failure mode origin and observation increase (Rhee and Ishii, 2003) and resolution of problems identified late in the design stage can cause large redesign costs and project delays (Buede, 1994; Thomke and Fujimoto, 2000). Redesign and problem resolution will incur direct financial consequences as a result of labour and material costs while time delays also incur an opportunity cost (Rhee and Ishii, 2003). O'Conner (2005) quotes the 'x10 rule' which states that a problem will cost a factor of 10 higher for each project stage that it goes unnoticed. This is an important consideration when establishing the requirements for a value based planning tool as analysis is the primary means of front loading potential failure mode realisation.

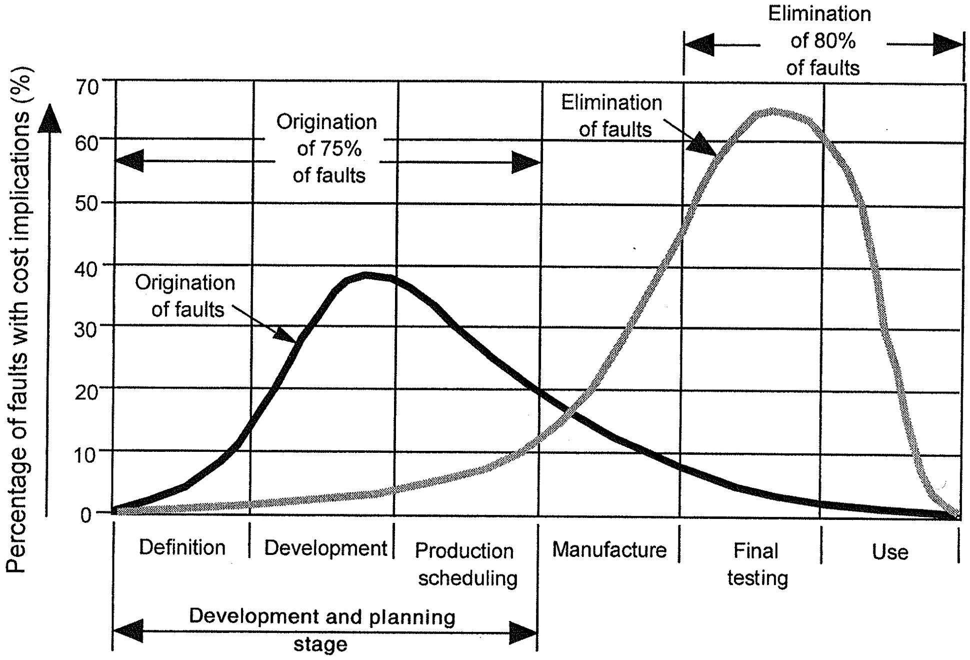

Figure 4-7 : Origin and removal of faults in design (Booker *et al.* 2001).

4.4.2. CAPEX Cost Element Behaviour

The process of design is an attempt to translate the required function of a system into a set of organized functions of units or components (Vliegen and Van Mal, 1990) via a specification. Throughout this process both the functional and physical architectures are defined in greater detail (Buede, 1994). Expenditures associated with purchase, installation and commissioning of an asset are significantly greater than those incurred during design. However, it is during design that the majority of the project costs are committed (Figure 4-3) and care must be taken to minimise the commitment of unnecessary cost. Creese and Moore (1990), citing other authors, state that design is responsible for approximately two thirds of the unnecessary cost and that unnecessary cost represents 20-30% of the life cycle cost. It is assumed that unnecessary costs are those expenditures that could have been avoided with adequate design analysis and decision making. The objective of design therefore may be two-fold; firstly, to translate a requirement into a specification and, secondly, to minimise the commitment of unnecessary cost.

The observed increase in the level of detail associated with the different design stages represents opportunities to increase the value of the design effort or a threat to commit further unnecessary cost. As the level of detail increase the number of components and potential failure modes also increases. The effective management and core competency of the design team will determine if the project design is adding value or committing unwanted cost.

If the objective of the design phase is to produce a specification, then the primary impact of design on the system reliability is to introduce potential failure modes and specify an acceptable probability of occurrence (e.g. a reliability specification). Two particular specifications are of note; the performance (or functional) specification created during FEED and the product specification created during detailed design. According to British Standard 7373-1 (2001), a performance or functional specification states the requirements that define the performance of the product, whereas a product or technical specification is the document that prescribes the product attributes necessary to conform to the performance specification. That is the functional specification requests (or demands) a set of (performance) characteristics and the intended conditions of use. The technical specification describes how the requested performance characteristics are to be achieved. The organization creating the functional specification is not necessarily the same organization that creates the technical specification.

A product specification should differentiate mandatory and preferred characteristics, in terms of requirements and targets (or goals). A requirement is an essential product characteristic for which evidence of conformance to the requirement is also necessary whereas goals are desirable characteristics for which evidence of conformance is either unobtainable or is not necessary (BS 5760-4, 2003). For contractors creating a technical specification, it may be more practical to view goals and requirements in terms of order winning and order qualifying factors (especially if the creation of a technical specification is part of a competitive bidding process); order qualifying factors (requirements) are those aspects that should be achieved in order to be considered by the customer whereas order winning factors (goals) are those aspects that significantly contribute to winning the business (Slack *et al.*, 2004).

The process of setting goals and requirements translates the project's objectives to the system and its constituent parts. The allocation of reliability to a system's component parts should be such that the system achieves its overall objectives without over-specifying reliability for one part whilst under-specifying for another (Smith, 2001). Whilst the topic of reliability allocation attracts much discussion and research, no general method exists to solve the reliability allocation problem satisfactorily (Elegbede *et al.* 2003). This may be due to the fact that a number of different techniques exist depending on the objective of the allocation activity.

The evidence of conformance to a requirement may be termed as assurance. British Standard 5760-4 (2003) states that a performance specification should include a request for assurance while British Standard 7373-1 (2001) states that a product specification should include evidence of the product's capability of conforming to the performance specification. This assurance can be either through testing or analysis.

Assurance in design is achieved through reliability analysis (BS 5760-4, 2003). Depending on the project stage, this analysis may assume different levels of detail and or analysis techniques (these techniques are reviewed in Chapter 5). This analysis does not measure the reliability in operation directly (BS 5760-4, 2003) as there can be a disjoint between analysis using historical data and the future achieved performance (Strutt *et al.* 2007). However, this analysis is an important input to the definition of goals and requirements and avoiding the commitment of unnecessary costs by minimizing the number of systematic faults or failure modes designed into the system.

In terms of accumulating cost in design, constructing a reliability specification can be minimal; the life cycle cost benefit is achieved through minimising the commitment of unnecessary costs committed as a result of (Strutt *et al.* 2007):

- Incomplete and ambiguous definitions of the operating environment;
- Misunderstanding the relationship between component reliability, system availability and project objectives; and
- Ambiguity in the definition of how performance metrics are calculated.

Decisions made during the design phases all relate to how the intended system can achieve the project objectives. In terms of reliability, this is achieved through allocating reliability performance to a system's constituent parts. For a subsea development there are typically four design stages (Design Feasibility, Conceptual Design, FEED and Detailed Design), each of which influences the CAPEX cost element behaviour to varying degrees.

The first question asked of any project is “can the field be economically developed?” The answer to which is dependent on the properties of the reservoir, available technology and economic drivers. Economic feasibility requires the identification of a technologically viable development scenario that could satisfy the investment criteria of the organization. The input of system reliability analysis to this assessment is perhaps minimal as the reliability and maintainability strategy can only be inferred from availability scenarios and the system may be insufficiently defined to accurately perform systems reliability analysis.

Concept selection requires the project team to identify the development scenario that provides the best opportunity to generate project value and shareholder wealth. At this stage, the major technological options are proposed and assessed to provide the scope for the preferred option. The decision making processes may consider each system’s ability to achieve certain availability goals, requirements or benchmarks and hence allocate reliability goals and requirements to the major system packages. By allocating these goals and requirements against what is currently achieved (assuming there is an historical benchmark) the scope of the reliability and qualification effort required in subsequent project stages can be inputted to the decision making process.

By the end of FEED (front end engineering design) the preferred solution is resolved into a functional specification and the project sanctioned if it satisfies the final investment decision making criteria. Sanctioning the project defines/commits a project budget such that the project can invite prospective technology and or service suppliers to bid for the next stages of work. The functional specification provides significant input to the decision to sanction a project as it demonstrates that the project is sufficiently well defined and that any major technical uncertainties have been (or can be) adequately managed such that the proposed solution is technically robust. In addition the functional specification provides the basis of the invitation to tender (ITT) sent out to potential detailed design contractors and or equipment suppliers. By defining how the system is intended to work the functional specification also establishes how the system can fail (although failure modes are not necessarily defined explicitly in a specification). Technical risk analyses support the definition of the functional specification as it can highlight system sensitivities to failure modes and identify where the system could benefit from design modifications and or risk reduction. Therefore, a reliability specification could (and should) be defined as part of the functional specification to support the achievement of project objectives. The reliability specification should include the allocation of the reliability performance to functions and define the assurance required given the perceived level of risk within the project.

Detailed design observes the transformation of the functional specification into a set of engineering drawings and documents intended to guide the remaining project phases. This procedure is initiated through clarification of the functional specification and results in the creation of detailed design drawings and procedures that satisfy and optimise delivery of the goals and requirements specified in the ITT. As an optimisation process, detailed design may observe an iterative loop of design, review and re-design and may observe design phases similar to those already discussed. Reliability goals and requirements specified in the ITT are allocated down to individual component parts or materials and combined with the definition of quality assurance procedures to ensure that the reliability designed into the system is delivered during the remaining project delivery stages. As the specification of the system increases in detail most of the technical uncertainty should be resolved.

Jahn *et al.* (2001) suggest that as much as 80% of the hardware may have been specified during detailed design at just 5% of the total project cost. Considering the fraction of life cycle cost committed by the end of the design phases for relatively small cost expenditure and reflecting on the observation that 30% of this committed cost might be unnecessary, it seems illogical to forgo reliability analyses if these had the potential to reduce the commitment of unnecessary cost.

The procurement stage observes the acquisition of all the necessary materials, components, assemblies, et cetera. The procurement stage is often significant in terms of the project schedule as lead times for specific items can determine the critical path for the project. This stage further increases the number of organizations associated with the project as the entire supply chain influences the reliability and quality of the system. Project expenditure begins to 'catch up' with the committed cost as up to 40% of the budget may be consumed in this stage (Jahn *et al.*, 2001). Procurement is one of the most visible parts of the CAPEX. Indeed the US Department of Defence developed life cycle costing to increase the effectiveness of government procurement (Shields and Young, 1991).

The scope of the manufacture, construction and installation stage is quite significant as it brings the physical components together into sub-assemblies and sub-systems and installs them in the required geographic location. The manufacturing lead time can pose a significant risk to the project schedule as can the installation of offshore and subsea equipment, which is dependent on the availability of the necessary installation support vessels. Manufacturing lead times often result in some sub-systems observing project stages out of phase with the rest of the project to account for the critical path. Unforeseen problems with the design identified during these stages also pose significant schedule risk. Quality management systems employed during this stage provide a significant input to the ultimate reliability of the system; poor quality control during construction and manufacture can undermine the design reliability.

The final project stage before the system enters operations and begins to payback the accumulated costs is system commissioning. This stage observes a series of tests designed to ensure that the system functions according to the specification. While tests do little to ensure the intended reliability of the system, they can identify unforeseen problems in the design and faults introduced to the system during manufacture, construction and installation. Hand-over to the operations team usually signifies the end of commissioning and the commencement of production. At this point the project may be reviewed to assess the performance of the project team and identify where improvements can be made to future projects.

4.4.3. Modelling CAPEX cost element behaviour

Vintr (1999) points out that the concept of life cycle cost is not a preferred selling point and states that purchase decisions are based more on the purchase price and the warranty offered. A manufacturer may therefore choose to determine the procurement cost as a combination of the cost price as a function of reliability, C_P, and the warranty cost, C_W according to Equation 1 (Vintr, 1999),

$$C = C_P + C_W = f(\lambda) + \lambda.t_w.g(\lambda) \qquad \text{Equation 1}$$

where $f(\lambda)$ is the cost price as a function of the hazard rate, λ, t_w is the duration of the warranty period and $g(\lambda)$ is the mean cost to repair as a function of the hazard rate. Rather than explicitly propose functions for the cost price and cost to repair, Vintr (1999) provides a set of assumptions for each:

1. The domain of the function $f(\lambda)$ is the interval $(0, \lambda_0]$, where λ_0 is the hazard rate of an item with no specific design for reliability effort.
2. The function $f(\lambda)$ is decreasing inside the domain.
3. $\lim_{\lambda \to 0+} f(\lambda) = +\infty$
4. $f(\lambda_0) > 0$ for all $\lambda \in (0, \lambda_0]$
5. The domain of the function $g(\lambda)$ is the interval $(0, \lambda_0]$, where λ_0 is the hazard rate of an item with no specific design for reliability effort.
6. $g(\lambda) \leq f(\lambda)$ for all $\lambda \in (0, \lambda_0]$
7. $g(\lambda) > 0$ for all $\lambda \in (0, \lambda_0]$

Equation 1 is effectively a life cycle cost model for a manufacturer where $f(\lambda)$ represents the CAPEX and $\lambda.t_w.g(\lambda)$ represents the OPEX model. The model is of limited use here as the CAPEX model is not well defined aside from stating that as the hazard rate of a component approaches zero (i.e. infinite reliability over any and all time periods) so the cost to produce the item also approaches infinity, suggesting that infinite reliability is financially unobtainable.

Mettas (2000) proposes an expression for the general behaviour of a cost function for increasing the reliability of a component from its current value of reliability to some specified amount according to Equation 2,

$$c_i(R_i) = \exp\left[(1-f_i)\frac{R_i - R_{i,\min}}{R_{i,\max} - R_i}\right] \qquad \text{Equation 2}$$

where $c_i(R_i)$ is the cost of the i^{th} component, f_i is the feasibility of increasing the reliability of the i^{th} component, $R_{i,min}$ is the current reliability, $R_{i,max}$ is the maximum achievable reliability for the i^{th} component and R_i is the i^{th} component's target reliability (where $R_{i,min} \geq R_i \geq R_{i,max}$). It should be noted that this is a penalty function used to describe the difficulty with which a component's reliability is improved relative to other components. In that respect it is not a CAPEX model and rather a decision aide with regard to those items within a system that should be improved (and by how much) to achieve the required reliability performance. However, it raises an important issue in that it considers the ease with which a component's target reliability can be achieved. This feasibility factor represents the difficulty of increasing one component's reliability relative to the rest of the components in the system (Mettas, 2000). The author does not detail how a value for this parameter is determined aside from proposing the use of weighting factors or expert opinion. In addition, it is not clear how the feasibility parameter relates to the improved reliability from R_{min} to R_i and suggests that the reliability improvement feasibility could be the same for all values R_i. It is not this author's opinion that the feasibility to raise the reliability from, for example, 0.7 to 0.8 is the necessarily the same as increasing the reliability from 0.7 to 0.9. While there is merit in including a feasibility parameter within a CAPEX model, Equation 2 assumes that reliability improvement is required at component level when in fact the reliability improvement could be achieved with system redesign through the inclusion of redundancy.

Quigley and Walls (2003) combine the expected cost of running tests with the cost of detecting faults to determine the expected total cost of testing, $E(C_t)$, according to Equation 3,

$$E(C_t) = C\left[\frac{e^{\delta\tau} - 1}{\delta}\right] + VE\left[\sum_{i=1}^{N(\tau)} \exp\left(\delta\left(\tau - X_{(i)}\right)\right)\right] \qquad \text{Equation 3}$$

where $C\left[\frac{e^{\delta\tau} - 1}{\delta}\right]$ is the cost of running a test, δ is a constant interest rate and τ is the test duration. $VE\left[\sum_{i=1}^{N(\tau)} \exp\left(\delta\left(\tau - X_{(i)}\right)\right)\right]$ is the expected cost of fixing the faults detected, V is the cost to repair a fault once detected and *E[.]* is the expected number of faults detected over the test interval, τ, where *X(i)* is the detection time of the i^{th} fault.

The model assumes that there are a predefined number of faults that exist within the system. These are removed upon realisation during testing. In doing so this model incorporates a reliability growth model into the cost behaviour of the fault identification and mitigation cost elements. The underlying assumption that there are a number of faults in the system is unavoidable, but there remains a question as to how the inclusion of faults is accounted for in a cost breakdown structure such as that proposed in Figure 4-4. Deming (2000) argues that injecting faults into a system incurs cost at the point of their introduction. However, if sufficient information were available to model when faults are injected into a system, then attention should focus on preventing the injection of faults.

The model fulfils many of the requirements of a CAPEX model reflecting the cost elements indentified in Figure 4-4 and clearly indicates that such a model should incorporate a reliability growth model. However, Equation 3, which is constructed for component testing rather than system design and analysis assumes perfect fault removal and does not consider potential failure modes. As discussed, potential failure modes can only be removed if the associated requirement, from which the failure mode was derived, is also removed. This may not be practicable. In this case the potential failure mode probability can be reduced by some amount; the efficiency with which this is achieved should be incorporated into the model.

Radaev (2004) defines the cost of assurance by testing, C_{at}, (Equation 4) through defining the number of tests required to provide the necessary assurance (Equation 5),

$$C_{at} = C_0 + c_f n \qquad \text{Equation 4}$$

$$n \geq n_0 = \frac{\ln(1-\gamma)}{\ln R_m} \qquad \text{Equation 5}$$

where C_0 is the fixed cost of the test facility, c_f is the cost of testing one item, n is the number of tests, γ is the required confidence that the required reliability R_m has been achieved. The model indicates that as the required reliability and the level of assurance increases so the number of tests increases (Figure 4-8). Clearly specifying high reliability with high levels of confidence demands a large number of assurance tests which may go beyond economic feasibility. This model has value during the goal setting phases as a guide of the practical level of assurance that should be requested through testing. However, the model does not consider if the reliability of the equipment actually meets R_m. For equipment where the actual reliability falls below the requirement, increasing the number of tests would increase the confidence that the required value has not been achieved. A reliability assurance cost element is an important addition the CAPEX cost breakdown structure, but should be based on assuring the actual reliability. In terms of subsea equipment it is not always practical to use testing to assure system reliability due to the high costs per test.

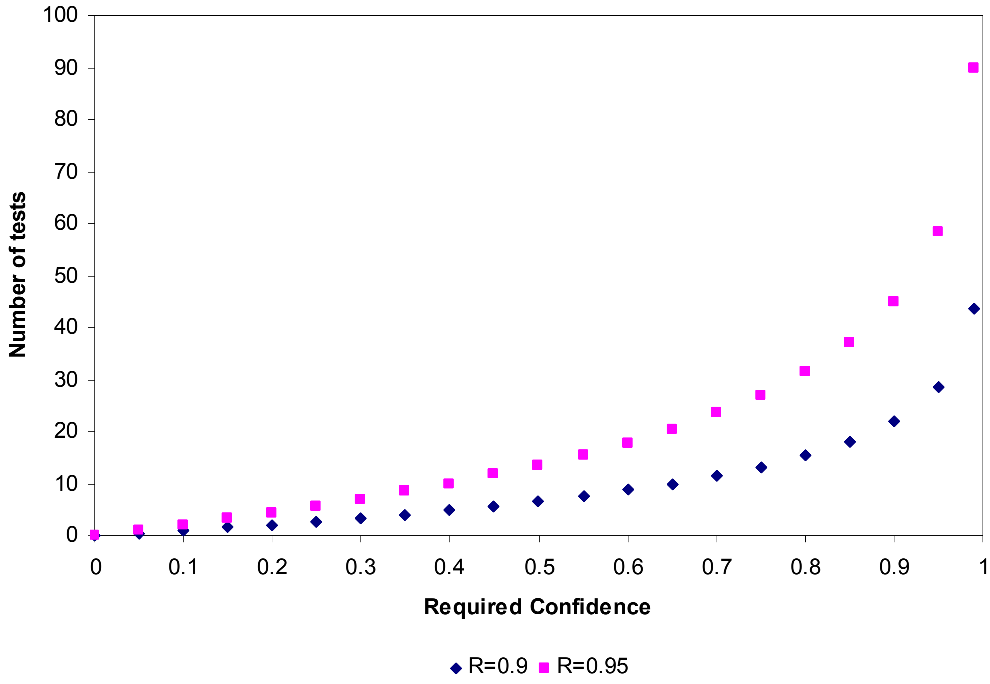

Figure 4-8: Number of tests required to assure reliability to a specified level of confidence**.**

The literature has highlighted some important features to consider when modelling the behaviour of the CAPEX cost elements identified in Figure 4-4. Quigley and Walls (2003) have incorporated reliability growth model within their cost model. In doing so, cost and reliability is estimated based on activities of finding and fixing faults. This concept should be expanded to consider management of potential failure modes. Mettas (2000) introduces the concept of reliability improvement feasibility, which acknowledges the practicality of improving reliability. The cost efficiency with which potential failure modes are mitigated should be considered within a planning model. Finally, Radaev (2004) proposes a cost model for defining the number of tests required to demonstrate reliability to a specified confidence.

Whilst it is not applicable to a planning tool in its current form, the cost of assurance may be a useful addition to the CAPEX model.

4.4.4. OPEX Cost Element Behaviour

The cost of operations may be considered to fall into five main cost elements:

1. Support cost;
2. Maintenance and intervention costs;
3. Insurance;
4. Revenue impact; and
5. Consequential cost.

While the first three items may be collectively referred to as operating expenditure (OPEX) it is important to consider them separately in a life cycle costing model. As with CAPEX, the relative contribution of each part can provide an indication of where cost reductions can be most effectively observed. For example, in their case study, Hanrahan and Chitwood (2005) indicate that 19% of the reported OPEX was attributed to subsea intervention; this suggests that the OPEX could be reduced by up to 19% though improvements to the reliability and or maintainability of the subsea system. The reason for including an OPEX model is to capture the cost of failure in operations of those faults or potential failures that have escaped detection during design and manufacture. It also provides the basis of the trade-off between fixing identified failure modes with letting them enter service unmitigated.

Support cost often comprises a fixed cost associated with the host facility, a variable processing cost and a variable transportation cost (Hanrahan and Chitwood, 2005). As system failure results in the termination of production, some of the variable costs may be terminated during production downtime. This results in the system deferring the processing cost to a later date while incurring costs elsewhere. It is not the intention of this research to consider the support costs within the OPEX model.

4.4.4.1. Maintenance and intervention costs

British Standard 4778-3.1 (1991) defines maintenance cost as "*the total cost of retaining an item in, or restoring it to, a state in which it can perform its required function*". The cost breakdown structure (Figure 4-4) indicates that this cost can be broken down according to the type of maintenance performed as part of the maintenance strategy. A maintenance strategy may be defined from a combination of maintenance elements; preventative maintenance, reactive maintenance, inspection, equipment spares and upgrade (Gallimore and Penlesky, 1988). While equipment spares are fundamental to the maintenance strategy their cost is usually attributed to the cost of acquisition. In the same respect, the cost of defining a maintenance strategy is a CAPEX item.

Maintenance can be defined as the activity of caring for physical facilities so as to avoid or minimise the chance of that facility failing (Slack *et al.* 2004). Alternatively it can be defined as a method of sustaining the reliability of a function (Kelly, 1997). These definitions tend to support the objective of preventative maintenance, which may aim to reduce the probability of breakdown by replacing equipment before it fails (Gallimore and Penlesky, 1988). Preventative maintenance can be either time based or condition based. In its simplest application, time based preventative maintenance replaces or overhauls equipment after fixed time periods (Eti *et al.* 2006). However, this method does not consider the condition of equipment and can, therefore, result in significant wastage through replacement of equipment that is showing no signs of wear out. Condition based preventative maintenance collects information relating to the state of the equipment until specific information is collected that signifies the need for maintenance (Schneider *et al*. 2006). The total maintenance activity cost, therefore, is a function of both the frequency of the data collection and the criteria that trigger the maintenance activity. The latter further differentiates condition based preventative maintenance depending on whether the maintenance activity criteria consider equipment condition in isolation or in terms of the overall system performance.

Reactive maintenance is the simplest maintenance strategy where equipment is operated until failure when it is then decided if replacement is necessary (Schneider *et al*. 2006). Reactive maintenance delays the cost of maintenance more than any other strategy, leaving the system in a productive state for a long as possible. However, this strategy compromises the supply reliability (Schneider *et al.* 2006) as system shut down is unscheduled. The unscheduled nature of a reactive breakdown strategy can also lead to longer system downtime and greater indirect costs. It follows therefore that a reactive strategy is best applied to equipment whose failure is inconsequential to system performance (Schneider *et al*. 2006). Despite this, the subsea oil and gas industry tends to operate a reactive approach to maintenance where the cost of planned preventative intervention is deemed too high (e.g. deepwater developments) compared to the revenue that could be generated. The cost of a reactive breakdown strategy can be mitigated through condition monitoring or the purchase of equipment spares. Condition monitoring can reduce the time taken to isolate the source of failure, while holding spares can reduce the lead time for replacement equipment.

Inspection can be defined as the assessment of equipment characteristics against a specified benchmark to determine conformity (ISO 8402, 1995). This quality driven definition suggest that inspection should be applied to reveal non-conformities or faults rather than equipment in a failed state. The activity of identifying equipment in the failed state may be more correctly referred to as diagnosis, which is discussed below. Both reactive and preventative maintenance strategies can be supported by inspection. The value of the information generated through inspection, however, depends on the maintenance strategy. As condition based preventative maintenance relies on the collection of data it clearly benefits the most from inspection. Indeed, inspection identifies those instances where maintenance activities are required either before or after a fixed time preventative maintenance strategy (Gallimore and Penlesky, 1988). Inspection costs are accumulated through the acquisition of the inspection equipment and the cost to perform the inspection. These costs are either planned (preventative maintenance) or accumulated on demand.

Much of the cost OPEX associated with a maintenance strategy is incurred when an intervention activity is required. The component parts of an intervention activity are outlined below.

1. **Realisation** is the time taken to recognize that there is a problem that requires (or might require) intervention. This may be triggered by a failure event or through inspection. Realisation time is often the longest for latent faults which are inconsequential to specific operations (e.g. a safety shut-off valve with a latent fault that prevents it from closing on demand may not be realised during normal production operations; that is not to say that the ‘failure to close on demand’ failure mode is inconsequential). For a reactive maintenance policy, realisation reflects the time at which the other maintenance costs (diagnosis, procurement, repair and verification

and check-out) may be triggered and as such may not incur a direct cost. However, realisation prior to the system failure event can reduce the costs associated with the subsequent logistic delay of the intervention activity.

2. **Diagnosis** is the process of determining the cause of the failure and identifying what remedial action is required. The speed with which the fault can be isolated is dependent on the availability and accuracy of data. Cost collection of this cost element is a function of the time taken to process the information and arrive at a decision. Preventative maintenance strategies can ensure that much of the diagnosis time is consumed whilst the system is still in operation. Reactive maintenance strategies, however, are more likely to observe diagnosis during downtime, which is reflected as revenue impact.
3. **Procurement** is the acquisition of the equipment (including spare parts and tooling) necessary to perform the active repair. Procurement can be a significant cost element in terms of replacement cost and replacement lead time. However it may be reduced through the acquisition of spare parts up front (which forms part of the CAPEX). Many subsea interventions require support from an external vessel capable of transporting equipment to or from the subsea location. The purchase of this service has been included as part of procurement. The cost of these vessels (usually calculated on a day rate) is dependent on the equipment that needs replacement and the global vessel availability. For example, an ROV support vessel required to change out a valve module in the North Sea is significantly cheaper and more readily available on site than a heavy lift vessel required to change out an entire production tree in the Asia-Pacific deepwater. The lead time for procurement can be significantly influenced by when realisation occurs. Procurement time is longest if realisation occurs when the item fails during demand for that item's function. If realisation,

through inspection, occurs prior to the failure event then diagnosis and procurement can be initiated before system failure, thus reducing the total downtime.

4. **Repair** is the actual activity of restoring the system to an operational state. Cost collection of this cost element is driven by the time taken to carry out the repair (which manifests as revenue impact) and may be limited to labour charges. Depending on the repair activity, 'hot' repair can be performed on an operational system. In this case the impact of repair on lost or deferred revenue is minimised.
5. **Verification and check-out** is the time taken to perform any final adjustments and confirm that the repair activity has returned the failed item to the operational state before restarting. As a cost element, verification may not collect as much cost as procurement, for example, but can have significant implications if it is discovered, at a later date, that the intervention has not corrected the problem.

Aside from any compulsory insurance that an operator may have to purchase, there are two types of insurance that could be purchased to protect the operator against the cost of failure. Engineering insurance provides compensation for damage to equipment caused by its own failure (Diacon and Carter, 2005). Interruption insurance covers losses in profit during downtime, overhead costs incurred irrespective of whether revenue is being generated and additional costs associated with restarting operations. Interruption insurance is usually conditional on purchasing an engineering insurance policy to cover the material damages (Diacon and Carter, 2005).

Insurance premiums are paid out on an annual basis to transfer risk (e.g. of failure) away from the operator to an insurer. Depending on the policy, insurance can offer varying levels of protection from the cost of failure. There are a number of general policies that can be purchased; full insurance, deductible insurance, franchise, coinsurance and first loss insurance (Diacon and Carter, 2005).

1. A full insurance policy protects the insured against the whole cost of failure. The insurer assumes responsibility for the total cost.
2. With a deductible insurance policy, the insured pays a fixed amount of the total cost of the failure event (which may result in paying for the entire cost of failure). The insurer pays the excess of the cost of failure over a specified amount.
3. Holding a franchise insurance policy means that the insured pays all costs under a certain amount, providing that the total cost remains below the specified amount. The insurer bares no cost for failures costing less than the specified amount but assumes responsibility for the total cost if it exceeds the specified amount.
4. Coinsurance can assume two different meanings. Firstly, it can mean the acquisition of insurance through multiple insurers. Alternatively it can be where the insurer covers a specified percentage of the total cost of failure, the insured pays the remainder.
5. With a first loss policy the insurer pays up to a specified amount for all failure events. The insured only pays the excess (this is essentially the reverse of a deductible policy).

The cost of the policy depends on a number of variables. Variables of note include the size of the pool of exposure units and the concepts of moral hazard and adverse selection. As the number of exposure units (the object being insured against a specific risk) increases, the insurer can be more accurate in calculating the premium as a result of the law of large numbers (Diacon and Carter, 2005). This law states that as the sample population increases the actual losses approach that which is expected. The concept of moral hazard means that policy holders are less risk averse (and hence more likely to claim) when they have insurance compared with when they do not; as a result insurers must be sure that the insured cannot benefit from a claim (Glenn, 2003). The concepts of adverse selection means that people who believe that they are at high risk are more likely to purchase insurance compared to those who do not; this is in conflict with the assumption that the pool of exposure units, used to calculate the expected loss, is homogeneous (Glenn, 2003). The level of risk and uncertainty in these factors combined with the administrative fees of the insurer influence the insurance premium. This is an interesting topic in terms of risk mitigation but insurance is a risk transfer strategy and as such is unlikely to support planning for design for reliability effort in the design stage.

Revenue impact may be considered as either lost or deferred revenue. Lost revenue is simply the revenue forgone as a result of not providing a product or service. Deferred revenue is money received for a product or service prior to the delivery of the product or service to the customer. As deferred revenue has not been fully earned (i.e. the product or service has not been supplied) it not recorded as income but as a liability (Myddleton, 2000) until the oil or gas has been supplied. In the oil and gas industry revenue impact from failure is usually in the form of deferred revenue as the oil or gas is ultimately produced. However, there are cases where failure can result in lost revenue. Clearly the total cost of revenue impact (deferred or lost production) is a function of the duration of time that the system is not in operation. This is a function of both the reliability (frequency of failure) and maintainability (duration of the failure).

Consequential costs in operation are incurred when the system becomes unavailable (IEC 60300-3-3, 2004). It may be argued that all failure related costs are therefore consequential costs. Indeed, IEC 60300-3-3 (2004) states that revenue impact may be considered a consequential cost; it does not, however, state that corrective maintenance, which can occur when the system is unavailable, is a consequential cost. Consequential costs can include direct and indirect costs. The direct costs include warranty and liability costs, whereas indirect costs include damages to image, reputation and prestige (IEC 60300-3-3, 2004).

Warranty costs tend to be consumed by the supplier, who bears the financial implications of hardware replacement (excluding revenue impact) should it fail within a set time period. While warranty costs are part of the cost of operation for the product life cycle, they are not part of the project life cycle cost from the view point of the operator. Indeed, ISO 15663-2 (2001) does not include warranty cost as a constituent part of the life cycle cost. Liability costs are the legal costs encountered as a result of failure or unavailability; along with damages the company's reputation, these costs may be very difficult to accurately estimate (IEC 60300-3-3, 2004).

4.4.5. Modelling OPEX cost element behaviour

Reliability based cost of operations models presented in the literature tend to focus on maintenance and intervention costs. Their application varies in complexity and accuracy from rule based equations to direct simulation.

Govil (1984) presented a set of equations for the logistic support cost component of the life cycle cost based on a set of underlying assumptions listed below:

- Logistic support cost (LSC) of a low reliability component is very high;
- LSC of a high reliability component is very low;
- LSC is a monotonic decreasing function of reliability; and
- Derivative of LSC with respect to reliability is a monotonic decreasing function of reliability.

Through analogy with existing cost of acquisition models, Govil (1984) suggests five analytical models for the logistic support cost (Equation 6 through Equation 10) shown in Figure 4-9,

$LSC1 = F(1-R)^g$ F, g > 0 Equation 6

$LSC2 = F[\tan(\pi(1-R)/2)]^g$ F > 0 , 1 ≤ g ≤ 2 Equation 7

$LSC3 = F.\exp[g/R]$ F, g > 0 Equation 8

$LSC4 = F\left(\frac{1-R}{R}\right)^g$ F, g > 0 Equation 9

$LSC5 = F.\ln\frac{1}{R}$ F > 0 Equation 10

where *F* is a cost scaling factor, *g* is a shaping factor and *R* is the reliability.

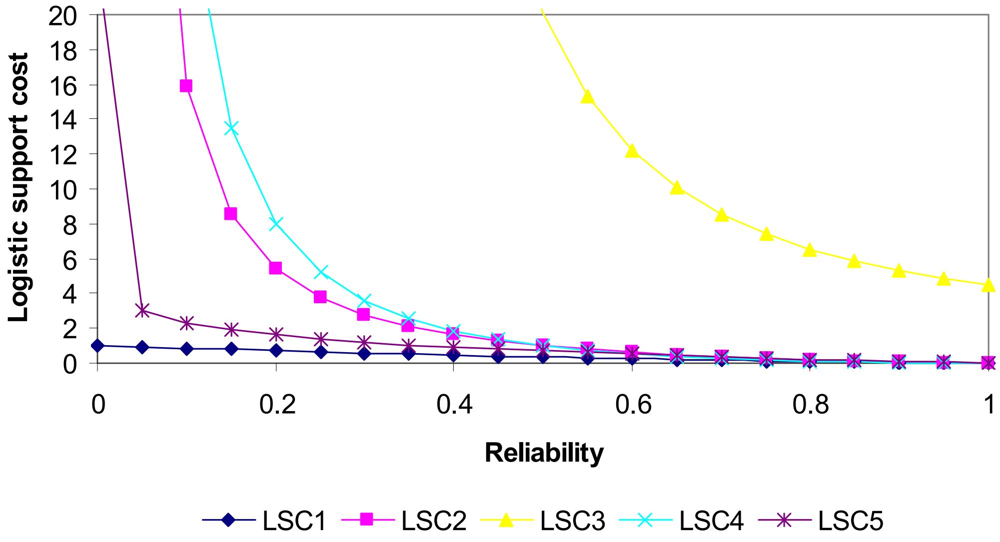

Figure 4-9: Graphical Representation of Govil (1984) LSC curves, F=1, g=1.5

Figure 4-9 shows the significant differences in sensitivity of the logistic cost curves to reliability; constants *F* and *g* have been arbitrarily selected to satisfy the condition specified for Equation 6 through Equation 10. All curves except LSC1 tend to infinity as reliability approaches zero, suggesting that this equation does not necessarily satisfy the first assumption noted. Application of any of these curves is dependent on collecting sufficient data to estimate the *F* and *g* constants (this is especially true for *g* as it relates to the tolerance of the LSC to reliability). As *F* is a cost scaling factor its value should be obtainable from the cost breakdown structure. For example the scaling factor for LSC3 relates to the cost of an infinitely reliable component while the scaling factor for LSC1 relates to an infinitely unreliable component. Neither of these values is particularly useful for calculating service life cost, especially if the cost of failure varies over time (as would be expected for a subsea production facility). The shape factor, *g*, indicates the sensitivity of the LSC to component reliability suggesting that the cost of failure escalates significantly at low reliabilities. However, all of these models are quite insensitive at high reliabilities, which could deter decision makers from investing in reliability improvements based on the OPEX. While they may be useful in a life cycle costing model where significant data already exists, they do little to establish how improvements can actually be made and whether a reliability improvement is, in fact, the best course of action. Indeed, Hennecke (1999) claims that for pumps with low reliability, life cycle cost reductions may be best achieved through enhanced condition monitoring rather than improving the reliability.

Ntuen (1987) presents a discounted cost of operations model based on the annual operating time and the hazard rate. The model draws on the assumptions from other authors, assumptions of note include:

- Each component observes a fixed penalty cost given failure;
- System failure cost rate is proportional to system hazard rate; and
- Life cycle cost is the additive components of the subsystem cost function.

By implementing a discounted cost model, Ntuen (1987) acknowledges the time value of money. However, it is not true for subsea systems that the penalty given failure is constant due to the variable production profile. The last assumption states that components' cost behaviour does not interact and is included due to the belief that the life cycle cost is too difficult to predict if the cost function does not satisfy simple criteria (Ntuen and Moore, 1986). While it may be the objective of any model to attain a suitable balance between simplicity and accuracy, it is not true that cost element behaviours do not interact. Complex systems can consume cost through the occurrence of system cut sets and individual items may belong to multiple cut sets. Furthermore, depending on the specific cut set intervention vessel requirements may varying meaning that failed items requiring high cost intervention vessel support can share this cost with other components. Modern computing capability has reduced the reliance on such oversimplifying assumptions.

Goble and Tucker (1993) calculate the cost of operations as the sum of the fixed maintenance cost, variable maintenance cost, engineering change cost and failure incident cost. Engineering change cost are those costs incurred to improve system operations that could not be (or were not) anticipated during design. The failure incident cost, C_{FI}, is a function of both the mean time to failure and the mean time to repair, according to Equation 11,

$$C_{FI} = \frac{(C_{RL} + C_{LP})MTTR}{MTTR + MTTF} \qquad \text{Equation 11}$$

where C_{RL} is the repair labour cost and C_{LP} is the cost of lost production. Equation 11 provides greater scope for decision making as it suggests that life cycle cost improvements can be made through the maintainability (i.e. reducing the cost given failure) and well as the reliability. However, this model is only applicable for single items or a system whose OPEX relates directly to unavailability.

De Leon and Ang (2003) construct a reliability based life cycle cost model for an offshore oil platform to assess alternative design options under the consideration of hurricane wave damage. The expected cost of operation model comprehensively includes the expected cost of structural repair, equipment damage, deferred production, injury, fatality and indirect losses. Each cost is estimated from a relation to a global damage index, which is calculated as the union of the response of critical structural elements to energy impact (Ang and De Leon, 1997); the response of these structural elements is a function of a damage index. Cost elements assume an upper limit and depending on the value of, and relation to, the damage index a proportion of this upper limit is consumed. For example the cost of deferred production is calculated according to Equation 12,

$$C_{DP} = 0.1 * P_P * T_P * P_R * D^2 \qquad D < 1$$

$$C_{DP} = 0.1 * P_P * T_P * P_R \qquad D \geq 1 \qquad \text{Equation 12}$$

where P_P is the price of oil per barrel, T_P is the time to restore normal production, P_R is the production rate, D is the global damage index and assuming that the loss due to deferred production is a 10% drop of the full cash flow (De Leon and Ang, 2003). The authors do not explain how the relation of the cost of deferred production to the square of the damage index was determined[2]. The model is included here as one of few cost estimates for deferred production presented in the literature. While De Loen and Ang (2003) where considering the effect of wave damage a similar construct for the cost given failure can be applied to functional reliability in terms of lost or deferred revenue.

Todinov (2004) derives Equation 13 as the basis of risk analysis driven by the cost of failure for M competing failure modes, which cause the system to fail should any occur,

$$K = \left(1 - \exp\left[-\left(\lambda_1 + \cdots + \lambda_M\right)a\right]\right) * \sum_{k=1}^{M} \frac{\lambda_k}{\lambda_1 + \cdots + \lambda_M} \overline{C}_k \qquad \text{Equation 13}$$

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[2] The previous work of Ang and De Leon (1996) suggest that the relationship is determined from damage and cost data collected from the 1985 Mexico City earthquake.

where K is the risk of failure, λ_k is the (constant) hazard rate of the k^{th} failure mode, a is the specified operating time and $\overline{C}_k$ is the mean cost of k^{th} failure mode given failure. Equation 13 can be used to find the set of hazard rates that satisfy a specified maximum acceptable risk of failure, K. As such it is presented in the literature, primarily, as a tool for setting requirements based on the cost of failure. Importantly, however, this model acknowledges that failure mode cost functions do interact and that for a series system observing a constant hazard rate, this interaction can be modelled accurately and simply. The total losses from failure can be determined from the Poisson distribution of the number of failures observed over the system's operational life. By using the Poisson distribution, a range of potential cost outcomes are presented. Todinov (2003) defines the concept of potential losses as the distribution function of the consequences from failure and its variance.

For more complex systems the expected or potential cost of failure over a system lifetime can be determined using Monte Carlo simulation (Todinov, 2006a). Todinov (2006a, 2006b) presents a cost of failure based net present value model for complex systems; the cost of operation is presented in Equation 14,

$$PV = \sum_{i=1}^{n} \frac{O_{F,i}}{(1+r)^i} \qquad \text{Equation 14}$$

where PV is the present value of the cost of operation, n is the system life, r is the risk free discount rate and $O_{F,i}$ is the actual negative cash flow in the i^{th} year. The actual negative cash flow in the i^{th} year is calculated from the support costs in the i^{th} year and the actual losses from failure in the i^{th} year. Losses from failure are calculated as the sum of the cost of lost production, the cost of intervention and the cost of repair/replacement (Todinov, 2006a). The cost of lost production is calculated as the product of the selling price, daily production volume and the number of lost production days (Todinov, 2006b). Todinov (2006b) has incorporated Equation 14 into a discrete event simulation for determining the losses from failure to assess competing design alternatives for subsea oil and gas production facilities.

The models proposed by Todinov (2003; 2006a; 2006b) are the most comprehensive of the literature reviewed. They recognise that the cost of failure should be presented as a distribution to reflect the stochastic nature of reliability and that for more complex system this should be achieved through simulation. As with all models though these concentrate on losses from failure rather than focus on improving the value of the project.

4.5. Traditional LCC Assessment Criteria

International standard ISO 15663 part 2 (ISO, 2001) specifies a number of financial performance metrics that can be applied to support the life cycle costing decision making process. These evaluation criteria deploy discounted cash-flow techniques to indicate the financial desirability of an investment at present time to account for the time value of money. Table 4-3 (modified from ISO 15663 – 2, 2001) suggests the preferred metric for each project stage, indicating that traditional investment appraisal techniques should be applied during the early project stages followed by calculating the life cycle cost as the project progresses through more detailed project stages.

Table 4-3: ISO 15663 recommended financial decision criteria through projects.

Project Stage	Feasibility	Concept Selection	FEED	Detailed Design	Procurement
Result	Go / No go	Preferred option	Functional specification	Design solution selection	Equipment
Metric	NPV / IRR	NPV / IRR	LCC	LCC	LCC

Net present value (NPV) is defined as the sum of present values of the annual cash-flows observed over the duration of the project and indicates how profitable a project might be to an investor given the opportunity cost of capital. Determination of the opportunity cost of capital is often through either calculation of the weighted average cost of capital or the capital asset pricing model (Brealey and Myers, 2003). These values may be adjusted if an investment option is considered more or less risky than the typical investment taken by the decision maker or company. NPV is calculated according to Equation 15,

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+k)^t} - I_0 \qquad \text{Equation 15}$$

where C_t is the expected net cash flow at the end of year t, k is the discount rate, I_0 is the initial investment and N is the project duration in years

The decision rule for a single investment is to reject the project if the net present value is less than zero. If the NPV is greater than zero, than the project investment exceeds the opportunity cost of capital and should be accepted. For a comparative decision, the decision maker should choose the option that maximises the NPV, given that it satisfies the single investment criterion.

NPV is the preferred capital investment appraisal method in many financial management texts as the method specifically accounts for the timing of all the relevant cash-flows expected during the project and it has a direct relation to the generation of shareholder wealth (Atrill and McLaney, 2002; Brealey and Myers, 2003). However, the technique can be insensitive to the scale of the initial investment when considering competing options. That is the NPV does not give any indication of the return on investment.

Life cycle cost (LCC) is defined as the sum of the cost of acquisition and the cost of operation and uses the same methods of discounting cash flow. However the C_t term in the LCC calculation only includes those items identified as OPEX cost elements and does not consider revenue generated or profit. Instead LCC considers revenue impact – the cost of lost or deferred revenue. LCC cannot therefore be used as an individual investment appraisal technique as it does not consider the profitability of a project.

The decision rule for competing options using the LCC criterion is to accept the option that minimises the life cycle cost. Without risk based assessment to support the LCC minimisation decision, however, this can lead to misleading results (Markeset and Kumar, 2001) and the possible selection of a sub-optimal solution (BS 60300-3-3, 2004).

Putting life cycle cost into the context of reliability, the total cost incurred to achieve a specific reliability, $L(\lambda)$ is given according to Equation 16,

$$L(\lambda) = Q(\lambda) + K(\lambda) \qquad \text{Equation 16}$$

where Q(λ) is the capital outlay required to achieve a hazard rate, λ, and K(λ) is the risk of operational expenditure associated with λ. Equation 33 can be implemented with specific regard to reliability investments, the total cost of a reliability investment for a system observing a constant hazard rate, is given according to Equation 17 (Todinov, 2004),

$$L(\lambda - x) = Q(x) + K(\lambda - x) \qquad \text{Equation 17}$$

where L(λ-x) is the total loss after decreasing λ by x, Q(x) is the investment required to reduce λ by x (Q(0)=0) and K(λ-x) is the risk associated with the hazard rate, λ-x (Todinov, 2004). By minimising L(λ-x) with respect to x in the interval (0, $x_{\max}$) ($0 \leq x \leq x_{\max} < \lambda$), an optimum hazard rate $\lambda_{opt} = \lambda - x^*$ can be determined where x^* is the investment that minimises L(λ-x) (Todinov, 2004).

The internal rate of return (IRR) is closely related to the net present value; it is the discount rate that returns an NPV of zero. IRR is calculated such that Equation 18 is satisfied.

$$I_0 = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} \qquad \text{Equation 18}$$

The decision rule for a single investment option is to accept the project if the IRR is greater than the opportunity cost of capital. For competing options the decision maker should favour that which maximises the IRR, given that it is greater than the opportunity cost of capital.

The IRR may be preferred as it does not require the definition of a discount rate (although it should be compared to a specified hurdle rate). However, there are a number of weaknesses with the IRR as an investment appraisal methodology. Firstly, the solution to Equation 18 is derived through an awkward trial and error process and spreadsheet solutions for the IRR calculation can give erroneous result for marginal investment decisions (Woods *et al*. 2006). Furthermore, it is possible to return multiple IRR values when there are multiple changes in the sign of the cash flow (Brealey and Myers, 2003). Additionally, the IRR can be insensitive to the scale of the investment made when assessing competing investment decisions (Myddleton, 2000).

The cost per standard barrel of oil or standard technical cost, STC, (Equation 19) is the minimum selling price required that can still return a profit. The metric suggests that a project is profitable if the cost per standard barrel is less than the market selling price. However it does not follow that the option which minimises cost per barrel maximises profit for competing options.

$$\text{Cost per standard barrel of oil} = \frac{\text{CAPEX} + \text{OPEX}}{\text{Expected total production}}$$ Equation 19

Profitability index (PI) is a variation of the net present value and is defined as the present value of the project cash-flow divided by the initial investment (Equation 20).

$$PI = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+k)^t}}{I_0}$$ Equation 20

The decision rule for a single investment decision is to reject the project if the profitability index is less than 1. For competing decision alternatives, the decision maker should favour that which maximises PI, given that it is above 1. The profitability index, as a ratio, provides an indication of the margin of safety for the project (Myddleton, 2000). The greater the PI, the more profitable the project and the less sensitive the decision is to cash-flow uncertainty. The PI is particularly useful for organizations that use capital rationing as it can be used to rank options such that the best combination of investments is achieved. The decision criterion for PI means that it agrees with the NPV criterion. In addition, it removes the sensitivity to scale that the NPV is sometime subject to. For the purposes of planning reliability effort the PI is attractive due to its application to capital rationing, where a budget is provided and the combination of smaller investments (totalling the capital ration) that maximise the PI offers the greatest return on the overall investment. Such an approach would allow a planning process to focus investments in reliability effort based on maximising the potential value generated within a specified ‘reliability budget’.

The payback period (Equation 21) defines the time required to pay back the initial investment.

$$\text{Payback period} = \frac{I_0}{\text{annual cash receipts}} \qquad \text{Equation 21}$$

Minimising the payback period is desirable but where there are fluctuations in the cash-flow the payback period cannot support the identification of the most profitable investment option. Definition of the payback period may, however, be useful in determining the early life period when defining reliability requirements.

The break-even volume (Equation 22) is related to the payback period as it defines the required production volume such that revenue is equal to the initial investment. That is, it defines the production volume at which the NPV first equals zero after having paid off the CAPEX.

$$\text{Break - even volume} = \frac{I_0}{\text{Price per unit - OPEX per unit produced}} \qquad \text{Equation 22}$$

As with the payback period, the break-even volume cannot identify the profit maximising option when there are fluctuating production profiles.

4.6. Chapter Summary

This Chapter has provided a review of the application of life cycle costing with specific regard to reliability. Life cycle cost is constructed from the costs of acquisition, operation and disposal, of which the cost of acquisition and operation were considered here. One of the objectives of the review is to assess the suitability of life cycle costing as a technique to support the planning of reliability analyses during design. To this end a cost breakdown structure, fundamental to the application of life cycle costing, is required that reflects the behaviour of the cost elements associated with performing the analyses during design and the subsequent effect they may have in operations. The cost breakdown structure for the cost of acquisition was originally constructed of three cost elements; the costs to introduce, identify and subsequently mitigate potential failure modes within the system. The cost breakdown structure for operations identified the costs of reactive maintenance and revenue impact as the primary components (although other cost elements exist).

None of the literature reviewed explicitly addresses the use of life cycle costing to plan reliability effort (specifically analyses). However, Quigley and Walls (2003) do demonstrate the use of life cycle costing to plan testing to find and fix faults that would otherwise undermine reliability. The authors' underlying assumption that a certain number of faults exist is key to the creation of a planning tool as the belief that faults exist or uncertainty that failure modes remain undiscovered or unmitigated should influence the decision to invest in reliability analyses. It is this uncertainty that is indirectly captured during the technical risk categorisation activity conducted during the *Define* phase of the reliability and technical risk management process.

It is not necessarily the case that systematic weakness is the result of faults; potential failure modes may exist within the system, which, if left unmitigated, could undermine reliability and erode project value. As potential failure modes are created as result of specifying a functional requirement, the failure mode can only be removed if the functional requirement is also removed. As this may not be feasible, the failure mode probability must be reduced (assuming that the consequences of failure are both unacceptable and cannot be mitigated). It follows that the management of these potential failure modes is dependent on the ability with which the organization can improve the reliability of the component. This is similar in concept to the feasibility described by Mettas (2000) but should relate more to organization capability rather than relative feasibility between components. Organizations that would otherwise not invest in design for reliability may not be able to identify where reliability improvements need to be made or be incapable of effecting an improvement to reliability.

The CAPEX model therefore should be based on a reliability growth model that considers the ability with which an organization can identify unacceptable potential failure modes and the effectiveness with which their frequency of occurrence is reduced.

An OPEX model is required to enable decision makers to trade off the certain cost of acquiring information through reliability analyses against the uncertain operational cost. The OPEX model, therefore, needs to simulate the occurrence of the failure modes during the operational life. Such models are quite well defined in the literature and the concept proposed by Todinov (2003; 2006a; 2660b) can be used as the basis for these models. The models tend to focus on the accumulation of cost rather than the generation of potential value. This may be attributable to the metric used or the definition of cost drivers. Identifying major cost drivers may lead decision makers to investigate how to cut cost out of the project. By redefining the cost breakdown structure to identify ‘value drivers’, decision makers may be encourage to investigate opportunities to generate project value beyond cutting cost out of the project. The decision metric can also shape the planning process; traditionally this been LCC or NPV but the preference, here, for a planning tool is to adopt the profitability index. The reasons are two-fold. Firstly the PI agrees with the decision criteria of the NPV with the benefit of removing the insensitivity to the scale of investment that the NPV is sometimes subject. Secondly and more importantly is the application of PI to capital rationing projects; the PI allows decision makers to identify the combination of smaller investments that maximise the overall project value. By adopting a capital rationing approach to planning, a pre-specified ‘reliability budget’ is formed allowing decision makers to focus on those investments in reliability that have the greatest potential value to the project. This value is generated through identifying potential failure modes (or faults) that would otherwise compromise system reliability and erode project value.

If the planning tool is to be created that supports investment in reliability analyses then the prior assumption that unmitigated failure modes (or faults) exist within the system should be made. If sufficient information were available to predict when faults or unmitigated failure modes where introduced into the system then the focus of reliability effort should be to prevent their introduction rather than plan when to look for them at a later date. Reliability analyses are performed to acquire information relating to the existence of unmitigated failure modes. It follows that analysis should only be performed if it has the potential to influence the design. The following chapter reviews the reliability engineer’s toolkit, discussing the strengths and weaknesses as it applies to reliability and technical risk management.

5. Application of Systems Reliability Analyses to LCC

5.1. Introduction

System reliability analyses are central to the application of reliability and technical risk management to support decision making during the design phases. This support is in the form of (API RP 17N, 2007; ISO 20815, 2007):

- Identifying potential failure modes and failure logic;
- Assessing the probability of occurrence of the failure mode;
- Setting reliability goals and requirements;
- Predicting reliability performance;
- Identifying weaknesses in design; and
- Identify opportunities for design improvement.

For this to add value to the project the analysis should be appropriate for the level risk within the project; for low risk projects, where minimal uncertainty exists, it may not be beneficial or even suitable to perform certain types of analysis. ISO 20815 (2007) and API RP 17N (2007) suggest that analysis is not required for low risk or repeat projects (under the assumption that relevant analysis has been performed during previous projects). When planning these activities it is necessary to understand the level of risk or uncertainty within the project and the analysis effort required to quantify risk and or reduce uncertainty about the reliability performance. This chapter reviews the analysis within the reliability engineer's toolkit, identifying their strengths and weaknesses with respect to their application within the reliability and technical risk management framework. It is not the intention of this chapter to review every tool/techniques that is at the disposal of the reliability engineer as the chapter is focused more on systems reliability analyses (for example, stress strength interference is not considered at the system level).

5.2. Failure modes effects and criticality analysis

Failure modes and effects analysis (FMEA) is a systematic method used to identify potential failure modes, their effects and possible cause (Cassanelli *et al*. 2006). It intends to identify those failures that have unwanted consequences affecting the functionality of the system. The application of criticality analysis (FMECA) provides a means to prioritise design improvement recommendations.

There are a vast number of standards providing varying degrees of guidance for conducting a FMECA over a range of industries (ISO 20815, 2007; SAE JA1000-1, 1999; US Mil-Std-1629, 1984; IEC 60812, 2006; SAE ARP 5580, 2001; SAE J1739, 2002). The general procedure is outlined here:

1. Define the system to be analysed, including a breakdown of the items to be assessed, their interfaces, performance expectations and definition of failure;
2. For each item, identify all possible failure modes and the immediate local and system effects;
3. For each failure mode assign a severity category based on the consequences given occurrence of the failure mode;
4. For each failure mode assign a probability of occurrence;
5. Plot the failure mode on a criticality matrix;
6. For each failure mode identify and rank detection method;

7. Identify corrective actions necessary to mitigate failure mode risk; and
8. Record the recommended/agreed actions.

FMECA is an extremely versatile technique that can be applied to functions, hardware and processes. The technique can be implemented at the first stages of system design and can be updated throughout the design and development phases. It is perhaps the most widely used member of the reliability toolkit and as such has received significant attention in the literature. One of the most documented criticisms of FMECA is the risk priority number. The risk priority number is defined as the product of the ranks given for severity, probability of occurrence and detection. Ben-Daya and Raouf (1996) and Bowles (2004) summarise these shortfalls;

- RPN is not a continuous scale (i.e. many numbers in the possible range can't be produced by the RPN calculation and many can be produced by more than one combination of severity, probability and detection) making it difficult to interpret the results;
- It doesn't satisfy the usual requirements for measurements and therefore cannot be used to evaluate the impact of remedial action;
- It offers no indication as to how the item can be improved;
- It hides the probability that a customer will receive a fault; and
- There is no logical reason as to why the RPN should be calculated as the product of the severity, probability and detection ranks (detection is not a ratio measurement).

Perroux (2007) provides a critical review of the FMECA process and its implementation and identifies further limitations of the technique:

- Can be a very time consuming technique (especially for large or complex systems);
- Cannot guarantee that all potential failure modes will be identified for new technology;
- Not suited to identifying common cause failure modes;
- Not suited to the assessment of combined failure mode effects; and
- Subjective assessment depends on the contribution of expert knowledge.

Teng and Ho (1996) highlight that a significant shortfall with the implementation of a FMECA is that it is completed to fulfil the customer's document requirement rather than improving design reliability. This observation tends to be true for the oil and gas exploration and production industry and can be extended to other reliability analysis techniques. Indeed, where analysis has been implemented and a potential weakness identified the industry has tended to question the input data rather than the design.

FMECA cannot necessarily identify the root cause of the failure mode; it is for this reason that a FMECA is often complemented by fault tree analysis (BS 5760-5, 1991) after failure mode prioritisation. Further examples of the versatility of FMECA and its inherent compatibility with other reliability analysis include:

- Use of FMECA to identify known repeat failures and drive a proactive root cause analysis (Latino and Latino, 2006);
- Using reliability block diagrams to help identify system failure modes (US Mil-Std-1629, 1984); and

- Using automated reliability block diagram reports to construct and populate FMECA work sheets (Perroux, 2007).

Rhee and Ishii (2003) present a life cost based FMEA as a solution to the problems associated with traditional FMECA using the risk priority number. The authors modify the existing FMEA worksheet to include the information contained in Table 5-1, which is used to calculate the expected labour cost, material cost and opportunity cost.

Table 5-1: Life cost based FMEA worksheet inputs (Rhee and Ishii, 2003).

Input	Description
Failure mode	Description of the failure mode
Root cause of failure	Description of root cause of failure mode
Effect of failure	Description of the result of failure
Origin	Project stage that failure mode was introduced
Detection Phase	Project stage that failure is realised
Re-occurrence	Indicates extent to which failure reoccurs over the lifetime
Frequency	Frequency of failure mode occurring over 1year period.
Detection time	Time to realise and identify failure occurrence and location
Fixing time	Active time required to fix the problem
Delay time	Logistic delay waiting for response, parts, et cetera.
Loss time	Total downtime; sum of detection, fixing and delay time
Quantity	Quantity of parts required to fix problem
Parts cost	Cost of parts required to fix the problem

Kmenta and Ishii (2004) develop this concept to present a scenario based FMEA where failure scenarios are allocated an expected cost based on when a failure cause was introduced and when the failure effect was discovered. By defining a failure scenario as a chain of events commencing with the introduction of a failure cause and leading to the eventual discovery of the failure effect (Figure 5-1, modified from Kmenta and Ishii, 2004), the authors replace the risk priority number with the expected cost of a failure scenario. The total cost of a system is defined as the sum of the expected costs of the individual failure scenarios, according to Equation 23,

$$\text{Expected Cost} = \Pr(\text{cause}) * \Pr(\text{end effect given cause}) * \text{Cost} \qquad \text{Equation 23}$$

where *Pr(cause)* is the probability that a failure cause has been introduced, *Pr(end effect)* is the conditional probability of occurrence of failure given the cause has been introduced and *Cost* is the financial consequence of the end effect of that failure. In terms of the cost breakdown structure discussed in Chapter 4, *Pr(cause)* can be related to the introduction of potential failure modes and *Pr(end effect)* relates to failure mode identification and *Cost* is failure mode mitigation. According to Equation 23 there are no costs associated with the introduction and identification of potential failure modes. The scenarios imply that the end effect is unexpected and the cost associated with the end effect is reactionary (i.e. worst case); design decisions are prioritised based on the rank of the expected cost. The calculation of the expected cost of the failure scenario requires some very specific data in the form of the probability that a failure cause is introduced, which may be difficult to obtain. When considering potential failure modes, however, this probability is known to be Pr = 1 as the existence of a potential failure mode is a consequence of specifying a functional requirement.

The scenarios assume a probability of detection, which may or may not reflect the ability of the organization to discover failures. However, there is no apparent consideration of the ability with which the failure cause is removed or the how the potential failure mode is mitigated.

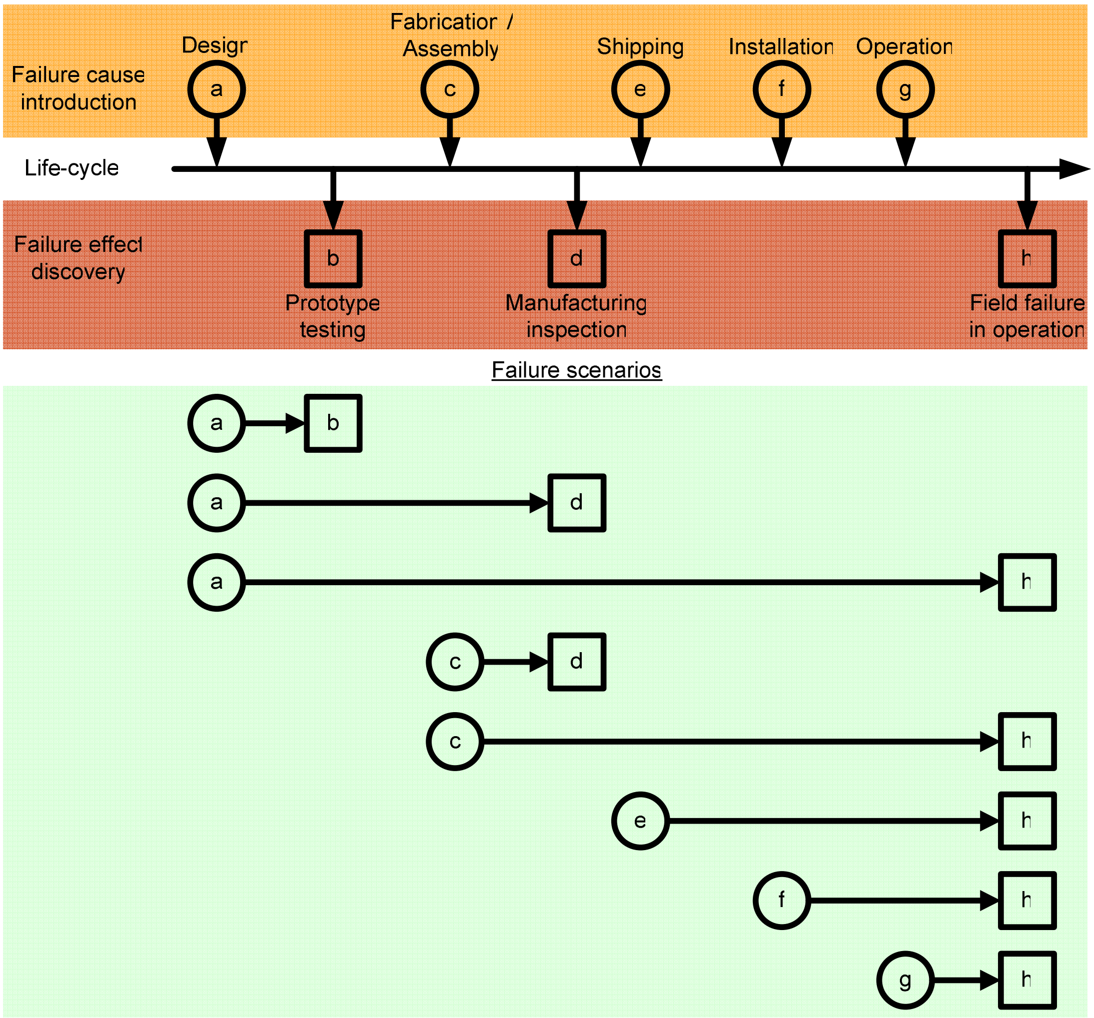

Figure 5-1: Failure scenarios, modified from Kmenta and Ishii (2004).

5.3. *Fault Tree Analysis*

Fault tree analysis (FTA) is a deductive method that graphically represents the conditions or factors causing or contributing to the occurrence of an undesirable (failure) event. This is a good method to determine the failure mechanism(s) of the failure mode and improves understanding of the physics of failure. Fault tree analysis can commence early in the design stage and progress concurrently with the design process, growing with the increasing detail of the design (BS 5760-7, 1991). Fault trees are ‘failure space’ models that describe a system in terms of how component failures lead to system failure (Gough *et al*. 1990). As such a fault tree is constructed, as follows, to describe the flow of events that lead to the occurrence of the top event (EN 61025, 2007):

1. Define the scope of the analysis including the system definition, analysis objectives, detail and any assumptions;
2. Clearly define the top event;
3. Identify the immediate cause event(s) necessary and sufficient for the top event to occur;
4. Define the relationship of the immediate event(s) to the occurrence of the top event and represent by a logic gate;
5. Repeat the procedure of defining immediate causes until the basic event is identified or there is insufficient information available to further expand the event causes;
6. Evaluation of the tree is either numerical, to define the hazard rate of the specified top event, or logical to define the cut sets or minimal cut sets for the top event.

The primary strength of fault tree analysis is through the identification of the causes for specified unwanted events. The method used in constructing a fault tree is often used in both common cause failure and root cause failure analysis. Fault trees are often used to analyse specific events prioritised by other, less detailed, analysis techniques. For example, FTA can be used to define the failure mechanism for failure modes identified during a FMECA or to determine the hazard rate of the component parts of a reliability block diagram.

Through identifying how a system can fail, fault trees define the system cut sets. Cut sets can be used to (Gough *et al.* 1990):

1. Determine the causes of system unavailability;
2. Determine the importance of each components;
3. Perform sensitivity analysis; and
4. Verification of the system model.

The ability to perform detailed assessment of singular top events means that FTA may not be suited to the analysis of entire systems. Indeed, as fault trees are a representation of Boolean logic, it is assumed that the events are binary (Bedford and Cooke, 2001); that is, the fault tree accommodates events that have two outcomes (i.e. success or failure) and therefore assessing partial or degraded failure modes can be difficult. Furthermore the logical dependencies between events can become difficult to represent, for a complex system, without detailed knowledge of the system (Gough *et al*. 1990). In addition, the evaluation of fault tress may require further techniques (for example, PAND gates require Markov analysis) and or software support.

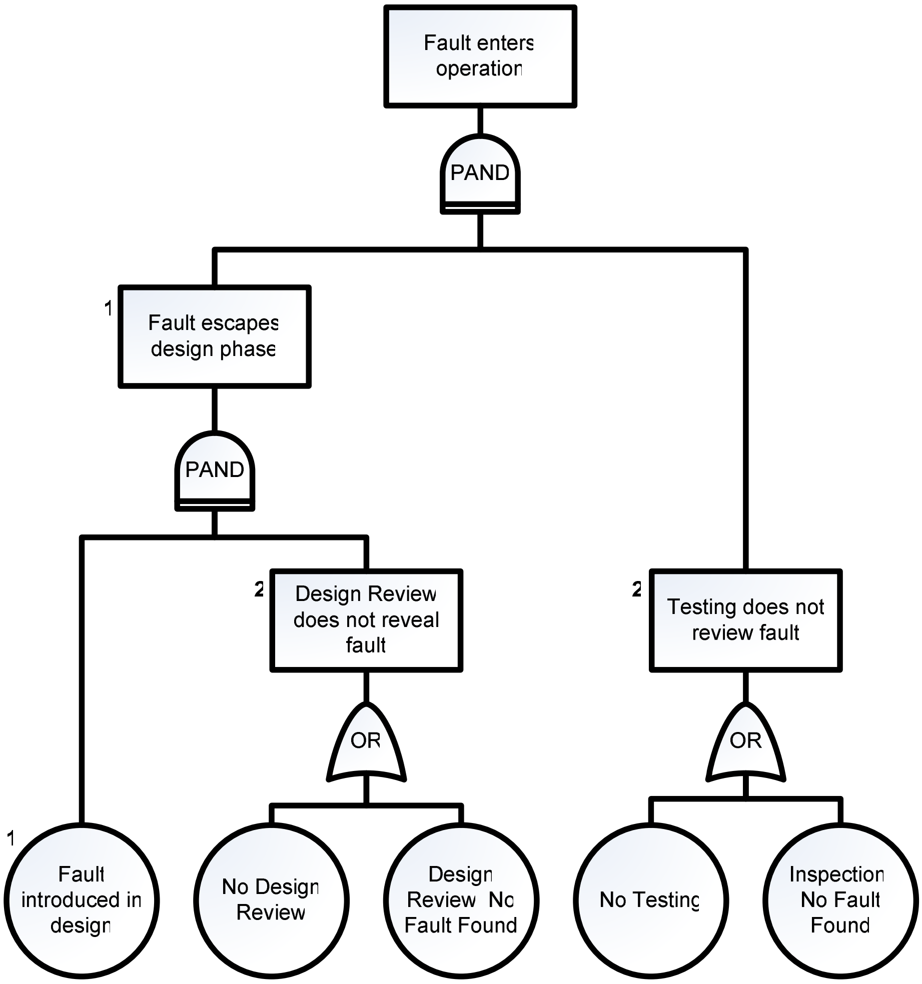

Figure 5-2: Example fault tree

Figure 5-2 indicates a simplified fault tree for how a design fault might be introduced during the design phase, escape detection and enter operations. The use of PAND gates indicate that a specific sequence is required (signified by numbering the input events to the gate) but it does not, and cannot, reflect the cyclic nature of the design phase. Furthermore, the probability of no fault found is dependent on existence of faults in the design (it seems valid to assume that the probability of not fault found will be higher when there is no fault to be found), which is not reflected in the tree; although conditional events can be incorporated into a fault tree, what seemed like a simple fault tree is actually fairly complex and awkward to evaluate. For these reasons FTA may not be suited to modelling project phases prior to operation.

Little research has been directed specifically at the application of FTA to life cycle cost based decision making, perhaps due to the fact that fault tree analysis is used to identify how specified unwanted events occur. That is, the events have already been identified as unwanted (in terms of cost) and FTA often serves as an input to systems level analyses. Clearly, FTA can facilitate the provision of a set of possible solutions, whose cost-benefit can be assessed to determine the optimum response. Latino and Latino (2006) use FTA to identify the root cause of persistent failures and suggest solutions; the return on investment used to determine the preferred solution is independent of the fault tree analysis.

5.4. Decision/Event Tree Analysis

Whereas fault trees aim to identify the cause of a specified unwanted event, event trees start with an initiating event and propagate through the system by considering all possible ways that the event can influence the behaviour of the system (Bedford and Cooke, 2001). This supports the identification of mitigation actions, which can prevent consequence escalation of a failure event. If the initiating event is a decision, then the tree may be referred to as a decision tree.

Event trees can identify any number of events resulting from the initiating event and allows the sequential modelling of events. There is no standard methodology for event tree analysis; however, a generalised procedure is provided here (from Billington and Allen 1983; Fjellheim and Fiksel, 1990):

1. Define the scope of the analysis, including: the definition of the system, the agreed level of analysis detail and any assumptions made;
2. Identify the initiating event to be assessed;
3. Identify all credible and immediate outcomes from the initiating event until the final outcome is identified;
4. For each immediate event assign a conditional probability with which they occur and consequence;
5. The numerical assessment of the event tree considers the cumulative expected consequence of each branched path defined;
6. Identify and recommend appropriate mitigations, review the event tree with these mitigations in place.

As event trees trace the propagation of an initiating event, they are particularly strong in conjunction with fault tree analysis in safety assessments and accident scenarios (Siu, 1994). They are also a fundamental part of the visualisation of decision models (i.e. decision trees) and can be used to model system reliability analysis. However, event trees can become unmanageable when dealing with large or complex systems and become time consuming when evaluated manually. For example, a system comprising 50 components, which have two states (success or failure) the subsequent event tree has 2^50 end states. As indicated by Siu (1994), event trees are best suited to modelling individual scenarios rather than dynamic systems or whole life assessments; however, event trees do give credence to the possibility that events can observe multiple outcomes (e.g. success, failure, partial failure).

Event trees are inherently related to cost based decision making due to their inclusion in decision trees. Many authors used decision trees to inform traditional risk based decision making (Roberts, 1999; Koller, 2000; Phelps, 2004) and real options[3] (Herath and Park, 2002; Boute *et al*. 2004; Lund, 2000; Trigeorgis, 2005). Decision trees provide a sound basis for formalising the decision structure and analysing the possible outcomes as each branch of the tree has an assigned probability and consequence of failure.

Event trees are suited to modelling the decision making process rather than addressing specific design for reliability issues. As such event trees may be more valuable as a tool assess the potential value of the other analyses.

5.5. Reliability Block Diagram

Reliability block diagrams (RBD) provide a graphical representation of a system’s reliability logic. They are constructed as a ‘success space’ model that describes a system in terms of the component successes required for system success (Gough *et al.* 1990). An RBD can also be used to describe the relationship between component failure and system failure (Willingham and Forster, 1990). Analysis of an RBD includes the identification of cut sets and the prediction of system reliability and probability of failure.

Reliability block diagrams look much like process flow charts or functional flow charts; however, because they describe the system reliability logic, they do not necessarily reflect how a system functions (Gough *et al*. 1990). Construction of an RBD is as follows (BS 61078, 2006):

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[3] Strictly speaking, real options are often presented as a binomial lattice which differs from a decision tree as certain event outcomes merge together as their result is the same; however, they are constructed with much the same methodology although their evaluation differs.

1. Define a state of system success;
2. Break the system down into the smallest number blocks that reflect the logical behaviour of the system and are statistically independent;
3. Define a start and end node;
4. Arrange the blocks to form a success path between the start and end node.

Compared with the other graphical methods discusses (fault trees and event trees), the reliability block diagram is the best method for graphically representing complex system reliability logic, as such it is often used as the basis of RAM analysis (below). However, the methodology requires comprehensive understanding of the way the system operates and can only treat one functional mode at a time.

The ease with which the system reliability is calculated depends on the system logic. For example, the reliability of a system whose constituent parts are logically arranged in series is calculated by taking the product of the reliabilities of those constituent parts. Conversely, the probability of failure for a system whose constituent parts are logically arranged in parallel is calculated as the product of all the probabilities of failure of those constituent parts. The reliability of systems that observe components logically arranged in both series and parallel is calculated through reduction; reduction presents a group of blocks (i.e. a group of series blocks or a group of parallel blocks) as a single block with a new reliability based on the rules stated above. This process of reduction can become quite complicated involving calculations which are prone to error (when completed manually) for large or complex systems. In addition, a system's functional architecture may observe numerous functional states that have to be resolved separately in the RBD, which can lead to time consuming calculations and when simplified (through reduction) may not return accurate results. The use of simulation packages for the assessment of reliability is discussed further in section 5.6. The sole purpose of a reliability block diagram is essentially that of a visualisation tool, which provides a logical framework for the techniques discussed below (RAM analysis and importance/sensitivity analysis).

5.6. Reliability Availability Maintainability Analysis

RAM analysis provides an assessment of the overall system performance over the operational phase of the life cycle. Its application during design can support the definition of reliability requirements (API RP 17N, 2007; BP, 2007b; Strutt *et al.* 2007), develop the maintenance strategy (Hall, 2006; Cockerill and Lavoie, 1990) and assess design alternatives.

There is no standard procedure for conducting RAM analysis as the term is often used as a collective noun for reliability, availability and maintainability analyses (ISO 15663-2, 2001; Smith, 2001). In addition, RAM analysis is often unique to the decision and system being assessed. Here, RAM analysis is taken to mean a systems analysis that considers the effect of a reliability and maintainability strategy on the overall system availability over the operational life of the system. Hall (2006) proposes a generalised approach for conducting RAM analysis:

1. Define the objectives and scope of the analysis;
2. Collect and review the system information;
3. Review data and assumptions used to develop the system model;
4. Construct, review and validate the RAM system model;
5. Collect model results and perform sensitivity analysis;
6. Document results and recommendations.

RAM models tend to be evaluated using Monte Carlo simulation techniques to assess the effect of input parameter uncertainty on the behaviour of the system; the steps required to perform Monte Carlo simulation are (Ayyub and McCuen, 2002):

1. Define system using a model;
2. Generate of random numbers;
3. Generate of random variables;
4. Evaluate model;
5. Perform statistical analysis on resulting system behaviour;
6. Review simulation efficiency and convergence.

RAM analysis goes beyond conventional RBD analysis to support a wide range of operational decisions during design. These decisions are often based on more practical decision metrics, such as production availability. Due to the added complexity of the input data and case specific assumptions, manual evaluation of the RAM model is not possible (Murphy *et al.* 2005). However, there is an array of commercially available software to perform RAM analysis, these include;

- OpSim (Relex, 2007)
- BlockSim (Reliasoft, 2007)
- AvSim+ (Isograph, 2007)
- RAPTOR (ARINC, 2007)
- MIRIAM Regina (CognIT, 2004)
- PLASMA (SimEng, 2007)
- MAROS (DNV, 2007)

Brall *et al.* (2007) provide a comparison of a selection of software packages over a variety of different reliability block diagrams, simulation lengths and number of trials. The authors reveal some inconsistencies in some of the test case results indicating that different software packages are iterating from different directions (Brall *et al.* 2007). This begins to raises concerns about the effort required to get accurate results for complex systems, which could present a significant barrier to active implementation of reliability software in the support of subsea projects.

RAM analysis is a very data intensive application and the acquisition of this data may be the rate determining step for RAM analysis; Sandtorv *et al.* (1996) indicate that up 30% of a reliability assessment is consumed by data collection. The time taken to actually run the simulation and evaluate the model is relatively short in comparison; Brall *et al.* (2007) record that evaluating complex systems can take in excess of one hour for some software packages. The time taken to perform the analysis is dependent on a number of variables such as the size of the RBD, the simulation length, number of iterations and specification of the computer running the analysis. Of fundamental importance is the ability to achieve convergence of the results; convergence is a measure of the stability of the results distribution statistics (i.e. extent to which the result distribution changes with additional trials or iterations) (Palisade, 2002). The number of iterations required to produce stable results ultimately lies with the tolerance of the decision maker (Murphy *et al.* 2001).

Of the reliability techniques discussed, RAM analysis is the most suited to cost collection over the operational life cycle. Any event that triggers lost production and or necessitates intervention also incurs a financial cost. As ‘conventional’ RAM analysis already simulates these events for the purposes of calculating system availability and reliability metrics it is a natural progression to extend RAM analysis to simulate the cost of operations. Indeed, many of the software package listed above include LCC modules while others can produce output files with sufficient data for post processing.

5.7. Sensitivity/Importance Analysis

Sensitivity or importance analysis is not usually conducted as singular analysis in isolation; instead, it is a technique often applied as a constituent part of the other analyses already mentioned. This is because the analysis is usually deployed to determine the effect of the input variables on the output metrics. The term importance usually refers to a ranking of the extent to which an individual component, basic event or cut sets contributes to the top event or system failure (Smith, 2001). The conventional reliability importance measures, which are usually applied to FTA or RBD, are described below (Bedford and Cooke, 2001);

1. The Fussel-Vesely importance of an item is the conditional probability that the item has failed given that the system has failed.
2. The Barlow-Proscham importance of an item is the average number of system failures up to a specified time cause by that component failure.
3. The Birnbaum importance of an item is the probability that item failure causes system failure.

Sensitivity analysis has a boarder scope of application compared to importance analysis as it considers the effect of all input variables on the output (performance) metric. Sensitivity to a variable can be presented as a regression or correlation co-efficient or graphically.

Sensitivity or importance analysis is the primary method for identifying the components that, if improved, could result in the greatest improvement in the overall system performance. Selection of an appropriate sensitivity or importance measure is important as conventional importance measures can be quite misleading. For instance, the Barlow-Proschan importance of a component is the average number of system failures up to a point in time caused by the failure of the component in question. This means that, for example, a frequent failure (e.g. one a week) of a topside component which causes shutdown for an hour at a time is more important than a subsea failure which occurs once a year but results in shutdown for two months. In reality a subsea failure may have a greater impact on the system's financial performance due to a prolonged reduction in the production capacity and the high cost of intervention. Traditional reliability importance analyses are more suited to component level design whereas project life cycle cost based decision making requires risk based sensitivity analysis. When considering a decision framework for adding to project value through reliability, sensitivity analysis provides a suitable platform for establishing potential benefit or even calculating a reliability budget.

5.8. Traditional system reliability assessment criteria

The tools and techniques discussed evaluate a component or system in terms of its ability to perform a function and the consequences should this ability cease. At the component level, reliability and maintainability is normally the metric of choice. At the system level availability is more appropriate as a function of the reliability and maintainability of the system's component parts.

Reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval (IEC 60050(191), 1990) and it usually calculated as a function of time and a hazard rate. For a component that observes a constant hazard rate (i.e. random failures) the reliability, R, is calculated according to Equation 24,

$$R = \exp(-\lambda t) \qquad \text{Equation 24}$$

where λ is the hazard rate and t is the time. For a component that observes a hazard rate that varies with time (i.e. early life failure or wear out failure) the reliability can be calculated according to a two parameter Weibull function according to Equation 25,

$$R = \exp(-t/\eta)^{\beta} \qquad \text{Equation 25}$$

where η is the characteristic life parameter and β is the characteristic shape parameter. In practice Equation 24 and Equation 25 are of little immediate value in terms of life cycle performance as they just represent a survival probability over a specified time period. That is, the equations only consider the probability of a single failure; in terms of operational performance, the failure pattern over the operation life is of more interest. These equations, however, are very important as the basis of generating the failure patterns required for discrete event time to failure simulations.

The assumption that a component observes random failures is traditionally reserved for electrical components; mechanical equipment is more susceptible to wear out characterised by an increasing likelihood of failure as the service life increase. However, the majority of data provided for the offshore and subsea industries assume all data reflects a constant hazard rate when expert opinion may suggest otherwise.

Maintainability is representative of the ease with which the system and be kept in or returned to the operational state. Maintainability can be defined as the probability that a failed item is restored to the operational state within a given period of time when the repair action is performed with the prescribed procedure (Smith, 2001). This definition, however, does not consider the ease with which a system is kept in the operational state. As a metric, maintainability is often quoted in terms of the mean time to repair (MTTR). The mean time to repair is usually reserved for the active repair time and does not necessarily consider the total downtime associated with a failure.

Availability reflects the combined effect of reliability and maintainability on a system's planned operational time and can be defined from a number of perspectives. The formal definition of instantaneous availability of a component is the probability that the component is in a state to perform its required function under given condition at a given instant of time assuming the required external resources are provided (IEC 60050(191), 1990). The steady-state availability of a component, A, is calculated according to Equation 26,

$$A = \frac{MUT}{MUT + MTTR}$$

Equation 26

where MUT is the mean uptime (MUT=MTTF if the component operates continually) and MTTR is the mean time to repair. That is, the steady state availability as defined as the ratio of uptime to total time (and unavailability is one minus the availability). This equation assumes a constant hazard rate and implies a constant production rate; steady state availability ignores the occurrence of early life and wear out failure and oil and gas production systems observe a dynamic (non-constant) production rate. The alternative is the production availability, A_p, which is the ratio of actual production to planned production; this may be defined in terms of production volume, according to Equation 27, or time, according to Equation 28,

$$A_p = \frac{\phi_a}{\phi_p} \qquad \text{Equation 27}$$

$$A = 1 - \frac{ETPLT}{MPTA} \qquad \text{Equation 28}$$

where Φ_a is the actual produced volume, Φ_p is the planned produced volume, *ETPLT* is the equivalent total production loss time and *MPTA* is the maximum production time available. To accommodate partial failure resulting in degraded performance (i.e. reduced production capacity), the equivalent total production loss time converts the time in a state of reduced output to the equivalent time that the system is in the zero production state. For example, suppose one of four subsea wells, all operating at full capacity, did not produce for one day (i.e. the system was operating at 75% capacity), the equivalent total production loss time is a quarter of a day (i.e. the losses associated with one well down for one day is equivalent to the losses of the entire system down for a quarter of a day). Conversely, if there is spare capacity in the system that can accommodate failure, the equivalent total production loss time may be reduced. Suppose the same four wells only operate at 75% maximum capacity and one does not produce for a day, if the remaining three wells could increases their capacity to 100% for that day then there is no lost production (i.e. output from four wells at 75% equals three wells at 100% and hence the equivalent total production loss time is zero). This introduces greater management flexibility by introducing the effect of operability into the availability metric.

5.9. Chapter Summary

This chapter has reviewed the primary systems reliability analyses that can be employed as part of reliability and technical risk management. Each analysis types observe strengths and weaknesses depending on it application. Many of the weaknesses are mitigated through the joint application of analyses as synergies exist between analysis types. This is clearly an important consideration when planning design for reliability activities.

The most common tool is failure modes and effects (criticality) analysis, which serves a primary purpose of identifying and prioritising potential failure modes. These failure modes may be identified through the construction of a reliability block diagram, which graphically represents the system reliability logic. Criticality analysis, used to prioritise failure modes, ranks failure modes based on a risk priority number, which has been the subject of much criticism in the literature. The RPN could be replaced by life cycle costs, the calculation of which requires RAM analysis to accurately capture the cost accumulation over the operational phase. Replacing the RPN with LCC prioritises potential failure modes based on cost accumulation, with sensitivity analysis used to identify where potential improvements to project value could be made. Having prioritised these failure modes, FMECA is not suited to identifying the root cause of the failure modes; this weakness of FMECA is mitigated through the application of fault tree analysis, which identifies the failure logic for unacceptable failure modes.

Of the tools/techniques reviewed, event tree analysis does not feature within the synergies discussed above. That is not to say it is unimportant. Event trees are beneficial as they can be used to determine the value of information and control. As the purpose of reliability analyses is to acquire information, event trees could play an important part in the planning process. The value of control and information are discussed here with the aid of a hypothetical decision scenario.

Value from control is generated through actively influencing the outcome of an event (de Klerk, 2001). Consider a decision (Figure 5-3) were a risk neutral decision maker can choose to invest in improved reliability by introducing redundancy; there is an incentive payment of £300,000 should the project succeed, it is assumed that the penalty for failure does not differentiate the decision. Suppose the probability of project success, with no extra reliability effort, is P=0.607 then the expected value of accepting the base case reliability is approximately £182,000. If it is assumed that the introduction of redundancy to the system, at the cost of £60,000, can increase the probability of project success to P=0.845 then the expected value from investing £60,000 to introduce redundancy is approximately £193,600. The value of controlling the reliability of the system is worth (£193,600 - £182,000) £11,600 to the risk neutral decision maker.

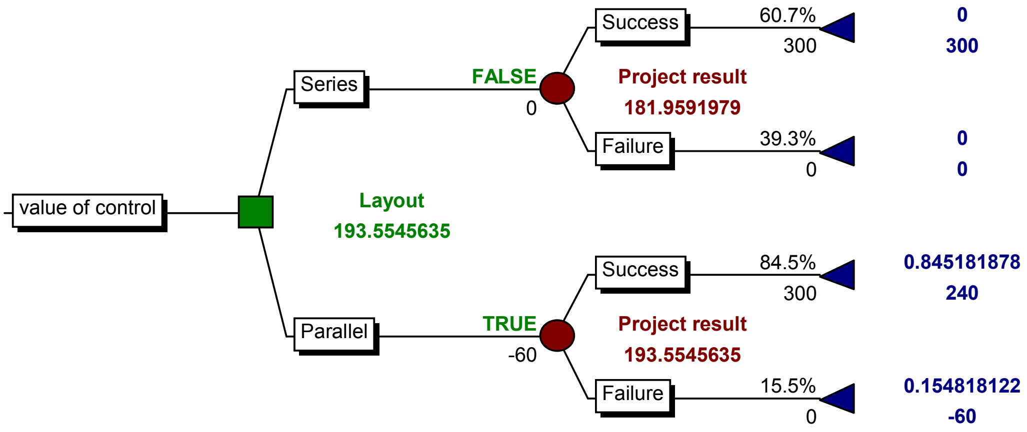

Figure 5-3: Simple reliability investment decision.

The value of information is defined as the worth to a decision maker of having information relating to the outcome of an uncertain event (de Klerk, 2001). Expanding the decision described in Figure 5-3, suppose the decision maker is uncertain as to the reliability of the component parts of the system; depending on the supplier (over which the decision maker has no prior knowledge) the component observes a relatively high reliability or a relatively low reliability. The component characterised by relatively low reliability observes a probability of P=0.607 that it will survive the mission while the component characterised by relatively high probability observes a probability of P=0.779 that it will survive the mission. Prior to knowing if the component parts of the system are of relatively high or low reliability, the decision maker has to choose whether or not to accept the base case reliability or introduce redundancy, at a cost of £60,000, and improve the system reliability performance. A rational risk based decision maker would choose to invest in the redundant system, observing an expected value of £209,400 (Figure 5-4). If the decision maker was furnished with perfect information regarding the reliability of the components prior to deciding whether or not to invest in reliability then the decision would change; Figure 5-5 indicates that if it was known with certainty that the component reliability was relatively high, then the risk neutral decision maker would opt for the base case series system. If, however, the component reliability was relatively low then the decision maker's preference is for the parallel system. The expected value of this decision under perfect information is approximately £213,600.

The value of perfect information is the difference between the decision with perfect information and the decision under uncertainty. In this case, the value of perfect information is £213,600 - £209,400 = £4,200 and the decision maker should pay not more than £4,200 to acquire the information relating to the reliability of the components. In reality it is unlikely that perfect information can be acquired; and thus the value of imperfect information is of more immediate interest. The expected value of imperfect information is the expected payoff with imperfect information less the expected payoff under uncertainty (Mian, 2002).

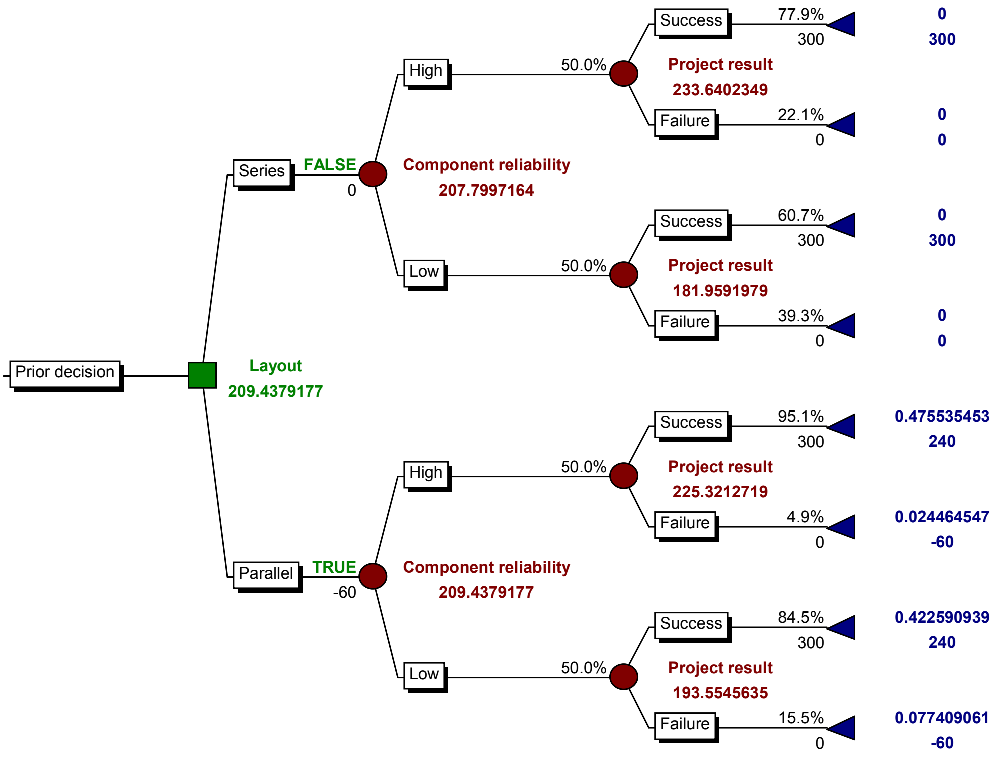

Figure 5-4: Expanded decision with uncertain component reliability.

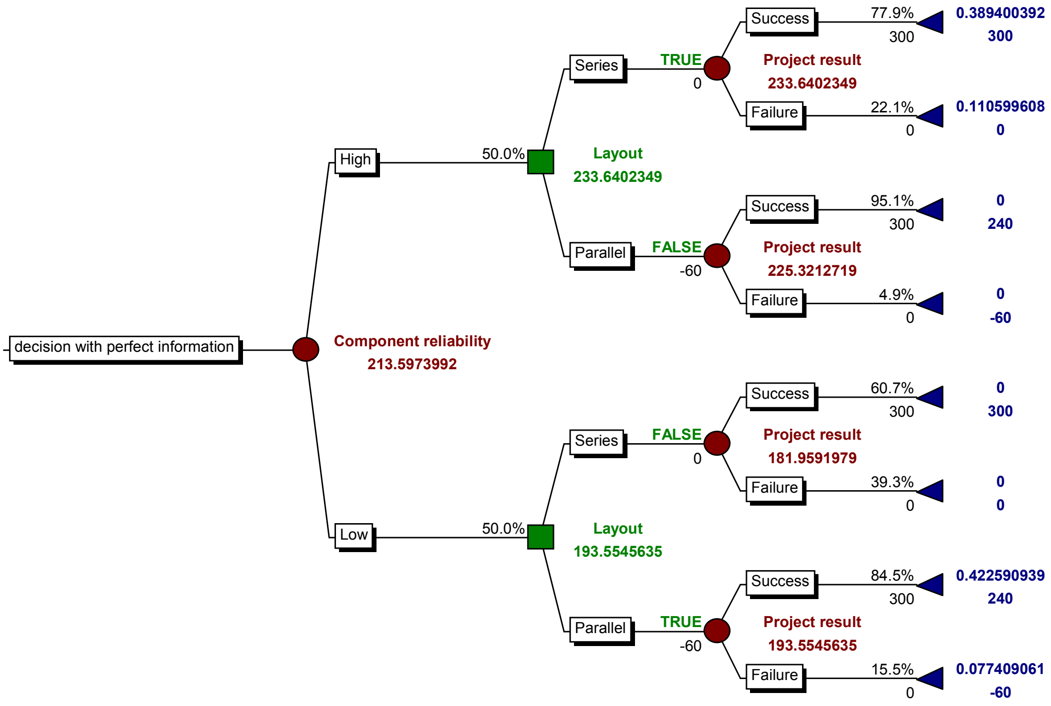

Figure 5-5: Figure 5-4 decision with perfect information.

The example in Figure 5-4 indicates a decision under uncertainty regarding the selection of a system layout given a prior perception of the component reliability; perfect information (Figure 5-5) indicates that if the component reliability is relatively high, then a series system is preferable but if the component reliability is comparatively low a parallel structure is preferable. Given the uncertainty about the component reliability a risk neutral decision maker maximises the expected value by choosing the parallel system layout.

Suppose the decision maker is given the option to test the components in order to gain better clarity of the reliability; how much should be paid for this information? Reliability engineers estimate that the conditional probability of passing the test given that the component has a high reliability is $P(Pass|R_{High}) = 0.85$ and that the conditional probability of passing the test given that the component has a low reliability is $P(Pass|R_{Low}) = 0.1$. Assuming complete uncertainty about the prior probability of the component's reliability, the total probability of passing the reliability test is the sum of the joint probabilities of the prior probability of the component's reliability and the conditional probability of passing the test (Equation 29).

$$P(Pass) = P(Pass|R_{Low}).P(R_{Low}) + P(Pass|R_{High}).P(R_{High})$$

Equation 29

$$0.475 = (0.1 * 0.5) + (0.85 * 0.5)$$

Similarly, the total probability of failing the test is calculated according to Equation 30,

$$P(Fail) = P(Fail|R_{Low}).P(R_{Low}) + P(Fail|R_{High}).P(R_{High})$$

Equation 30

$$0.525 = (0.9 * 0.5) + (0.15 * 0.5)$$

where $P(Fail|R_{Low})$ is the conditional probability that the test is failed given a low reliability component and $P(Pass|R_{High})$ is the conditional probability that the test is failed given a high reliability component.

The conditional probability, $P(A_i|B)$, of a prior probability, $P(A_i)$, given the result, B, of an event is updated according to Bayes formula (Equation 31),

$$P(A_i|B) = \frac{P(B|A_i).P(A_i)}{\sum_{i=1}^{n} P(B|A_i).P(A_i)}$$

Equation 31

where $\sum_{i=1}^{n} P(B|A_i).P(A_i)$ is the total probability of the result of an event. For example, the probability of the component being of high reliability given that the test has been passed is updated according to Equation 32.

$$P(R_{High}|Pass) = \frac{P(Pass|R_{High}).P(R_{High})}{P(Pass|R_{High}).P(R_{High}) + P(Pass|R_{Low}).P(R_{Low})} \qquad \text{Equation 32}$$

The updated probabilities of the component reliability given the result of the test are shown in Figure 5-6. Note that the system layout decision changes depending on the outcome of the test; if the test is failed then the decision favours the parallel layout, if the test is passed then the series layout is preferred.

Figure 5-6 indicates that the risk neutral decision maker observes an expected value of £209,400 if the decision to test the reliability is not made. If the decision maker chooses to test the reliability, at no cost, than the expected value increased to £212,400. The difference £212,400 - £209,400 ≈ £3,000 is the value of imperfect information, in this case, offered by testing the component reliability. That is, the decision maker should reject the decision to test if it costs more than £3,000.

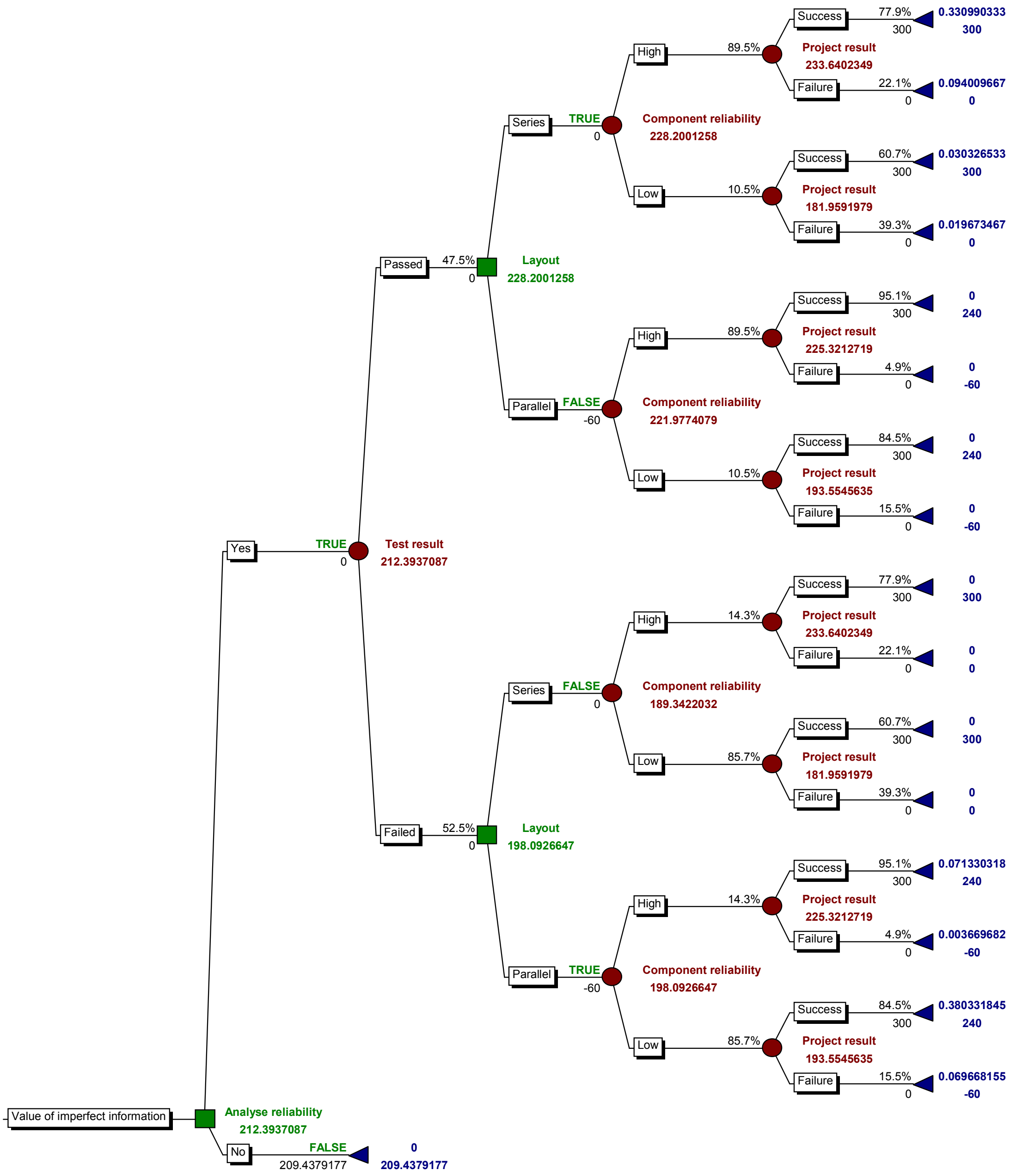

Figure 5-6: Value of imperfect information (no analysis payoff is payoff from Figure 5-4).

The example above demonstrates how reliability analyses can generate financial value through the provision of information. However, this value can only be realised if the analysis has the ability to alter a decision. The selection and planning on these analyses, therefore, should be based on the perception that any information provided by analyses could alter the current approach to reliability and technical risk management based on potential results and the timely acquisition of data. Any planning tool should take these issues into consideration. In terms of a life cycle costing model, analyses accumulate cost within the CAPEX cost driver but may reduce cost accumulation in the OPEX cost driver. Their influence, therefore, must be made transparent during the planning process and as such a decision making process should indicate the potential cost benefit of performing such analysis. That is the planning process is both risk based in terms of the inherent technical risk within the project and the risk that the analysis does not generate value added information. The following chapter discusses the application of economics of reliability models to support the decision making process.

6. Economics of Reliability

6.1. Introduction

Product design and micro-economics share a common goal of achieving a competitive advantage. However, the methods by which they can be achieved are often opposed; it does not follow that the best product satisfies the economic goal of cost minimisation (Noble and Tanchoco, 1990). Therefore, the life cycle cost is often presented in terms of a key performance metric with the intent to assess the optimum cost-performance. The development of an economics of 'X' model can facilitate the identification of key cost driver elements and provide the basis for a cost-performance improvement process. The economics of quality (EOQ) has received significantly more attention in the literature compared to other economics of 'X' models. Naturally these economics of quality models provide a reference point for other economics of 'X' models to be developed through analogy.

Many different approaches to modelling the cost of quality have been proposed in the literature (Hwang and Aspinwall, 1996). Of the models proposed, variants of the prevention, appraisal and failure (Feigenbaum, 1956) model have received the most attention; Plunkett and Dale (1988a) provide a thorough critique of the numerous models that have been developed between 1963 and 1986, during which time this area received substantial attention. The authors concluded that many of the models were inaccurate despite there being sufficient collective knowledge to propose a reasonable hypothesis (Plunkett and Dale, 1988a) of the behaviour of cost as a function of quality.

Despite the proposal of a large number of theoretical models, there has been a lack of empirical studies presented in the literature (Hwang and Aspinwall, 1996). Difficulty exists in distinguishing and costing quality specific activities from good/essential engineering practice (Plunkett and Dale, 1988b). This problem is often attributed to the ambiguous definition of cost parameters (Chen and Tang, 1992). Furthermore, there is a pre-occupation with in-house costs (often excluding supplier's costs) that can become distorted due to the incorrect allocation of overheads (Plunkett and Dale, 1988b). In addition, Anderson and Sedatole (1998) argue that quality cost management is restricted by the focus on the capability of the manufacturing processes to consistently conform to the design specification rather than capability of the product's design specification to meet the needs and expectations of the customer. This chapter reviews the prevention, appraisal and failure (PAF) economics of quality models, their analogous development for design for reliability and their use as a decision support tool.

6.2. Prevention, Appraisal and Failure Model

The PAF model defines the total cost of quality as the sum of the cost of prevention, appraisal and failure. Although adopting a variety of meanings, quality costs are defined as those costs associated with poor quality (Gryna, 1999).

Prevention costs are the costs incurred in preventing shortfalls against specification from occurring (Hwang and Aspinwall, 1996). That is, prevention costs are those costs incurred to keep failure and appraisal costs at a minimum (Gryna, 1999). Prevention costs include design analyses such as FMEA and HAZOP studies (Johnson, 1995).

Appraisal costs are incurred when implementing a system with the intent of detecting non-conformances as soon as they occur (Hwang and Aspinwall, 1996) and determining the degree of the conformance to the quality requirement (Gryna, 1999). These costs include activities such as inspection and testing (Johnson, 1995; Hwang and Aspinwall, 1996; Gryna, 1999).

Failure costs are broken down into two sub-categories; internal and external failure. Internal failure costs are those resulting from a product failing to meet requirements before reaching the customer (Gryna, 1999), including; scrap, reworking and redesign (Johnson, 1995). External failures occur after delivery to the customer (Gryna, 1999); that is, they have avoided prevention and appraisal (Hwang and Aspinwall, 1996). Costs associated with external failures include warranties and loss of customer goodwill and revenue (Johnson, 1995).

6.2.1. Competing views of the economics of quality

There are two competing views regarding the economics of quality; the traditional acceptable quality level proposed by Juran and Taguchi and the more recent zero defects view of Schneiderman and Crosby (Love *et al*. 1995). The acceptable quality level model states that there exists an optimum amount of quality effort (and hence an acceptable quality level) that minimises the combined costs of prevention, appraisal and failure (Figure 6-1, Weheba and Elshennawy, 2004). This model has come under criticism from advocates of total quality management who argue that adoption of the optimum quality model means accepting of the inevitability of failure (Slack *et al*. 2004). The more recent view is that the optimum quality level occurs at 100% quality and that higher quality costs less (Figure 6-2, Weheba and

Elshennawy, 2004). This paradigm shift has evolved from increasingly automated processes which have made zero defects economically viable (Yasin *et al*. 1999).

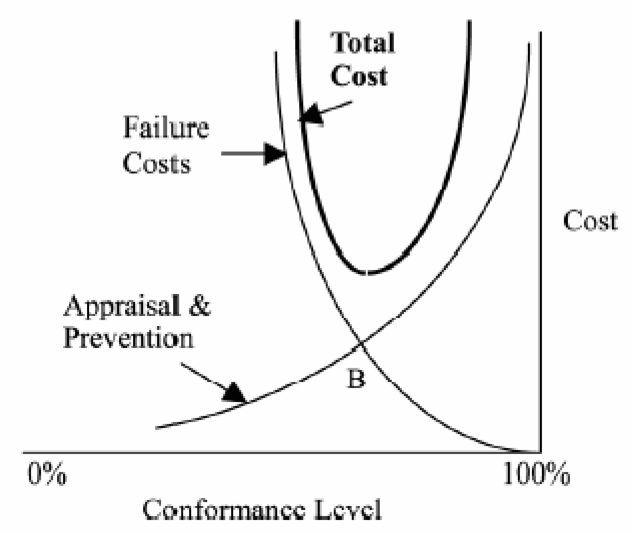

Figure 6-1: Traditional economics of quality model (Weheba and Elshennawy, 2004).

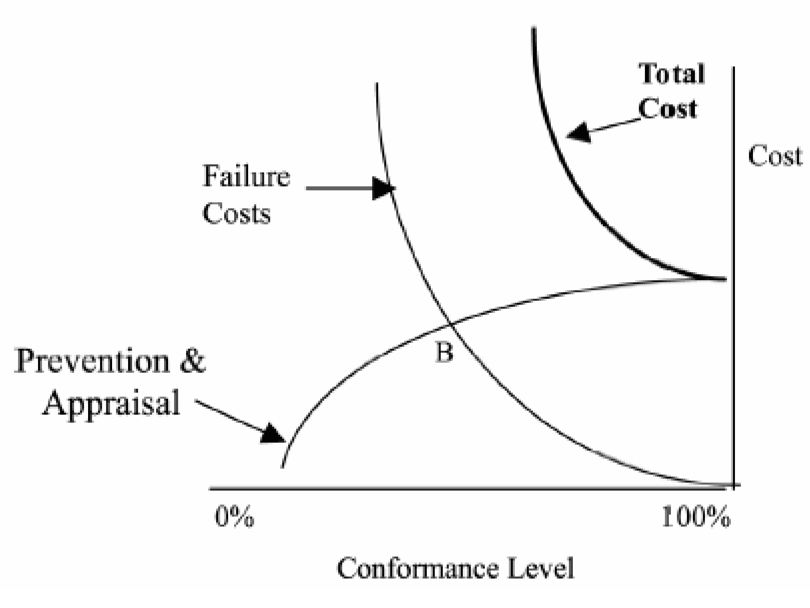

Figure 6-2: Zero defect economics of quality model (Weheba and Elshennawy, 2004).

6.3. *Economics of reliability*

The relationship between quality and reliability provides a basis for the development of an economics of reliability model through analogy with the EOQ model. O'Conner (2002) has extended the zero defect model to suggest that cost minimum occurs at the 100% reliability/quality level due to under-estimations in the cost of failure. In accordance with the zero defect philosophy, O'Conner argues that the total cost will decline as the reliability of a product increases to perfection. Other literature (Lakner and Anderson, 1985; Smith, 2001; BS 5670-4, 2003; Hecht, 2004) suggests that there exists an optimum cost-reliability (Figure 6-3), where the marginal increase in the cost to improve reliability equals the marginal saving in the cost of failure (IEC 60300-3-3, 2004). The economics of reliability models, however, differ from the EOQ models as the cost elements are not defined as parts of prevention, appraisal and failure cost drivers. Instead, the economics of reliability models tend to follow the life cycle cost drivers due to the concurrent development with life cycle costing.

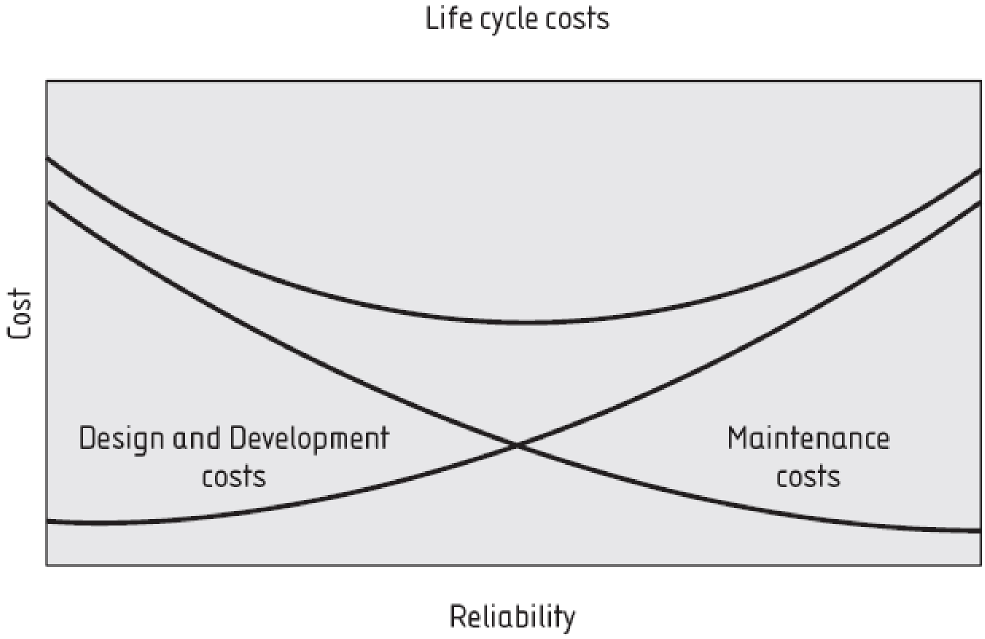

Figure 6-3: Optimal economics of reliability model (BS 5670-4, 2003).

6.3.1. The relationship of quality to reliability

The development of an economics of reliability model through the extension of EOQ models has a number of conceptual difficulties, some of which can be attributed to the vague relationship between quality and reliability. Reliability is often defined as the continuation of quality over time (Levin and Kalal, 2003) and quality defined as the degree to which a set of inherent characteristics fulfils requirements (ISO 9000, 2005). ISO 9000 also defines reliability as a temporal quality characteristic (ISO 9000, 2005), suggesting that equipment has to demonstrate reliability to achieve a level of quality.

More correctly, reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval (IEC 60050(191), 1990). While the implementation of reliability concepts, models and strategies may benefit from showing a strong affinity with the well established field of quality assurance and management it is important that oversimplifying the relationship between reliability and quality does not devalue their synergy.

Consider, for example, a normally distributed component strength and operational stress, the reliability index, β, is determined from Equation 33,

$$\beta = \frac{\mu_S - \mu_L}{\sqrt{\sigma_S^2 + \sigma_L^2}}$$

Equation 33

where μ_S and μ_L are the respective mean strength and mean operational stress and σ_S and σ_L are the standard deviations of the strength and stress, respectively. The reliability on demand, *R*, is determined from R=Φ(β), where Φ(•) is the cumulative distribution function of the standard normal distribution. Suppose a quality system exists that can deliver a component whose strength is known with certainty (i.e. zero defects). Then the reliability is determined from Equation 34,

$$\beta^* = \frac{\mu_S - \mu_L}{\sqrt{\sigma_L^2}} \qquad \text{Equation 34}$$

where β^* is the reliability index when the strength is known with certainty. Although β^* corresponds to increased reliability it is still not 100% because of the uncertainty associated with the load. Designers rarely know the operational loads with certainty and as such the reliability will always be less than 100% even with zero defects. Reliability is designed into a component or system. Quality management can only ensure that the design reliability is achieved. If the reliability is incorrectly specified during the design phase, then quality management can only serve to guarantee poor reliability.

Conversely, consider a system that utilises standby redundancy and suppose that the supplier of the switching mechanism does not implement a quality control system. The poor quality of the switching mechanism will only be exposed when the primary component fails requiring the redundant component to function. If the reliability of the primary component is such that the redundant component is not required during the mission time then the reliability of the primary component has masked the poor quality of the switching mechanism. That is the complete system has defects but the reliability of primary function could render this lack of total quality (zero defects) inconsequential.

6.3.2. Competing reliability functions reduce system reliability

Within a system there are often competing reliability functions as a result of technical practicality or mandatory requirements. ISO 13628-4 (1999) states that a subsea production tree requires at least one production master valve which operates on a failsafe closed basis. This requirement introduces a mechanism for the flow of hydrocarbons to be blocked. Table 6-1 (Modified from Rausand and Øien, 1996) indicates the functions and failure modes of a process shutdown valve. Introducing the function 'keep flow path open' introduces the potential failure mode 'flow path closes'. Unless the reliability of the keep flow path open function is unity then the mandatory inclusion of a production master valve reduces the system's ability to maintain the flow of hydrocarbons over the specified field life.

Table 6-1: Functions and respective failure modes of a process shutdown valve (Modified from Rausand and Øien, 1996).

Function	**Failure mode**
Close flow path on demand	Not closing at all Not closing completely Closing too slowly Closing too fast Improper operation
Keep flow path closed	Opening spuriously

Function	Failure mode
	Internal leakage External leakage
Open flow path on demand	Not opening at all Not opening completely Opening too slowly Opening to fast Improper operation
Keep flow path open	Closing spuriously External leakage Plugged

Another example for a subsea system might be through the inclusion of a high integrity pressure protection system (HIPPS). HIPPS are usually required when a new field development is tying into an existing processing facility whose pressure rating is below peak pressure spikes expected from the newly exploited reservoir. If the HIPPS records a specified high pressure then a safety shutdown valve is closed, halting the flow of hydrocarbons. As safety critical equipment, the ability of a HIPPS to function on demand is paramount and as such comprises more than one shutdown valve. If it is assumed that the HIPPS has two shutdown valves then the reliability block diagram logically arranges these valves in parallel for the shutdown on command function; both valves would have to fail to close on command for the HIPPS to fail to close on demand. As a further safety measure, shutdown valve are design to fail safe in the closed position. This introduces a failure mode that, should it occur, would cause the system's production function to fail. It follows that if only one valve is required to stop production on demand, then only one valve failing closed will halt production. The reliability block diagram, therefore, logically arranges these valves in series for the system's production function, reducing the reliability. Clearly the trade-off between safety measures and production reliability must be balanced, but the reliability of safety critical equipment takes priority. It is this priority that can potentially compromise the maximum reliability achievable for the system's revenue generating function.

6.3.3. Reliability growth function

Economics of reliability models do not differentiate between failures caused by residual and systematic weakness. Reliability growth models presented in the literature make a clear differentiation between failures caused by residual and systematic weakness (Walls *et al.* 2005). Systematic failures are a result of weaknesses in the system relating to inefficiencies in the product design and development process such as; product design, component selection and the manufacturing process (IEC 61014, 2003). These inefficiencies manifest as service life failures given exposure of the systematic weakness to particular conditions. Two examples of systematic failures in the subsea oil and gas industry have been listed in the SIREN database:

- A flowline was connected to the wrong valve due to incorrect correlation between the design drawings and the underwater identification markers on the hardware. As a result, when the valve supposedly connected to the flowline was opened, there was no oil on start-up (SIREN, 1995).
- The second example features a cathodic protection system designed for an ambient temperature of 4°C but the temperature measured on location was 70°C which resulted in accelerated wastage of the anodes (SIREN, 1999).

In both examples, the (near) failure occurred as a result of exposing the systematic weakness to certain conditions. In the first example the inefficiency in correlating the design and hardware markings was exposed when the open valve command resulted in the realisation of failure (i.e. there was no oil on start-up). In the second example, exposing the cathodic protection system to a greater operational temperature resulted in an accelerated failure mechanism. In contrast, wear out or random failures can occur as a result of residual weaknesses in the system. Residual weaknesses left in the system are due to the uncontrolled random variation of the system's constituent parts (IEC 61014, 2003) and the uncontrollable random variation in the operating stresses.

6.3.4. The relationship of reliability to maintainability

Although the economics of reliability models include maintenance costs, the cost reliability curves do not necessarily reflect the relationship between reliability and maintenance cost. Some economics of reliability models (Figure 6-3) imply that the maintenance costs only reduce as a function of reliability. While this implication can be true as improved reliability reduces the demand for maintenance, reliability can be improved at the cost of maintainability. Consider a system designed with a slot-modular architecture (Ulrich and Eppinger, 2000) where each functional component in the system is attached to a host with a specific interface. Any component can be changed out independently given failure without the need to replace the entire system. System reliability could be improved removing these interfaces and adopting an integrated design. However, the ability to replace individual functional components is lost (or at least greatly reduced) and the maintainability decreases, potentially increasing the cost per maintenance demand (and hence OPEX).

Combining life cycle cost and system availability performance acknowledges the trade-off relationship between the availability growth factors (reliability and maintainability) and life cycle cost (Hwang, 2005).

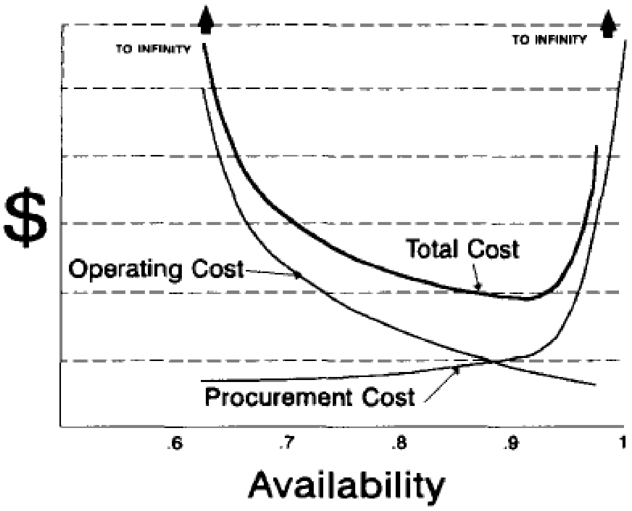

Figure 6-4: Optimal economics of system availability (Goble and Tucker, 1993).

Goble and Tucker (1993) propose an economics of availability model (Figure 6-4) where incident cost, $C_{INCIDENT}$, (part of the total operating cost) is determined according to Equation 35,

$$C_{INCIDENT} = (C_{RL} + C_{LP})U \qquad \text{Equation 35}$$

where C_{RL} is the repair labour cost per unit time, C_{LP} is the cost of lost production per unit time and U is the system unavailability. Equation 35 indicates that the conditional loss for a failure event is determined from the cost rates (C_{RL} and C_{LP}) and the duration over which the cost rates are incurred. By defining the system performance as a function of MTTR and MTTF, the economics of availability model allows more scope for cost reduction through both maintainability and reliability. This OPEX model is only applicable to individual components or simple systems. It is too much of a simplification to assume that, for complex systems, $C_{INCIDENT}$ observes a linear relationship with unavailability. However, availability provides a better indication of the system's ability to generate revenue compared with reliability (or quality[4]), which is not explicitly considered otherwise. Although reliability is of fundamental interest, ultimately it is the availability of a system that is critical to the economic performance of the facility (Center for Chemical Process Safety, 1998).

6.4. Chapter Summary

This chapter has provided a brief overview of the PAF economics of quality models that have spawned the analogous development of economics of reliability and availability models, due to the close relationship between reliability and quality. The economics of quality models have been criticised in the literature due to the inability to construct an accurate cost of quality model despite a wealth of data. One of the primary reasons for this is the difficulty in distinguishing quality management applications from what is otherwise considered good engineering practice; this is a significant reason for rejecting similar applications to reliability and technical risk management. Many of the systems reliability analysis techniques discussed in Chapter 5 (such as FMEA) are already considered within economics of quality models and cannot necessarily be singled out for inclusion in an economics of reliability model. This is actually beneficial when considering the ability of reliability analyses to generate project value.

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[4] Deming (2000) argues that increased availability is implied with increased quality as increased quality means less reworking, which leads to greater productivity and hence improved availability.

Firstly, if analyses are already considered part of good engineering practice, then the cost to perform the analyses can be split across project functions already employing them. The potential value generated from analysis increases by effectively reducing the associated implementation cost. Chapter 5 concluded by demonstrating the relative value of perfect and imperfect information; imperfect information is worth less to a decision maker than perfect information. As analyses can only provide imperfect information to the decision making process, reducing the implementation cost increases probability that the analysis will add value.

Secondly, it is not the intention of reliability and technical risk management to isolate the reliability function. Isolating the reliability function only serves to introduce barriers to implementation and increase scepticism of analysis output. Reliability should be considered part of best engineering practice and managed through decentralised decision making across all project functions.

While this is perhaps the most significant reason for rejecting an economics of 'X' approach to reliability and technical risk management, the graphical presentation is also problematic as it does not truly reflect the decision making scenario of certain expenditure traded off against uncertain cost or value improvement. The economics of 'X' models provide a point estimate of cost for all levels of performance, revealing no uncertainty about the cost performance. As the models do not state otherwise it is assumed that they represent the expected value.

The inapplicability of the expected value has been discussed by Todinov (2006a) with the use of simple counter examples. To counter the possible risks in decision making based on the expected value criterion, Todinov (2003) introduced the concept of potential losses, which expresses the distribution function of the consequences of failure and its variance. By generating a distribution of the losses, the decision maker is furnished with a broader view of what *could* happen rather than being constrained to the view of what is *expected* to happen. Potential losses describe the distribution of the consequences of failure and acknowledge that for a system of any given reliability there is uncertainty about the related cost of operation. It should be noted that there is also uncertainty about reliability performance and the stochastic nature of the cost during operation is exacerbated by the uncertainty of the input data.

A final issue relating to the inapplicability of the economics of 'X' models to the decision scenario is that decisions made during system design are normally comparisons of discrete options, rather than attempting to optimise across a continuum. For example, during concept selection, a number of bespoke system designs may be considered that cannot be rationalised within a single economics of reliability model. The implication that life cycle cost follows a continuum can only be reserved for individual components or simple systems and even then, reliability growth may be discrete rather than continuous (i.e. adding redundancy causes a step change in the reliability).

The rejection of economics of 'X' models is not to say that a guiding decision making criteria is unimportant or unnecessary. The decentralised decision making approach to reliability and technical risk management advocated here needs a central decision making framework in order to ensure consistent decision making and avoid conflicts of interest. The following chapter proposes a decision making framework to guide decentralised decision making.

7. Proposition of a Potential Value Framework

7.1. Introduction

This research has considered the need for a framework that can provide evidence to decision makers, early in the design decision making process, of the value of investing time and management effort in design for reliability activities during the design life cycle. A review of relevant literature has focused on concepts of life cycle costing and economics of 'X'. In reviewing this literature no application was identified that explicitly relate to the use of life cycle costing or economics of 'X' to justify reliability analyses, which is fundamental to the application of reliability and technical risk management strategies proposed in API RP 17N (2007) and ISO 20815 (2007). However, the literature has identified many important aspects to be considered when constructing a support framework for planning reliability analyses. Along with the basic requirements established as part of the research objective, the features (as identified from the literature) that should be included within the framework are as follows:

- Support the implementation of a reliability and technical risk management strategy such as that proposed in API RP 17N;
- The ability to support the planning process;
- Links decisions in design to operational performance;
- Support discrete option comparison decisions;
- Consider both systematic and residual weakness (i.e. incorporate a reliability growth model);
- Assume the prior existence of systematic weakness;

- Consider the ability with which weaknesses are mitigated;
- Reflects uncertainty in cash flow (OPEX) performance;
- Be able to identify value improvement opportunities;
- Have the ability to allocate budgets for reliability improvement;
- Assess multiple investments in reliability improvement; and
- Support decentralised decision making.

This chapter constructs a reliability value framework to address this need. The framework defines a potential reliability value index employed as the overriding decision metric and generates a breakdown structure to support the decision making process.

7.2. The reliability value index

Functional value can be defined as a measure of the cost required to supply the desired function (Park, 1999) and can be measured according to Equation 36 (Dejmek and Ford, 1997).

$$\text{Value} = \frac{\text{Functional performance}}{\text{Cost}} \qquad \text{Equation 36}$$

Assuming a baseline functional performance, *P*, is achieved at cost, *K*, then the decision to invest in reliability analyses at cost, *Q*, is guided by the inequality in Equation 37,

$$\frac{P}{K} < \frac{P^*}{K^* + Q}$$ Equation 37

where P^* is the system performance measure after implementing the analysis and K^* is the resultant life cycle cost (excluding Q). If system performance is measured in terms of the change in service life cash flow, then the reliability activity adds value to a project when the inequality in Equation 38 is satisfied,

$$\frac{\sum_{n=1}^{n=life} \frac{\Delta C_{Fn}}{(1+r)^n}}{Q} > 1$$ Equation 38

where Q is the implementation cost for the reliability improvement activity, ΔC_{Fn} is the change in cash flow in the n^{th} year as a result of implementing the reliability analysis and r is the discount rate. Defining ΔCF(*strategy*)= $\sum_{n=1}^{n=life} \frac{C_{Fn}}{(1+r)^n}$ as the present value of the relevant cash flow as a result of a reliability investment, Q, then the reliability effort investment criterion is to invest when the reliability value index, *RVI*, satisfies the inequality in Equation 39.

$$RVI = \Delta CF(strategy) / Q > 1$$ Equation 39

There is a clearly a range of potential outcomes for *RVI* depending on how Δ*CF*(*strategy*) is influenced by the analysis; the intervals of particular note are outlined below:

- *RVI* > 1. The investment decision criterion has been satisfied and the improvement to the resultant cash flow is greater than the cost required to implement analysis. The investment in reliability effort should be made.
- *RVI* = 1. The cost to implement the reliability analysis is exactly equal to the present cost of the resultant cash flow.
- 1 > *RVI* > 0. The result cash flow is better than the baseline condition but the improvements are not justifiable at the cost of the analysis.
- RVI = 0. The resultant cash flow is no different to that of the baseline option and hence analysis is not influencing the decision making process.
- *RVI* < 0. The resultant cash flow is less than that observed from the original system. In this case the reliability improvement may be seen as forgoing greater value by implementing the strategy and the project value and should not be undertaken.

While the *RVI* metric is equivalent to the profitability index, its application to justify the implementation of reliability analysis has not been considered previously in the literature. The adaptation of the *PI* to form *RVI* considers the initial investment to be that of the reliability analysis, which is traded off against the resultant life cycle cash flow. Its analogy to the *PI* also means that *RVI* can be used to rank reliability analyses where projects have budgetary constraints.

7.2.1. Potential reliability value index

One of the highlighted shortfalls of the economics of 'X' model was the implied use of the expected value criterion. For non-repetitive decisions such as those observed during subsea development projects, the decision made is often not that of the expected value criterion

(Benedikt, 1993). This can be resolved by implementing a utility function. However, many decision makers are reluctant to use such decision analysis due to the information required to define the utility function (Moskowitz *et al.* 1993). The solution proposed here is to incorporate the concept of potential losses (Todinov, 2003) into the reliability value index.

The profitability index provides an indication of the margin of safety for an investment (Myddleton, 2000). It follows that the reliability value index also indicates the margin of safety for the reliability investment; however, this is only implied as the probability that the reliability value index satisfies the investment criteria is dependent on the distribution function of the reliability value index. In analogy with potential losses, the potential reliability value index describes the distribution function of the reliability value index (Equation 39) and its variance. By presenting the distribution of the component parts of the reliability value index, the probability with which the reliability investment satisfies the reliability value index decision criterion can be calculated using the stress strength interference model. Assuming a normal distribution for the investment cost and potential cost savings, adapting Equation 34 to the cost items defined in Equation 39 gives Equation 40,

$$\beta_{RVI} = \frac{\overline{\Delta CF}(strategy) - \overline{Q}}{\sqrt{\sigma^2_{\Delta CF(strategy)} + \sigma^2_Q}} \qquad \text{Equation 40}$$

where β_{RVI} is the safety margin for the reliability investment, $\overline{\Delta CF}(strategy)$ is the mean change in operational cash flow as a result of the mean analysis investment, $\overline{Q}$; $\sigma_{\Delta CF(strategy)}$ is the standard deviation of the change in operational cash flow and σ_Q is the standard deviation of the reliability analysis investment. In reality it is likely that the cost to perform analysis is known with certainty and thus Equation 40 simplifies to Equation 41.

$$\beta_{RVI} = \frac{\overline{\Delta CF}(strategy) - Q}{\sqrt{\sigma^2_{\Delta CF(strategy)}}} \qquad \text{Equation 41}$$

The probability that the reliability value index satisfies the investment criteria $P(RVI > 1) = \Phi(\beta_{RVI})$, where $\Phi(\bullet)$ is the cumulative distribution function of the standard normal distribution.

7.3. RVI model

Adopting the approach taken to model life cycle cost, the reliability value index is logically decomposed into RVI drivers and elements. A generic reliability value index breakdown structure is presented in Figure 7-1. The RVI breakdown structure adopts the same cost elements of failure mode identification and mitigation to differentiate the decision alternatives but applies them to all major RVI elements (CAPEX, OPEX and Revenue). As with other reliability growth models (Quigley and Walls, 2003), the prior existence of faults and or potentially unwanted failure modes is assumed and hence this cost element is excluded.

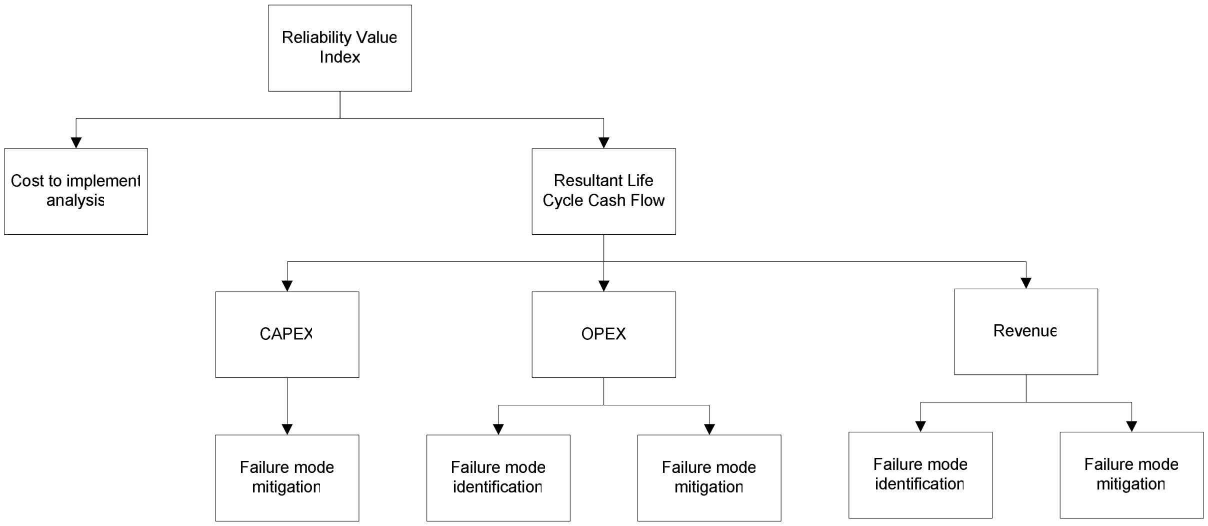


Figure 7-1: Reliability value index breakdown structure.

In accordance with Equation 39, the reliability value index is constructed from the cost to implement reliability analyses and the resultant cash flow. The resultant cash flow is subsequently decomposed into CAPEX, OPEX and Revenue. The relevant cost associated with CAPEX is the design response to the analysis only (failure mode mitigation). Note that fault or failure mode identification is not considered a cost element of CAPEX as it is assumed that faults/failure modes are identified as a result of analysis. Any subsequent discovery of the failure modes during design would be purely fortuitous and it does not seem logical that supposed risk averse decision makers would factor in such chance events into a decision making process. As such it is assumed that faults or potentially unwanted failure modes escape the design process unless there is concerted effort to find them.

The cost of operations is presented as OPEX and revenue, both of which are affected by failure mode identification and mitigation. OPEX costs for failure mode identification include those costs relating to inspection and diagnosis. Failure mode mitigation costs are those costs required to return an item, known to have failed, to the operational state. Revenue is constructed from the deferred or lost revenue observed during failure mode identification and mitigation. The remaining sections of this chapter define how each of these elements is estimated.

7.3.1. Cost to implement analysis

Reliability analyses should be deployed to influence design decisions. This is usually achieved through the identification of design weakness, which is considered either systematic or residual. Analysis, therefore, should be selected to identify systematic or residual weakness based on a prior assumption that these weaknesses exist. API RP 17N (2007), through application of technical risk categorisation identifies four potential sources of systematic weakness; technology, environment, architecture and organization. The reliability stretch factor may be considered in relation to the target residual weakness. If it assumed that these (five) weakness sources can be characterised by a hazard rate then, assuming that all hazard rates are mutually exclusive, the overall hazard rate of an item can be defined as the sum of the individual residual and systematic hazard rates according to Equation 42,

$$\lambda_{item} = \lambda_R + \lambda_T + \lambda_A + \lambda_E + \lambda_O \qquad \text{Equation 42}$$

where λ_R is the target residual hazard rate that reflects the reliability goal or requirement and λ_T, λ_A, λ_E and λ_O are the systematic hazard rates attributed to technology, architecture, environment and organization, respectively.

If it is assumed that there are five hazard rates then it follows that there are five potential focal points of any reliability analysis performed. As with the CAPEX driver, it is assumed that failure modes relating to a specific source of weakness can only be identified if the analysis is examining issues relating to those potential sources of weakness. For example, recall the SIREN case of rapid anode wastage, failures relating to environmental loads and stresses can only be identified if the environment is being considered as a potential source of weakness. In addition, it cannot be assumed that directing attention to a specific source of weakness guarantees the provision of sufficient information to allow mitigating activities. There exists some probability that despite investing in reliability analyses, the fault or unwanted failure mode remains undetected; this probability depends on the 'detectability' of the failure mode and the duration over which the source of weakness is analysed. Finally it is logical to assume that there exist diminishing returns on the probability of detection versus time invested. A simple model satisfying the above criteria is provided in Equation 43,

$$P_{identify} = 1 - \exp\left(-\gamma_{\lambda i} t_{\lambda i}\right) \qquad \text{Equation 43}$$

where $P_{identify}$ is the probability with which the failure mode is detected, $\gamma_{\lambda i}$ is a measure of the detectability, measured in units of inverse time over the range (0,∞], of the i^{th} potential source of weakness and $t_{\lambda i}$ is the duration of the respective reliability analysis. It follows therefore that the analyses should be selected based on the perceived presence and detectability of a given source of weakness.

The cost of performing reliability analysis, C_{RA}, is a function of the time spent analysing each potential source of weakness and the cost rate of the person or persons performing the analysis, according to Equation 44,

$$C_{RA} = t_{\lambda R}.C_{\lambda R} + t_{\lambda T}.C_{\lambda T} + t_{\lambda A}.C_{\lambda A} + t_{\lambda E}C_{\lambda E} + t_{\lambda O}.C_{\lambda O} \quad \text{Equation 44}$$

where $C_{\lambda i}$ is the cost per unit time of the assessment of the i^{th} failure type and $t_{\lambda i}$ is the duration of the assessments of the i^{th} failure type.

7.3.2. Cost of failure mode mitigation

The CAPEX response to failure mode identification is treated differently depending on the specific response to the analysis. If it is assumed that some mitigating action occurs then the design response to reliability analysis is either system reconfiguration or reliability growth (or a combination of the two). System reconfiguration may be considered to include introducing redundancy or selecting a different technology to achieve the same function, whereas reliability growth influences the hazard rate of the existing component parts of the system.

System configuration is achieved through changing the system reliability logic or changing the technology required to achieve same function. Changes to the system reliability logic include such design decisions as introducing redundancy with no attempt to influence the residual or systematic weaknesses of the component technology. The resultant cost accumulation is the cost differential required to implement that change (i.e. the cost to add a redundant component or procure alternate technology) and the resultant system reliability is defined according to the updated reliability block diagram.

Reliability growth models have been developed to support the management of reliability effort during reliability growth programmes by estimating the number and magnitude of product reiterations required during design and development to achieve a specific reliability target (Krasich *et al.* 2004). IEC 61164 (2004) details the Modified Bayesian IBM-Rosner model (Quigley and Walls, 1999) and the Modified Power Law model for planning reliability growth in design. Although the models more readily applied to product development and reliability growth through testing, they are applicable to reliability growth through design as it is still assumed that the more significant (systematic) weaknesses have a higher probability of identification. Where a residual or systematic failure mode evaluated during reliability analysis has identified that reliability growth is required it is assumed that the growth observes a power function (Krasich *et al.* 2004) according to Equation 45,

$$\lambda_{Gi} = \lambda_{0i}\left(1+M\right)^{-\alpha i} \qquad \text{Equation 45}$$

where λ_{Gi} is the hazard rate of the i^{th} failure mode as a result of the reliability growth programme, λ_{0i} is the historical or original hazard rate of the i^{th} failure mode (relating to one of the sources of weakness) prior to the reliability growth program, M is the number of design modifications and α_i is the growth rate for the i^{th} hazard rate. The cost associated with the reliability growth model defined in Equation 45 is a function of the number of design modifications; the Power Law model is not strictly a discrete model for reliability growth in design. However, as the design reliability improves as a function of the number and efficacy of the modifications, the activity cost is defined as $C_G = M.C_{DM}$ where C_{DM} is the cost of a single design modification.

7.3.3. Potential cost of operations

The resultant cash flow in operations is a function of the OPEX accumulation relating to restoring the system to the operational state given component failure and lost or deferred revenue. These costs are incurred whenever a cut set, as defined by the system reliability logic (i.e. the design response to analysis), occurs. For complex systems it is necessary to model cut set occurrence and cost accumulation through simulation. This can be achieved through the development of a discrete event time to failure simulation tool, which has been initially developed as part of this research using a combination of MS Visio^{TM}, MS Excel^{TM} and Palisade's @Risk add in for Excel. The tool observes four parts:

- A Method for data collection and system reliability logic definition;
- The generation of pseudo-random component failure patterns;
- Network analysis to determine system functional states based on component failure state; and
- Discounted cost accumulation at appropriate event triggers.

Data collection and system reliability logic definition is managed through MS Visio. Data collection utilises MS Visio's reporting feature that enables the user to export specific data to Excel. In order to export all the relevant information required to drive the simulation, a custom Visio stencil is required. The RBD stencil created includes four basic shapes; 'RBD start node', 'RBD end node', 'RBD Block' and 'Connection'. Each shape has a set of custom properties that have been defined to support the network analysis and reliability based life cycle cost simulation. Table 7-1 describes the custom properties, which are generated in the RBD report; the 'X' in the final column defines which shape master (node, block or connection) has the specified custom properties. Custom properties ‘Name’, ‘Cost’, ‘MTTF’ and ‘MTTR’ require manual input from the creator of the RBD.

Table 7-1: Description of custom properties presented in RBD report created in MS Visio.

Custom Property	Description	RBD Node	RBD Block	Connection
Master Name	Label of master shape for all similar shapes	X	X	X
Shape ID	Unique identification tag for each shape in RBD drawing	X	X	X
BeginX	X-coordinate of the starting point of RBD connection			X
BeginY	Y-coordinate of the starting point of RBD connection			X
Connection1X	X-coordinate of 1st connection point on RBD Block/end node	X	X	
Connection1Y	Y-coordinate of 1st connection point on RBD Block/end node	X	X	
Connection2X	X-coordinate of 2nd connection point on RBD Block		X	
Connection2Y	Y-coordinate of 2nd connection point on RBD Block		X	
Connection3X	X-coordinate of 3rd connection point on RBD Block/start node		X	
Connection3Y	Y-coordinate of 3rd connection point on RBD Block/start node		X	
Connection4X	X-coordinate of 4th connection point on RBD Block		X	
Connection4Y	Y-coordinate of 4th connection point on RBD Block		X	
Cost	Active cost to repair given failure		X	
EndX	X-coordinate of end point of RBD connection			X

Custom Property	Description	RBD Node	RBD Block	Connection
EndY	Y-coordinate of end point of RBD connection			X
MTTF	Mean time to failure of RBD block, in years		X	
MTTR	Mean time to repair of RBD block, in days		X	
Name	Equipment name for RBD block		X	

The generation of random failure patterns is driven by the underlying assumption of the failure pattern. Consider a component with constant hazard rate, λ; the probability of failure over time, *t*, is given according to Equation 46.

$$P_f = 1 - \exp(-\lambda t) \qquad \text{Equation 46}$$

The time to failure of the component, TTF, can be simulated by using the inverse transform method (Banks and Carson, 1984).

$$TTF = -\frac{1}{\lambda}\ln(1-U) \qquad \text{Equation 47}$$

Equation 47 returns an exponential distribution of TTF when *U* is a random number uniformly distributed in the interval (0, 1].

For a component that does not observe a constant hazard rate the probability of failure is characterised by the two parameter Weibull function (Equation 48),

$$P_f = 1 - \exp^\wedge\left(-t/\eta\right)^{\beta} \qquad \text{Equation 48}$$

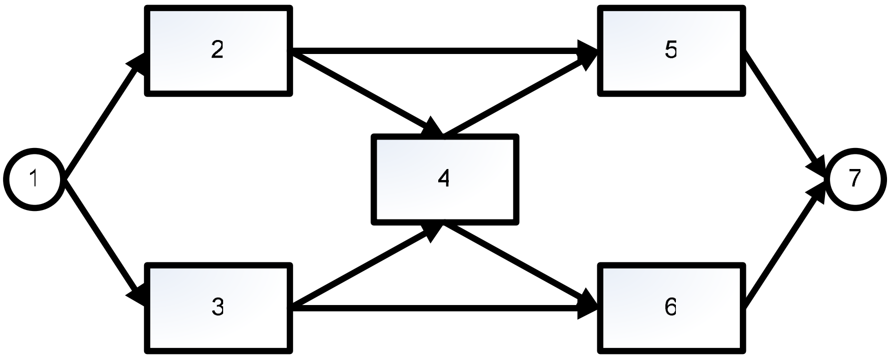
where η is the characteristic life parameter and β is the characteristic shape parameter. Using the inverse transform method the time to failure distribution is determined according to Equation 49 where U is a random number uniformly distributed in the interval (0, 1].

$$TTF = \eta\left[-\ln(1-U)\right]^{1/\beta} \qquad \text{Equation 49}$$

The failure pattern of a component is determined from its randomly generated time to failure, delay to the repair activity (i.e. the time to system failure if the component failure does not trigger a requirement for intervention) and the time taken to repair the component/system. Random component times to failure are generated using Palisade's @Risk software, which is a Monte Carlo add-in to Excel.

The time to system failure is dependent on the component times to failure (above) and the failure logic. The failure logic is determined from analysing the data collected from the Visio RBD. From the reported information exported from the Visio RBD, a connectivity matrix is created which indicates the connections between the blocks of the RBD. The algorithm for creating the connectivity matrix takes the (x, y) coordinates that correspond to the beginning of the connection link and finds the RBD block that has the matching (x, y) coordinates as one of its connection points. After recording this RBD block, the process is then repeated for the (x, y) coordinates for the end of the link. Once all (x, y) coordinates for the links have been matched to a connection point on an RBD block a two column 'connection list' of start blocks and finish blocks for each link is created. This information is then represented in an '*n* by *n*' matrix where *n* is the number of blocks in the RBD. The matrix is constructed according to Figure 7-2.

Each column in the matrix has a column header identifying one of blocks in the RBD. Likewise, each row has a row header identifying one of the blocks in the RBD. The information from the connection list is transposed onto the connection matrix such that the (x, y) coordinate of the matrix marked with a '1' indicates a link between two blocks interpreted as column header 'x' is linked to row header 'y'. For example in Figure 7-2, which provides a reliability block diagram for a typical bridge network with the corresponding connectivity matrix, reading down from column header '4' reveals that block four is linked to block five (row header '5') and block six (row header '6').



	2	3	4	5	6	7	1
2	0	0	0	0	0	0	1
3	0	0	0	0	0	0	1
4	1	1	0	0	0	0	0
5	1	0	1	0	0	0	0
6	0	1	1	0	0	0	0
7	0	0	0	1	1	0	0
1	0	0	0	0	0	0	0

Figure 7-2: Bridge network RBD with corresponding connectivity matrix.

RAM analysis programs require a method of determining the system status given failure of individual components and sets of components. A network analysis algorithm has been developed specifically for the connectivity matrix constructed from the MS Visio report, called the 'deteriorating path' algorithm and outlined in Figure 7-3. The algorithm gradually restricts the paths through the network by disabling blocks that do not link to others until either a path is found or the start node is disabled.

The deteriorating path algorithm travels through the connectivity matrix by starting at the column header that represents the start node of the RBD. The program runs down the column until a '1' is found, at which point the row header is collected and checked to see if it matches the shape ID of the RBD end node. If it does not, the program finds the column header that matches the row header and runs back down the column looking for a '1' again and collecting the row header. The process continues until either the row header found matches the shape ID of the RBD end node (at which point the system is recorded as being in a working state) or the program runs through a column and does not find a '1' (i.e. no connection is found). If no connection is found, then the program disables the block (that does not link to any working block) by back tracking to find the row header that matches the current column header and setting all values in that row to zero, which stops the program from travelling to the recently disabled block. The program then starts again at the top of the column corresponding to the RBD start node. If the program runs down the column corresponding to the start node and does not identify a '1', then the system is recorded as having failed.

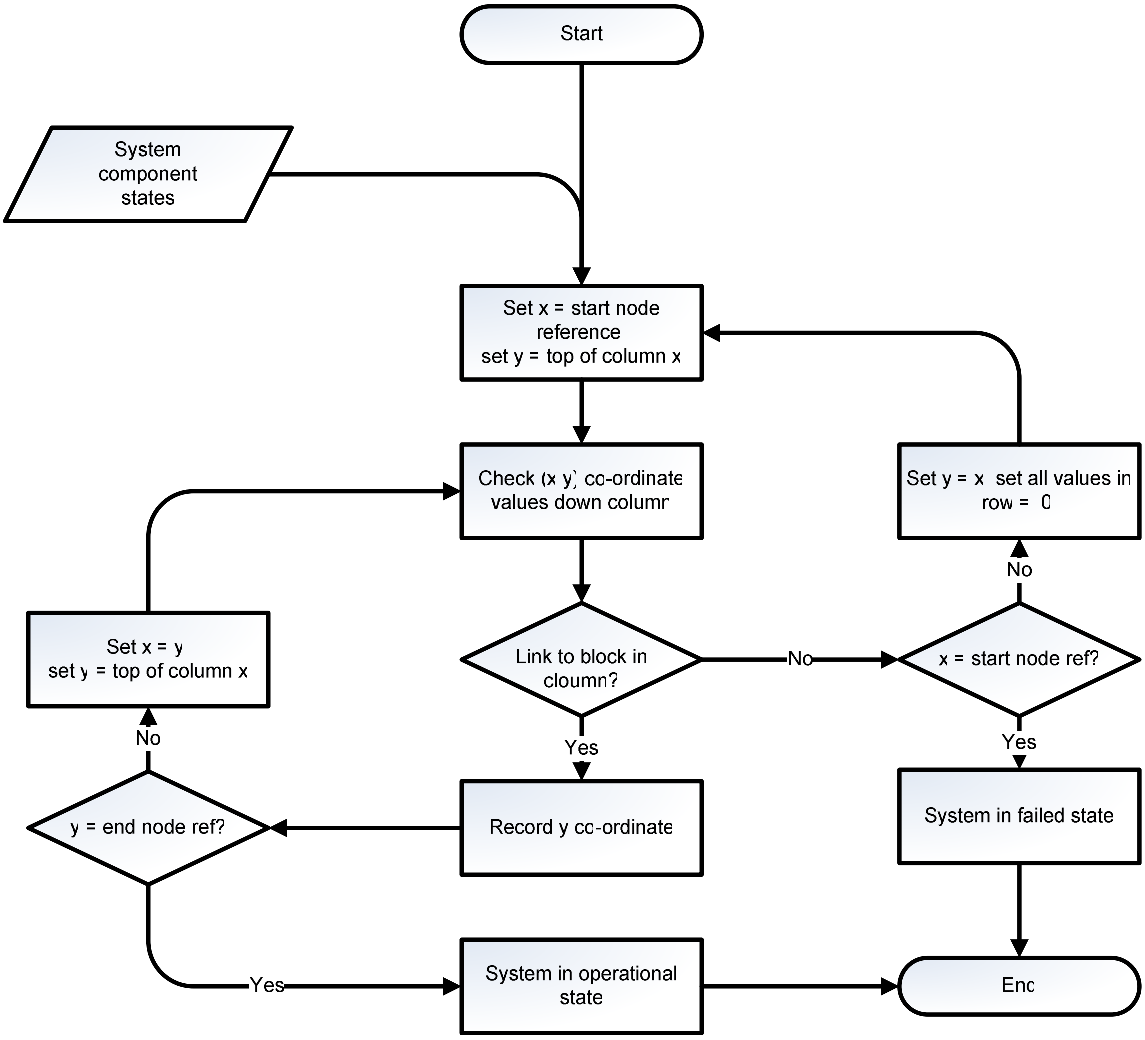


Figure 7-3: Schematic of the deteriorating path network analysis algorithm.

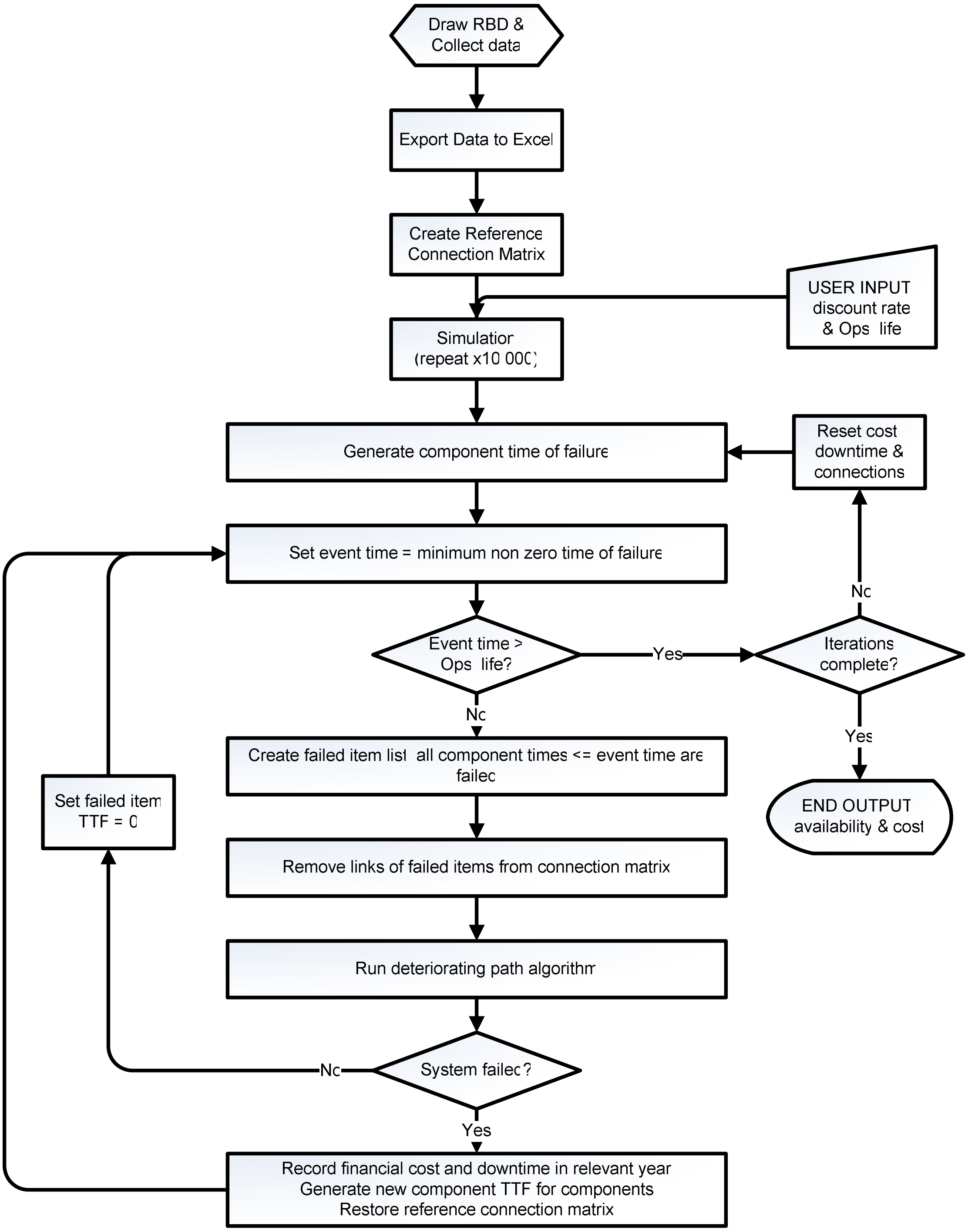


Figure 7-4: Cost of operation algorithm flow chart.

The algorithm for collecting the potential cost of operation for a system is outlined in Figure 7-4. Data collected during the construction of the RBD in Visio is exported to Excel, which is supplemented by direct user input of the discount rate and operational lifetime ("Ops. Life" in Figure 7-4). Once an in initial reference connection matrix has been created, which describes the system reliability logic, the cost of operations can be simulated. The simulation runs over 10,000 iterations in order to capture the variation in the potential cost. Each iteration starts by generating a set of component times to failure (Equation 47 or Equation 49) and identifies the smallest non-zero value, which is set as an event time. A list of failed items is created, all items equal to or below the event time are considered in the failed state, and the connections of all failed components are removed from the connection matrix. The deteriorating path algorithm is executed to determine the system state; if the system is still operational then the failed component's time to failure is set to zero and the next event time determined. If the system has failed as a result of the component failure then the present cost of the repair and associated downtime is recorded, new times to failure are generated and the reference connection matrix restored. The process repeats until the event time exceeds the operational life time. When the event time is greater than the system life then the iteration is halted and the lifetime availability and present value of the cost of operations recorded. Once all iterations are complete the present value of the cost of operation and availability are presented in @Risk. Reliability sensitivity analysis is conducted by holding all other input variables (i.e. Mean times to failure) constant whilst changing the input of one variable.

7.4. Chapter Summary

This chapter has outlined the foundations of a decision support framework, constructed with the intent of providing decision makers, during the design process, evidence of the value that can be generated from implementing reliability and technical risk management such as that proposed in API RP 17N (2007). While the approach draws on recognised theories and concepts already presented in the literature, it is unique in its focus on reliability analyses and the technical risk categories identified in API RP 2007 (2007).

The framework is grounded on the definition of a reliability value index (RVI). The index draws analogy from the profitability index by assessing the cash flow as a result of an initial investment. The decision criteria for the reliability index is to invest if RVI > 1. As with the profitability index, the RVI gives an indication of the margin of safety of the investment. However, the expected value gives no indication of the probability that a specified investment will add value (although it may be true that a decision alternative returning RVI = 1.1 is less attractive than an alternative returning RVI = 3). By incorporating the uncertainty of future cash flow (specifically from operations) a distribution of the RVI is generated, referred to as the potential reliability value index. This distribution can be used to determine the probability with which the RVI exceeds the acceptance criteria.

The analogous development of the RVI from the profitability index enables the use of RVI to identify the best selection of smaller investment decisions given a prescribed capital budget. The RVI can also be used to identify an acceptable budget available for the achievement of a specified improvement in reliability. This is elaborated later in this section.

Having defined the decision metric its logical decomposition is presented as a reliability value index breakdown structure. A generic RVI breakdown structure is provided to indicate the relevant cost/value elements of immediate concern for the decision making process. The RVI breakdown structure excludes all cost elements not directly relating to the cost of failure mode identification and or mitigation. While this agrees with the initial cost breakdown structure proposed in Chapter 4 it excludes fault or failure mode identification as, in agreement with other authors (Quigley and Walls, 2003), their presence in the system design is already assumed. If sufficient data was available to model the introduction of faults or failure modes then effort would surely be focused on preventing their introduction rather than planning when to remove them.

The assumed presence of potential failure modes is driven by the application of technical risk categorisation as defined by API RP 17N (and ISO 20815). Technical risk categorisation (presented in Chapter 2) is an activity used to identify changes in the current project compared with previous projects; this activity attempts to draw analogy with previous projects and identify where changes have occurred. It is these changes that are the potential sources of weakness in the system. The activity makes no attempt to quantify the number of potential weaknesses or characterise them with a hazard rate. Rather, the intention of technical risk categorisation is to prioritise the focus of analyses (or other design for reliability effort). The assumption that either an unacceptable residual weakness and or up to four sources of systematic weakness exist within the system demands that further effort is required to analyses these areas of potential weakness. The cost to implement these analyses defines the first component of the RVI breakdown structure, Q.

It is not sufficient to cost Q alone; doing so only serves to accumulate cost within the design process. The RVI breakdown structure also requires that the resultant cash flow is subsequently considered. To achieve this, a probability of fault or failure mode identification is required to give designers the opportunity to make decision as a result of the analysis. After all, this is the purpose of acquiring information through analyses. The probability of fault or failure mode identification is calculated as a function of the time spent analysing the system and the detectability of the fault of failure mode. This detectability parameter is an important feature not previously considered as it relates to the ability with which an organization can identify the causes of systematic or residual weakness. FMECA can address detectability, but this relates to the identification of known failure modes once they have occurred; the efficiency with which failure modes are identified during the FMECA is dependent on the capability of the team conducting the workshop. That is, one organization may find the cause of weakness much more cost efficiently than another. It is not illogical to assume that an organization, that otherwise pays no attention to system reliability, might be incapable of identifying certain sources of weakness. While improvement feasibility has been considered in the literature it presupposes that the failure cause is known, which might not be true.

Having invested in attempting to identify potential weaknesses in the system, the RVI breakdown structure identifies the design response to analysis. There are two active design responses (excluding taking no action); system reconfiguration or reliability growth. The system reconfiguration decision includes decisions to change the basic system layout or to achieve the functional requirement with different technology. While it is unlikely that reliability analysis would force a change to the system layout it is included to enable the assessment of discrete decision alternatives such as those observed during concept selection. The second system reconfiguration option is to change the technology providing the required function; in this instance the system reliability logic does not change, just the component parts. This decision may be applicable when selecting specific technology solutions that deliver the same functional requirement. In both options no attempt is made to change the reliability of the component technology. That it, there is no reliability growth at the component level, which is considered separately. The alternative design response, reliability growth, attempts to reduce the hazard rate through mitigating residual or systematic weakness. The extent with which this mitigation alters the characteristic hazard rate is modelled according to a growth factor. This growth factor, as with detectability, relates to the capability of the organization implementing the change.

The cost of operations is defined, in the RVI breakdown structure, as the combined effect of the design response to analysis on both revenue and OPEX. OPEX models (which can be extended to include revenue) have received the significant coverage in the literature and the application of discrete event simulation is well known. The cash flow model presented here used a combination of software capabilities to collect the information required and to simulate the resultant cash flow in operations. Fundamental to its application, Visio is used to collect the relevant data, which it exports to Excel (an example of the exported datasheet is provided in Appendix A). Excel, through VBA, interrogates the data imported from Visio to determine the system reliability logic and drive the discrete event simulation (the VBA code is provided in Appendix B). While commercially off the shelf software may be available to support this part of the RVI calculation, the use of MS Office^{TM} tools removes some of the perceived exclusivity of reliability analysis. While bespoke code is required for the network analysis and simulation the calculation of operational cash flow as a result of design decisions is generated from an engineering drawing package, not separate reliability software.

The code is not the most efficient, nor is it intended to be for a number of reasons. Firstly the code is presented to demonstrate that separate reliability tools are not required, just an engineering drawing package. Secondly, processing speed is not the rate determining step in such an application, data collection is. The preoccupation with software processing speed is due to its visibility, but significantly more time is spent collecting all the necessary inputs (and not just reliability and maintainability data). Although it is beneficial to generate quick results (especially when conducting sensitivity analysis or generating 'what if' scenarios) there is greater scope for value improvement is making the data acquisition phase more efficient before the 'start simulation' button is even pressed. This can be achieved through a decentralised approach to reliability and technical risk management and is considered further in the discussion to this research.

It is accepted that the decision scenario presented within the RVI breakdown structure may not always be appropriate. The potential RVI metric can be used for other applications, specifically the allocation of a reliability improvement budget. Recall Equation 39 where RVI = $\Delta CF(strategy)/Q$; if Q is redefined as the design expenditure relating to fault/failure mode identification and the design response (i.e. fault/failure mode mitigations), then setting $\Delta CF(strategy)=Q$ can facilitate the identification of capital ration available to improve the reliability by a specified amount. By discounting the benefit of the operational cash flow as a result of the reliability improvement to the time at which the reliability investment is made, the available resources for reliability improvement can be determined (Figure 7-5). The resources available for the reliability improvement strategy are dependent on both the degree to which the reliability is improved and the measure of cost of failure.

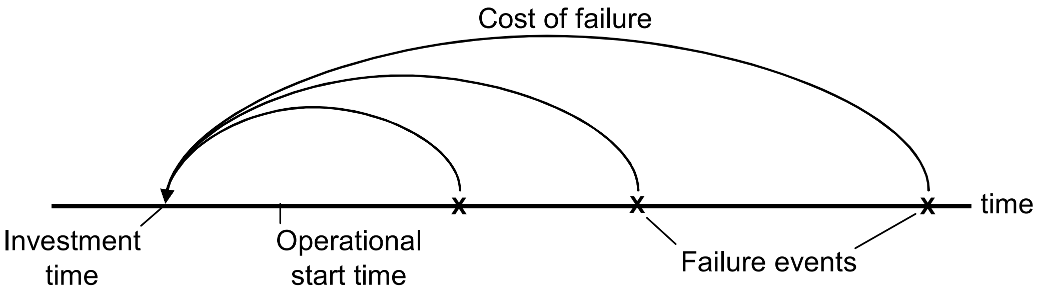


Figure 7-5 Establishing the financial resources available for a reliability improvement activity.

The reliability improvement governs the number of service life failures that are removed; as more failures are removed, so the available resource increases. Consider a failure that occurs n years into the operational life and incurs a cost of C; the resource available to remove that failure in design is $\frac{C}{(1+r)^n}$ (where r is the discount rate). If, however, two failures were to occur n years into the operational life, both incurring a cost C, then the available resource is $\frac{2C}{(1+r)^n}$; the resource available has increased, although there is an implied assumption that a greater reliability improvement is required.

Furthermore, there are more resources available to remove early life failures then there are for wear out failures. Consider an early life failure that occurs in year n and required a cost C to repair, a wear out failure event occurs in year m ($m>n$), requiring the same cost C; the time value of money dictates that $\frac{C}{(1+r)^n} > \frac{C}{(1+r)^m}$.

The constituent parts of $\Delta CF(strategy)$ also determine the level of resources available for the reliability effort. Consider a failure that occurs in year n and requires a cost C to repair, as the system is in the failed state it cannot perform its function and forgoes revenue R. The resources afforded to the design team to remove the failure are $\frac{C+R}{(1+r)^n}$ or $\frac{C}{(1+r)^n}$ depending on the inclusion or exclusion of the lost revenue, respectively. It should be noted however, that if the resources available for the reliability improvement strategy includes the revenue lost or deferred due to failure and all of the available resources were consumed whilst improving the reliability, then the financial performance of the system is compromised; the NPV would remain unchanged but the return on investment would be reduced.

The probability the design response satisfies the RVI decision criteria even at zero cost is not unity. This is due to a finite probability that despite the improvement the system characterised by improved reliability observes the same failure pattern as the original system reliability. This includes the probability that both components are reliable (i.e. no failures) or that they both observe the same number of failures in the same financial time intervals. Figure 7-6 indicates the effect of the magnitude of the reliability investment on the probability that the investment will add value to a reliability improvement that observes an mean $\Delta CF(strategy)$ of £71,600 with a standard deviation of £20,000 (diamonds) and £10,000 (squares).

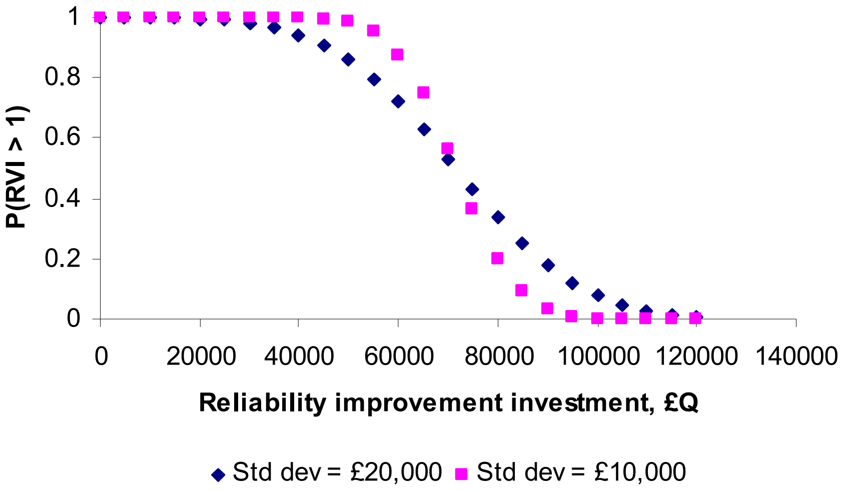


Figure 7-6: Effect of Q on $P(RVI > 1)$ where $\Delta CF(strategy)$ = £71,600 and $\sigma_{Stratgy}$ = £20,000.

As the investment cost for the same the design response, Q, increases so the probability that it will add value reduces. The operator is required, therefore, to specify a design response budget that returns an acceptable probability of satisfying the RVI decision criterion and is a feasible budget to achieve the specified reliability improvement. The determination of a reliability improvement budget presupposes that the design response does not modify the system reliability logic at the current level of system indenture. That is, it is assumed that the specification of a reliability budget is applied to an individual block within the reliability block diagram. The approach is more applicable to improvements to the residual weakness or technology selection as, in most cases data used to assess Δ*CF*(*strategy*) assumes the residual hazard rate. That is, databases such as OREDA do not report early life failure, which tend to be the result of a systematic weakness. Specifying a reliability improvement budg*et al*so assumes a different decision scenario to that previously discussed. These decision scenarios are compared in Figure 7-7. Decision scenario 1 observes a decision to react to the analysis immediately after the analysis has identified potential system weaknesses. Each reaction is subsequently assessed and a decision to implement, modify or reject the reaction is made. In decision scenario 2 the identification of system weakness is analysed further to determine the potential value from the reliability improvement achieved at no cost, from which a reliability budget is specified. This allows an immediate decision as to whether or not an improvement is financially viable. The decision reaction, then, can focus on achieving the improvement within the specified budget. This removes the design reaction modification iterations as the financial constraints have been established up front. This decision scenario also provides the opportunity to generate multiple design reactions from which the best combination of smaller investments can be selected within the constraints of the budget.

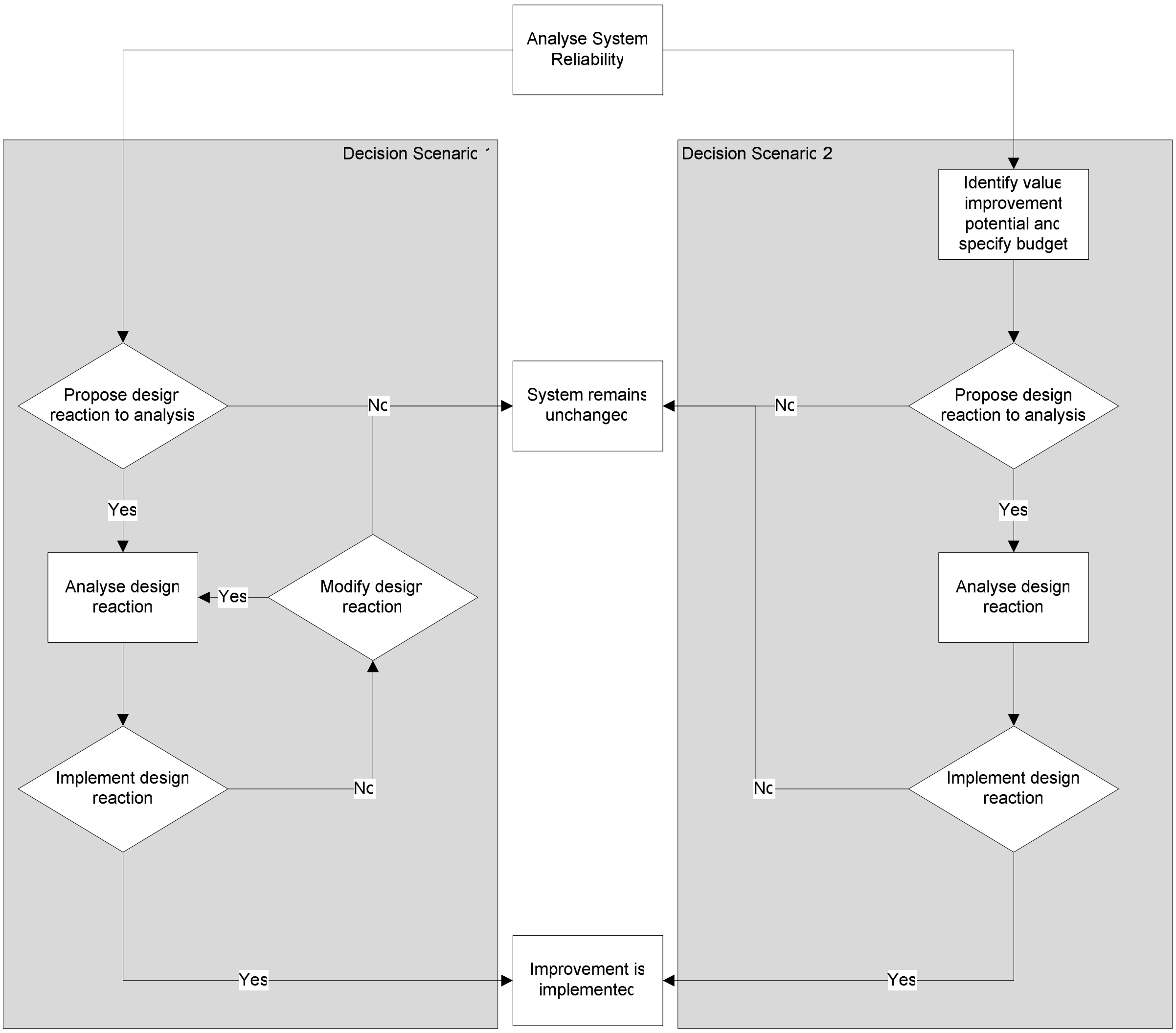


Figure 7-7: Comparison of alternate RVI decision scenarios.

The RVI approach is differentiated as it supports proactive reliability improvement to enhance project value rather than minimise losses. That is, the metric encourages investments in reliability improvements rather than cutting cost. The following chapter presents some case studies to demonstrate the features of the RVI framework presented in this chapter.

8. Potential Value Framework Case Studies

8.1. Introduction

The RVI breakdown structure proposed in the previous chapter describes a design decision scenario that is driven by an initial investment in analysis whose effects propagate through to operations. The purpose of which is to support the planning process for reliability and technical risk management. Based on the prior assumption that weaknesses exist in the system, reliability analysis is performed in an attempt to identify these weaknesses. In response to the analysis an active design reaction may be employed to change the layout of the system (i.e. change the system reliability logic), change the technology required to deliver the function or increase reliability of the technology. This chapter demonstrates the application of these decision scenarios through a selection of case studies. It also demonstrates the effect of setting a reliability budget for a reliability improvement based on the probability that it will add value to the project. The case studies are based on reliability and technical risk management training material given to subsea engineers. Reliability data has been sourced from OREDA (SINTEF, 2002) and the sponsoring company's proprietary datasets. The latter was also the source of all remaining input data. Operational costs were simulated according to the cost of operations model described in the previous chapter.

8.2. Decision Scenario 1 – Discrete Options and Changing Technology

8.2.1. Problem definition

The first decision scenario considered is that of changing technology; this scenario may be applied to concept selection where competing design options are considered. The case assumes the identification of a small reservoir which can be exploited economically using a single production well, utilising production boosting technology, tied back to an existing facility. Three production boosting technologies are considered; water injection (WI), an electric submersible pump (ESP) and a seabed mounted multiphase pump (MPP).

All systems are assumed to observe series reliability logic, failure of any component results in total system failure. Given any failure during the 10 year operational lifetime items are restored to as good as new. The revenue trade-off between the production boosting technologies is captured through the production decline function; the daily production rate for the nth year, φ_n, is determined from a decline function according to Equation 50,

$$\varphi_n = \min\left(\varphi_i\left(1-\frac{\sum_{n=0}^{n=n-1}\Phi_n}{RR}\right)^b, \varphi_{tp}\right) \qquad \text{Equation 50}$$

where φ_i is the initial flow rate, $\sum_{n=0}^{n=n-1}\Phi_n$ is the cumulative production to date (year n-1), *RR* is the recoverable reserves, *b* is the decline rate and φ_{tp} (φ_{tp} = 5kbopd) is the topside processing capacity. The following cost assumptions are common to all options but are collected at different rates depending on the reliability performance.

- Standard OPEX per barrel: £1/bbl;
- Market price of oil less tax and other royalties: £20/bbl;
- Discount rate: 10%;
- Vessel charges collect cost according to Table 8-1.

Table 8-1: Vessel charges for case study 1.

Vessel ID	Day rate (£)	Mobilisation time (days)
0	0	0
1	30,000	20
2	60,000	30
3	90,000	60
4	250,000	90

Water injection

Reliability and repair cost data for the water injection option are given in Table 8-2. The relevant CAPEX for the water injection system is £60,057,000 and the production decline function variables are RR = 22MMbbls, φ_i = 8kbopd and b = 2.4.

Table 8-2: Water injection option reliability and repair cost input data.

Item	MTTF (yrs)	Replacement cost	MTTR (days)	Vessel ID requirement
Control umbilical	26.7	110000	21	2
Production flowline	260	150000	30	3
Production riser	36.3	75000	7	1
Production tree	7	575000	3	2
Production well & completion	167	200000	2	4
Subsea control equipment	1.3	100000	1	1
Topside control equipment	1.3	15000	1	0
Water injection flowline	260	150000	30	3
Water injection riser	36.3	75000	7	1
Water injection tree	7	575000	3	2
Water injection well & completion	167	200000	2	4

Electric submersible pump

Reliability and repair cost data for the electric submersible pump (ESP) are given in Table 8-3. The relevant CAPEX for the water injection system is £36,585,750 and the production decline function variables are RR = 20MMbbls, φ_i = 18kbopd and b = 2.4.

Table 8-3: Electric submersible pump reliability and cost input data.

Item	MTTF (yrs)	Replacement cost	MTTR (days)	Vessel ID requirement
Control umbilical	26.7	110000	21	2
Electric submersible pump unit	1.75	45000	2	3
Production flowline	260	150000	30	3
Production riser	36.3	75000	7	1
Production tree	7	575000	3	2
Production well & completion	167	200000	2	4
Pump topside control	1.3	10000	1	0
Subsea control equipment	1.3	100000	1	1
Topside control equipment	1.3	15000	1	0

Multiphase pump

Reliability and repair cost data for the multiphase pump (MPP) option are given in Table 8-4. The relevant CAPEX for the water injection system is £35,585,750 and the production decline function variables are RR = 20MMbbls, φ_i = 8kbopd and b = 1.9.

Table 8-4: Multiphase pump reliability and cost input data.

Item	MTTF (yrs)	Replacement cost	MTTR (days)	Vessel ID Requirement
Control umbilical	26.7	110000	21	2
Electric submersible pump unit	1.75	45000	2	3
Production flowline	260	150000	30	3
Production riser	36.3	75000	7	1
Production tree	7	575000	3	2
Production well & completion	167	200000	2	4
Pump topside control	1.3	10000	1	0
Subsea control equipment	1.3	100000	1	1
Topside control equipment	1.3	15000	1	0

8.2.2. Results

The conventional life cycle costing and system availability (uptime/total time) are provided for each option in Table 8-5. The results indicate that while the water injection option benefits from the greatest availability, the pump options offer superior financial performance. Values for the net present value and profitability index do not significantly differentiate the pump options. However, the ESP option has a significantly lower availability and higher life cycle cost, suggesting that the cost given failure of the ESP system is much greater than that of the MPP option.

Table 8-5: Life cycle costing metrics for decision scenario 1.

Metric	WI	ESP	MPP	Preferred option
NPV	£75.2 million	£99.7 million	£100.1 million	ESP/MPP
LCC	£85.2 million	£83.6 million	£65.8 million	MPP
IRR	43.4%	70.2%	78.6%	MPP
STC	£10.2/bbl	£8.2/bbl	£7.2/bbl	MPP
PI	2.07	3.72	3.8	MPP/ESP
Payback	2.07 years	1.31 years	1.21 years	MPP/ESP
Availability	0.921	0.856	0.897	WI

Using the same input data, the RVI metrics are calculated. If the application of RVI to discrete options is considered first, the RVI can be calculated from the data provided in Table 8-5 where RVI = (NPV + CAPEX)/CAPEX (adding back the CAPEX to the NPV gives ΔCF(strategy) where the cash flow prior to the decision to invest the CAPEX is zero). In this instance, for discrete options, the RVI is equivalent to the profitability index. Calculating the RVI for the change in technology decision requires that one of the options is defined as the base case. As the RVI reflects investment criteria, the base case option has to be that which observes the minimum capital expenditure. The RVI for each pair wise comparison is calculated according to Figure 8-1 and provided in Table 8-6, where the first technology specified is the CAPEX minimising option. The water injection option, despite being the availability maximising option is clearly the least favourable option based on the RVI; the cash flow as a result of the design reaction is actually negative so despite the increase in system uptime, the design decision is not justifiable when compared to either of the pumping options. When comparing the two pumping options, the RVI gives a clear indication that the multiphase pumping option is preferable, unlike a number of the life cycle costing metrics.

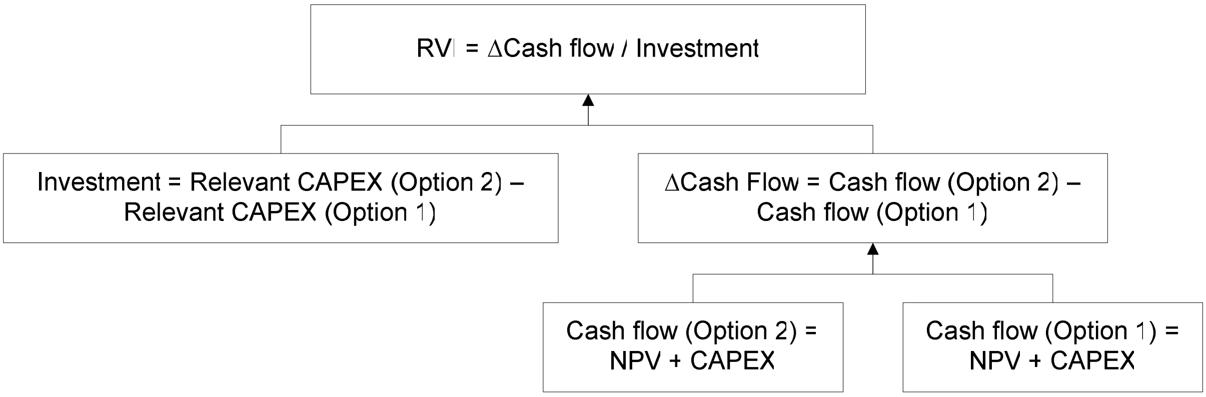


Figure 8-1: RVI calculation for decision scenario 1.

Table 8-6: RVI for discrete comparison.

	MPP:ESP	MPP:WI	ESP:WI
Additional CAPEX (£m)	1	24.47125	23.47125
ΔCash Flow (£m)	0.6	-0.42875	-1.02875
RVI	0.6	-0.0018	-0.04
Preferred option	MPP	MPP	ESP

8.3. Decision Scenario 2 – changing system reliability logic

8.3.1. Problem definition

The second decision scenario is system reconfiguration by changing the system reliability logic. For mature hardware, one of the simplest methods deployed to improve the reliability is to introduce redundancy into the system. Using a single component as the base case scenario, redundant components are added to increase the reliability for a system that observes a high cost given failure.

The relevant cost of the CAPEX is the sum of the redundant components; each component costs £100,000. On failure the entire system is replaced at a cost equal to the CAPEX plus a logistic support cost of £1,500,000. Repair consumes 50 days of operation at a cost of £100,000 per day in revenue impact, totalling £5,000,000. Costs are incurred at a discount rate of 10%.

The design life of the system is 10 years and each component observes a mean time to failure, MTTF = 8 years. The system observes a 1 out of n failure logic (system is operational providing one component is operational).

8.3.2. Results

Figure 8-2 provides mean results from the problem presented in a typical economics of reliability model. The optimum reliability is characterised by seven components logically arranged in parallel, giving a reliability R = 0.906. Figure 8-3 indicates the results in terms of the reliability value index. The RVI indicates that any number of additional items in parallel adds value when compared to the base case. The economics of reliability model agrees with this as all life cycle costs for all reliability improvements are less than the base case scenario. The marginal RVI curve indicates the value added from adding one extra component in parallel, where the marginal RVI is less than one the benefit of adding an extra component in parallel does not satisfy the RVI investment criterion. In this case the first instance when the marginal RVI is less than one is when eight components are logically arranged in parallel, meaning that, in agreement with the economics of reliability model, the optimum reliability is achieved with seven components arranged in parallel.

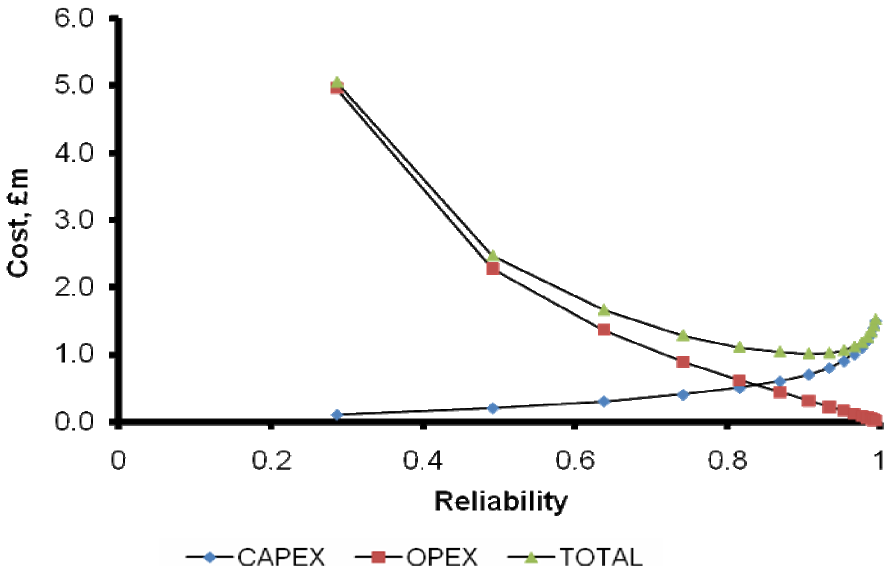


Figure 8-2: Economics of reliability model for decision scenario 2.

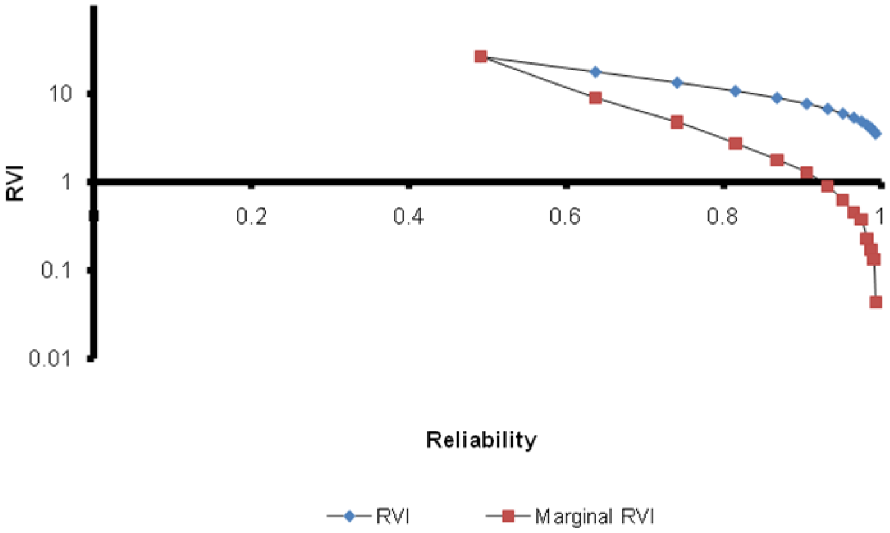


Figure 8-3: Reliability value index for decision scenario 2.

8.4. Decision Scenario 3 – Reliability Analysis Decision

8.4.1. Problem definition

Figure 8-4 provides a decision tree for the RVI breakdown structure and associated decision scenario described in the previous chapter whereby the design team considers the potential financial value of performing reliability analysis. Consider, for the base case, a decision to invest present cost of £30,000 to perform some form of reliability analysis based on a prior assumption that unacceptable system weakness exists within the proposed subject of the analysis (derived from the technical risk categorisation activity recommended by API RP 17N, 2007). Should the decision maker choose to implement the analysis and subsequently discovers a systematic weakness, there is a further decision to react to the analysis findings and improve the component reliability through design modification, at a present cost of £250,000. If a systematic failure exists within the system and it escapes detection or no mitigation is implemented then it is assumed to incur a present cost of £4,000,000 should it failure in the first year of operations. The decision to analyse the system is under uncertainty with respect to the following parameters:

- The existence of a systematic failure mode;
- The ability to identify the systematic failure mode; and
- The capability with which a systematic failure mode is rectified.

The existence of weaknesses within the system is based on a prior assumption as a result of performing an activity such as technical risk categorisation. Technical risk categorisation ranks items based on deviations from previous applications of the same or similar items. As the deviations from previous project increase so the perception that unwanted weaknesses exist in the system also increases. For the base case it is assumed that the decision maker is completely uncertain about the presence of any systematic weaknesses in the system and assumes a probability, P = 0.5, that a systematic weakness exists.

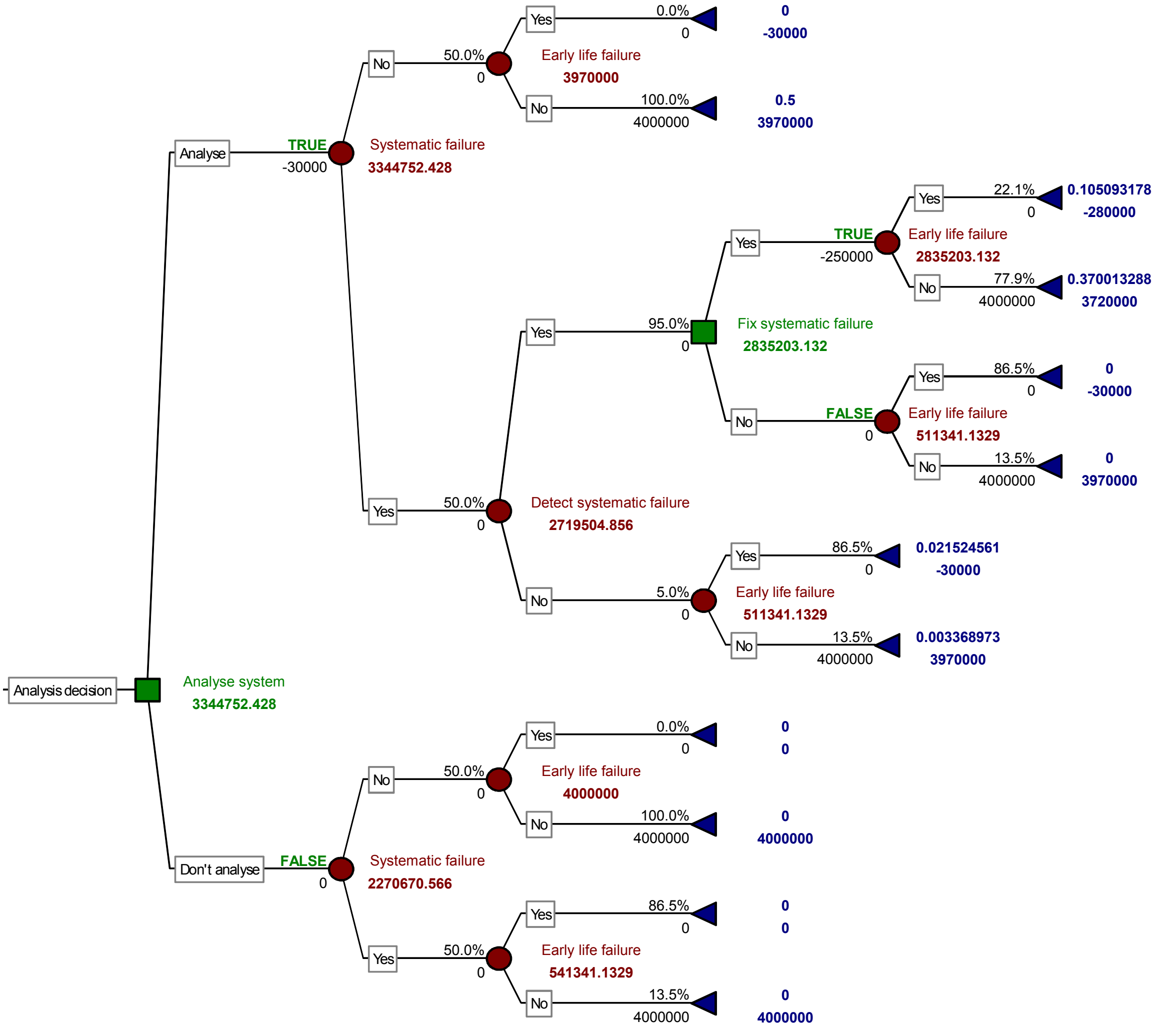


Figure 8-4: Decision tree for systematic failure mode management.

The ability to identify system weakness is determined according to $P_{identify} = 1 - \exp(-\gamma t)$ (Equation 43) where t = 1 and the detection rate, γ, is uniformly distributed over the range (0, 5]. The ability with which the systematic weakness is mitigated is determined according to $\lambda_{Gi} = \lambda_0 (1 + M)^{-\alpha}$ (Equation 45) where the base case systematic weakness is characterised by a hazard rate $\lambda_0 = 2$ and the fix coefficient, α, is uniformly distributed over the range (0, 5]. It is assumed that the design response it typified by one reliability improvement activity.

8.4.2. Results

The results are presented in terms of a decision region graph indicating the decision to invest in analysis based on the perceived capability of the organization to find and fix systematic weaknesses. Figure 8-5 indicates the decision region graph for the base case described above. The decision region indicates the organizational ability required to manage the system weakness, through identification and mitigation. The results suggest that the decision to invest should only be rejected if the organization has almost no ability to detect the system weakness or has limited ability to improve the reliability.

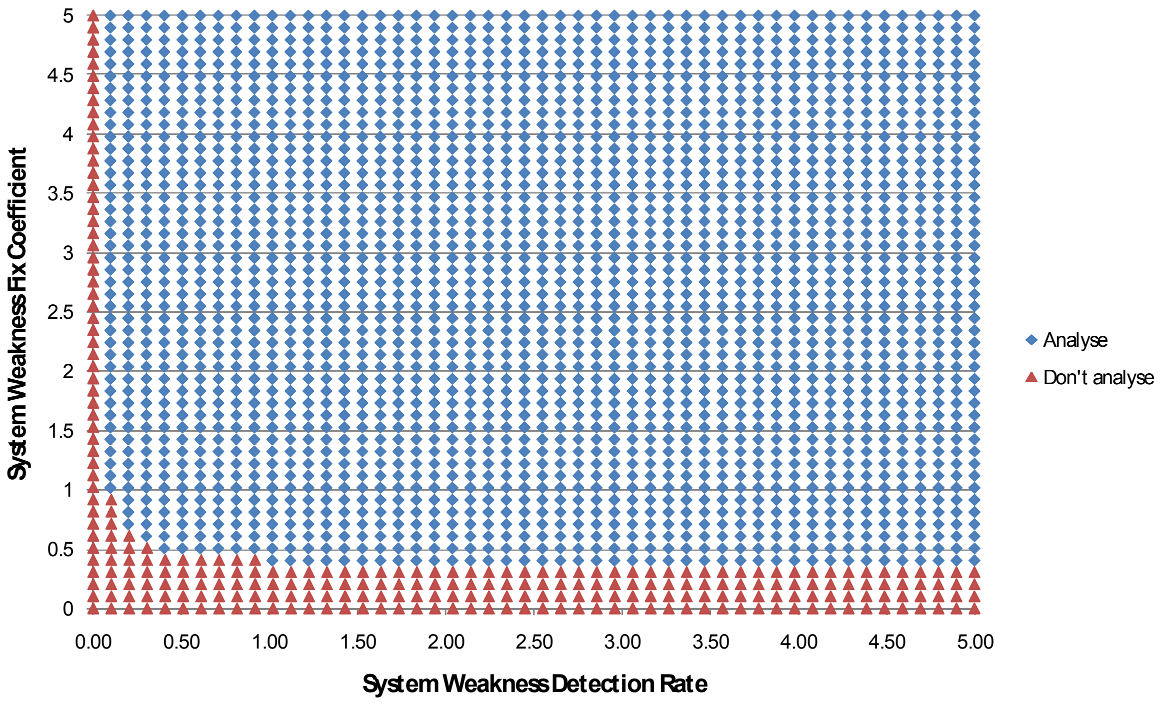


Figure 8-5: Decision region graph based on detection rate and fix coefficient.

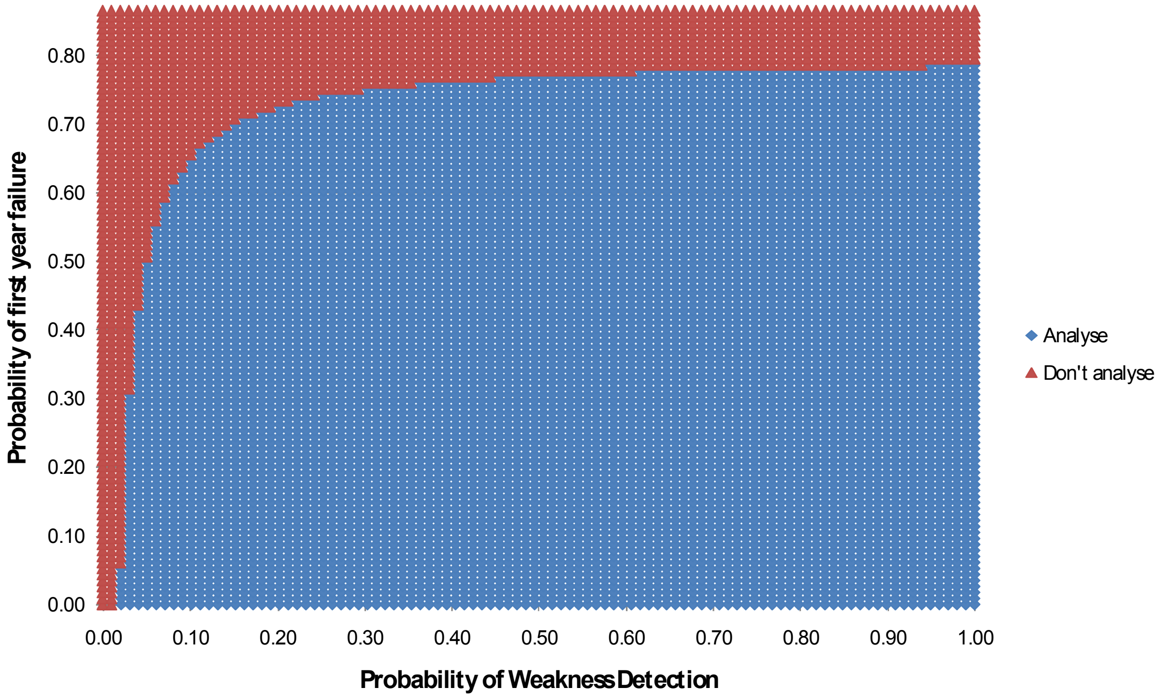


Figure 8-6: Decision region graph based on probability of detection and probability of first year failure.

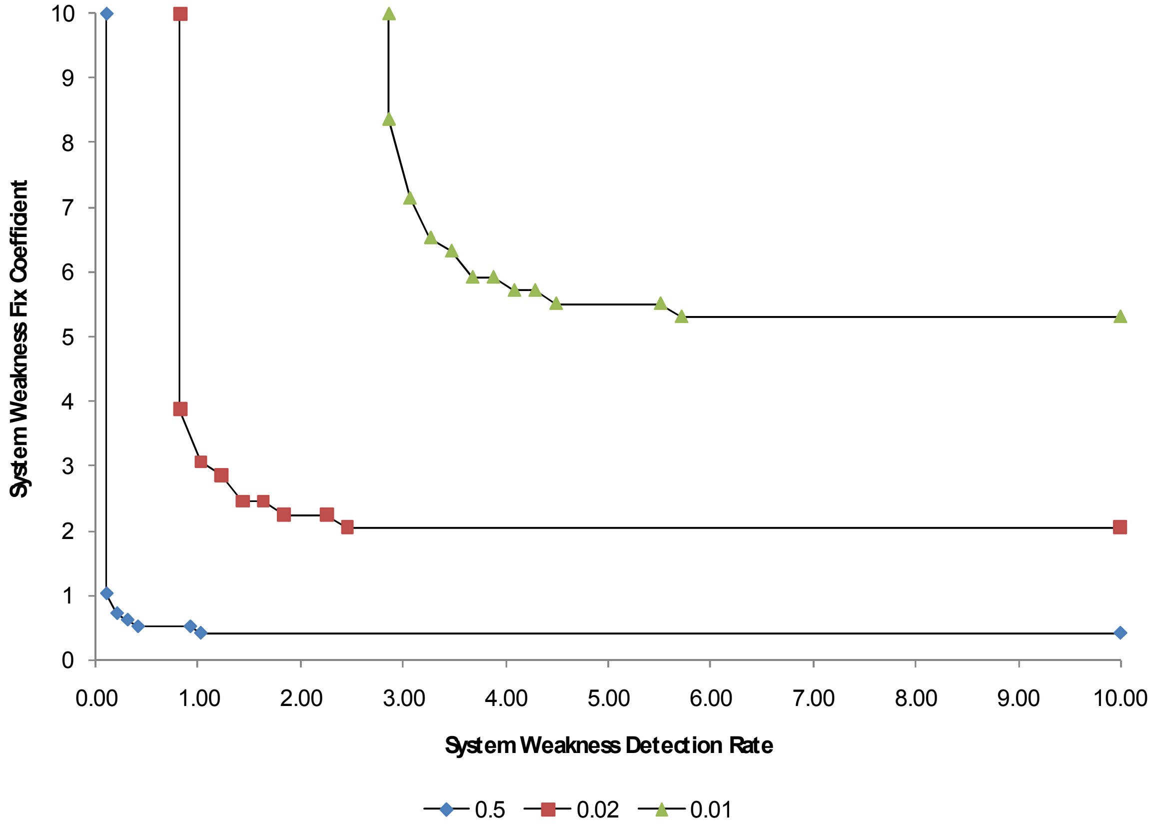


Figure 8-7: Decision Region sensitivity to system weakness existence.

Figure 8-6 provides the decision region for the same decision scenario based on the probability of detection and the probability of first year failure rather than detection rate and the fix coefficient. Figure 8-7 indicates the decision switching point sensitivity to the probability of existence of a system weakness. As the probability of existence of a system weakness decreases so the required capability to manage the weakness increases.

8.5. Decision Scenario 4 – Specifying a reliability budget

8.5.1. Problem definition

By discounting the potential losses avoided by improving the reliability of system to the point at which the initial investment is made, a budget for the reliability improvement can be defined. However, the probability with which this investment adds value is dependent on the fraction of the potential benefit allocated to the reliability improvement.

The base case scenario observes a system with a mean time to failure MTTF = 4years and a standard deviation of 1 year, intended to operate for 15years. Given failure the component is instantaneously replaced at a cost of £2,000,000. The mean time to failure is enhanced over half year intervals (up to MTTF = 8years) to observe the potential losses avoided by improving the reliability. Values for P(RVI > 1) are calculated for incremental values of Q.

8.5.2. Results

Figure 8-8 indicates the probability of satisfying the reliability value index decision making criteria given a reliability improvement investment, Q. The results confirm that as Q increases so the probability that the investment adds value decreases.

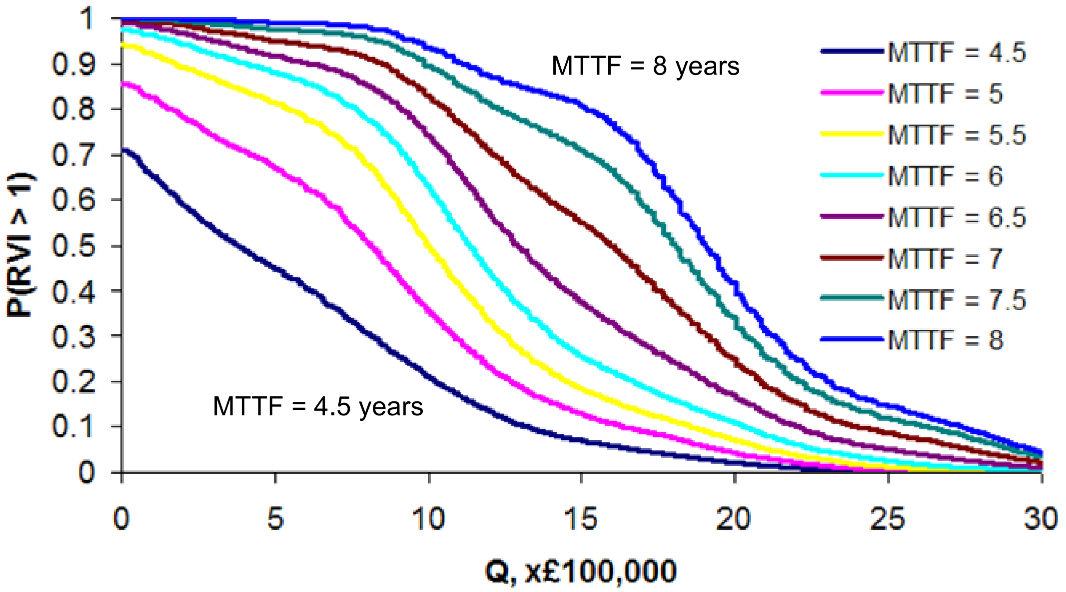


Figure 8-8: P(RVI > 1) for increasing values of Q.

8.6. Chapter summary

This chapter has demonstrated the application of the RVI decision metric and decision scenarios defined by the RVI breakdown structure. Decision scenarios 1 and 2 are presented to validate the application of the RVI metric against the existing concepts of life cycle costing and economics of reliability. Decision scenarios 3 and 4 demonstrate the unique application of the RVI breakdown structure to investing in reliability analyses and specifying a reliability improvement budget.

ISO 15663-2 (2001) recommends that during the concept selection phase, traditional investment criteria, such as net present value, profitability index and internal rate of return, are the preferred decision metrics to drive life cycle costing applications. Based on the results generated in Table 8-5, these criteria, with the possible exception of IRR, only suggest a marginal preference for the multiphase pumping option. Implementing the RVI metric and applying the change system reconfiguration decision scenario appears to generate more definitive results. The application of the RVI breakdown structure explicitly considers the change in future cash flow as a result of a design decision. For concept selection, this requires a pair wise comparison between options that evaluates one concept against another by trading off the extra capital expenditure required against the future change in cash flow as a result of the decision to change options. In the example provided, the water injection concept drops out quite clearly (it is also the least favoured when considering the traditional life cycle costing metrics) leaving the two pumping options. However, using the tradition investment appraisal techniques, these options are not clearly differentiated. By applying the RVI breakdown structure the comparison of the two options is simplified down to a decision to invest £1 million to achieve a future cash flow benefit of £0.6 million, which does not satisfy the investment criteria.

Decision scenario 2 as with decision scenario 1 is presented to demonstrate compliance with more conventional applications. The economics of reliability model clearly demonstrates the trade off between capital expenditure and operating expenditure when considering the optimal number of elements logically arranged in parallel, and hence reliability, required to minimise life cycle cost. However, separating the CAPEX and OPEX derives a preoccupation with cost. The RVI breakdown structure, when applied to the same decision, ultimately returns the same result but the reporting structure only considers if the result of the decision is to enhance the project value. The application forces a change in focus, switching the driver for decision making from reducing cost to improving value.

The third decision scenario considers the primary purpose of the RVI breakdown structure, to assess the value of investing in reliability analyses. The decision under uncertainty, defined in Figure 8-4, is evaluated to determine the reliability and technical risk management capability required to manage the perceived system weakness. This capability is characterised by the ability to detect system weaknesses and subsequently mitigate the related probability of failure. The resultant switching point for the decision to invest is defined here as the reliability management efficiency frontier. It is this efficiency frontier that becomes the determining factor of whether or not reliability analyses add value to the project. The capability efficiency frontier supports the conventional view that, in terms of project management, control offers greater value than information. The decision to implement reliability analyses is dependent on the prior assumption that system weaknesses exist, the potential value that could be generated through mitigating these weaknesses and the reliability management efficiency frontier that characterises the organization. However, it is the cost efficiency with which an organization can actively influence the probability of failure that ultimately drives the decision to implement reliability analyses. If the design decision maker has no intention of reacting to the analyses, or has no ability to influence the design's reliability then there is no value in performing reliability analyses. In fact, under these circumstances, the implementation of reliability analyses actually deteriorates project value.

The RVI breakdown structure used to determine if reliability analysis adds project value requires some very specific data. This data includes:

- A prior assumption that system weakness exists in the system;
- A probability of failure that characterises the system weakness;
- The cost associated with the system weakness being exposed during operations;

- Data characterising the ability with which the organization performing the analysis can identify system weaknesses;
- Data characterising the ability with which the organization can mitigate system weakness; and
- Data characterising the cost of mitigating the system weakness in design.

Much of this data is specific to the individual project and the reliability and technical risk management capability of the organization and may, in fact, be unknown or at least uncertain. The prior assumption that a system weakness exists can be inferred from a process such as technical risk categorisation. Through technical risk categorisation, API RP 17N (2007) implies that up to four classes of systematic failure can be introduced into a system as a result of technological, architectural, environmental and organizational uncertainties. If these systematic failure modes escape the project delivery process then they are revealed as early life failures, which observe a high operational cost of failure. While the cost to replace or repair equipment that has failed may be estimated, the probability with which this event occurs is highly uncertain; much of the data available in industry standard reliability databases does not reflect early life or systematic failures.

The data characterising the reliability efficiency frontier and the response to identifying system weakness in design is specific to the system weakness and the organization. Williams *et al*. (2003) present a five level reliability capability maturity model, which describes the increasing ability of organizations to manage reliability achievement in projects. While this does not discuss the reliability efficiency frontier, it follows that as an organization's reliability capability maturity level increases so their reliability efficiency frontier expands.

As the reliability efficiency frontier expands, the likelihood with which reliability analyses adds value also increases.

Case 4 demonstrates the use of the RVI breakdown structure to specify the budget for reliability improvement. The methodology supposes that by discounting the improvement in cash flow as a result of a specified reliability improvement a budget to achieve that improvement can be estimated. Due to the stochastic nature of reliability performance, the probability with which the budget adds value is dependent on the fraction of the future cash flow benefit allocated to the reliability improvement activity. The approach is similar to that of the sensitivity analysis recommended in the life cycle costing standards (ISO 15663-1, 2000) but this application focuses solely on the benefit in cash flow after a design decision to identify an investment amount that can be fed back into the project in order to achieve the specified reliability improvement. The purpose of the RVI structure and the allocation of a reliability improvement budget is to analyse the propagation of design for reliability decisions (specifically analysis) through the life of the project and as such does not give an opportunity for cost cutting.

The reliability value index and its associated breakdown structure are reliability and technical risk management specific applications of life cycle costing, not previously considered in the literature. The breakdown structure reflects how the output generated through reliability analyses propagates through the remaining life of the project and is intended to support decision makers in planning for design for reliability. Central to this is the ability with which organizations actively influence system reliability, which is characterised by the reliability efficiency frontier. Organizations that consider reliability as a source of competitive advantage should actively seek methods that enhance their reliability capability maturity and hence expand their reliability efficiency frontier. The following chapter discusses the measures, such as decentralising reliability and technical risk management, which can help to expand the reliability efficiency frontier, making more reliability effort potentially value added.

9. Discussion and Final Conclusions

9.1. Introduction

90% of deep sea hydrocarbon reserves are not economically feasible (Chitwood *et al*. 2004) due to the cost associated with installing more traditional topside host facilities (Leffler *et al*. 2003). The current trend to achieve economic feasibility is to reduce the capital expenditure, often accomplished through the deployment of subsea equipment. The financial benefit afforded to a field development project by deploying subsea equipment is offset by the potential risk of high operational costs associated with subsea failure. In an attempt to tackle the potential risks to reliability achievement, the industry has produced API RP 17N (2007), a subsea specific framework for reliability and technical risk management.

A key component of reliability and technical risk management is the reliability analysis that supports many of the primary activities associated with the management system. These analyses, in theory, are implemented to influence design by identifying weaknesses introduced to the system. However, all projects are different and reliability and technical risk management systems, such as that proposed in API RP 17N (2007), cannot be applied in the same fashion for all projects. Engineers applying the recommended practice need a rational methodology to provide evidence to decision makers, early in design decision making process, of the value of investing time and management effort in design for reliability activities during the design life cycle.

Existing techniques such as life cycle costing do specify reliability analyses as cost elements that can be included within a cost breakdown structure, but only as cost consuming activities. Applications of life cycle costing presented in the literature do not consider the potential value generate from reliability analyses. In order for reliability analysis to add value, they must have the ability to influence design decisions and therefore must be considered in terms of how actions resulting from analyses effect the remaining project life cycle. A potential reliability value framework is presented herein, as an advanced life cycle costing application, to support the reliability management planning process.

The framework derives an RVI breakdown structure that describes the logical decomposition of the cash flow elements required to calculate the reliability value index, a value metric based on the profitability index. The breakdown structure is presented to reflect a generic decision scenario where the effects of reliability analyses propagate through the design process, via a design response to the analysis and the subsequent effect on the operational cash flow. Quantifying the resultant reliability value index confirms if the decision scenario has the potential to enhance project value.

While the potential reliability value framework can be applied to more conventional investment decisions, the intended application is to support the planning process. The reliability value index and its associated breakdown structure are driven by the cost efficiency with which organizations can identify and mitigate system weaknesses. It is this organizational characteristic, presented here as the reliability management efficiency frontier, that defines if reliability analyses add project value.

9.2. *Decentralising Reliability Management to Enhance the Reliability Management Efficiency Frontier*

Traditionally, reliability is managed through a central reliability function. This structure is expensive to maintain and is subject to the possibility of a specialist discipline silo becoming disjointed from the rest of the project organization. The centralisation of the reliability function is the cause for many of the barriers to implementing reliability and technical risk management, specifically the industries perception of the reliability discipline and the lack of knowledge of failure causation. One organizational solution is to decentralise reliability and technical risk management. Figure 9-1 provides an organizational structure for a subsea project, which reflects the decentralised reliability function.

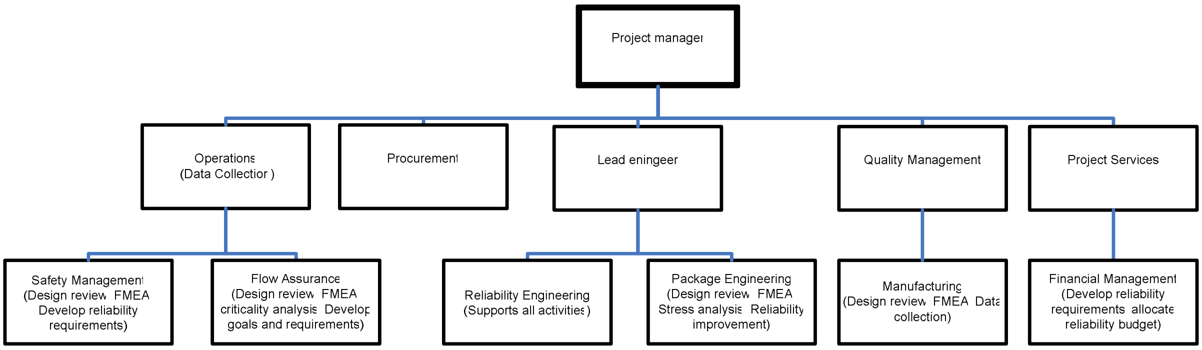


Figure 9-1: Centralised reliability function within project organization structure (developed from Brall, 2004).

The major project functions (operations, procurement, engineering, quality management and project services) all assume some responsibility for reliability and technical risk management. A (small) reliability engineering function is still present in the organization to support some of the more specialist activities. The organizational structure indicates that the specialist reliability function is subordinate to engineering. Despite the affinity between quality and reliability, it is this author's opinion that quality is a more necessary feature of reliability than reliability is of quality. As a result the reliability function cannot be a subordinate to quality in any project organization.

While decentralised reliability and technical risk management is proposed here as a method for enhancing the reliability management efficiency frontier there are other benefits that can result from decentralisation. The expense relating to a central reliability function has been discussed; decentralising the reliability and technical risk management function should reduce the specialist headcount and hence the project overhead associated with sustaining a centralised reliability function. While this is perhaps not a significant CAPEX reduction for an individual project, it is more attractive as a long term objective of sustaining competitive advantage, especially for smaller organizations.

By decentralising the reliability function, awareness and responsibility for application of the reliability activities expands to other project functions. The decomposition of a specialist reliability discipline silo widens the scope of involvement throughout the organization by integrating the reliability and technical risk management activities into the pre-existing project organization structure. As the scope of involvement widens throughout the organization, different project functions are exposed to the reliability strategy and greater awareness of the reliability discipline is generated throughout the organization. Training can increase awareness of the reliability strategy and is a pivotal starting point of the roll out of any strategy but increasing the scope of application to the other project functions provides direct exposure. Decentralisation of reliability will only work if certain reliability activities become an integral part of the skill set required for a given project function. Figure 9-1 suggests the reliability skill set that each project function should be conversant with or actively implement.

The lack of knowledge of failure causation results from poor communication of the information relating to failure. While a decentralised reliability function may not remove the fear of a blame culture within a project organization, it can enhance the communication between project functions in terms of the reliability objectives, how they might be achieved and what might prevent their achievement. By increasing reliability awareness and communication between project functions through decentralising the reliability function, the capability efficiency frontier should expand. A decentralised reliability function means that more people are involved in the collection and communication of data, thus increasing the probability that system weaknesses are found. Ultimately, organizations with greater awareness and an increased likelihood of identifying system weakness are less likely to institutionalise a blame culture due to their greater understanding of the organization dependencies that lead to failure. Furthermore with the reduced overhead generated from the decomposition of the specialist reliability discipline silo more resources could be afforded to investigating where reliability improvements might be made.

It has been reported in the literature that up to 85% of the life cycle cost is committed at the end of FEED, which is the point at which the performance or functional specification is constructed. Some of this committed cost is unnecessary and relates to equipment failure as a result of poorly specified reliability. By enhancing the communication of reliability goals and requirements throughout the project organization some unnecessary failure cost can be avoided.

9.3. *Central guidance to decentralised reliability and technical risk management*

Decentralised reliability and technical risk management is not without its own potential problems. The greatest potential weakness of decentralising reliability and technical risk management is uncontrolled decision making based on what the decision maker believes to be the optimum solution. Decentralised decision making is not necessarily the best for the organization or project as a whole as these 'local' decisions can result in conflicts of interest unless they are guided centrally. That is a common driver for reliability and technical risk management is required to influence consistent decision making.

This research has proposed a reliability value index and RVI breakdown structure as a common guide. The approach requires that the effects of design reactions to reliability analysis are propagated through the remaining project life to determine if they add value to the project. The responsibility and participation in analyses by multiple project functions means that the propagation of design reactions to analysis is better understood throughout the organization. Decisions are not made based on an individual's perception on what is best for the project or the project function that they are accountable for.

What this means in reality is that it is the process of assessing the decision scenario described by the RVI breakdown structure that actually becomes the common guidance for decentralised reliability and technical risk management. To recall, the decision scenario commences with reliability analysis, intended to identify potential weaknesses in the system. As a result of the analysis a design reaction is proposed, which is analysed to determine if its effects, when propagated through the remaining project life, add value. That is the application of reliability analysis, as defined by the decision scenario in the RVI breakdown structure, becomes the primary vehicle of central guidance. Figure 9-2 expands the decision scenario to include the application of the reliability analyses.

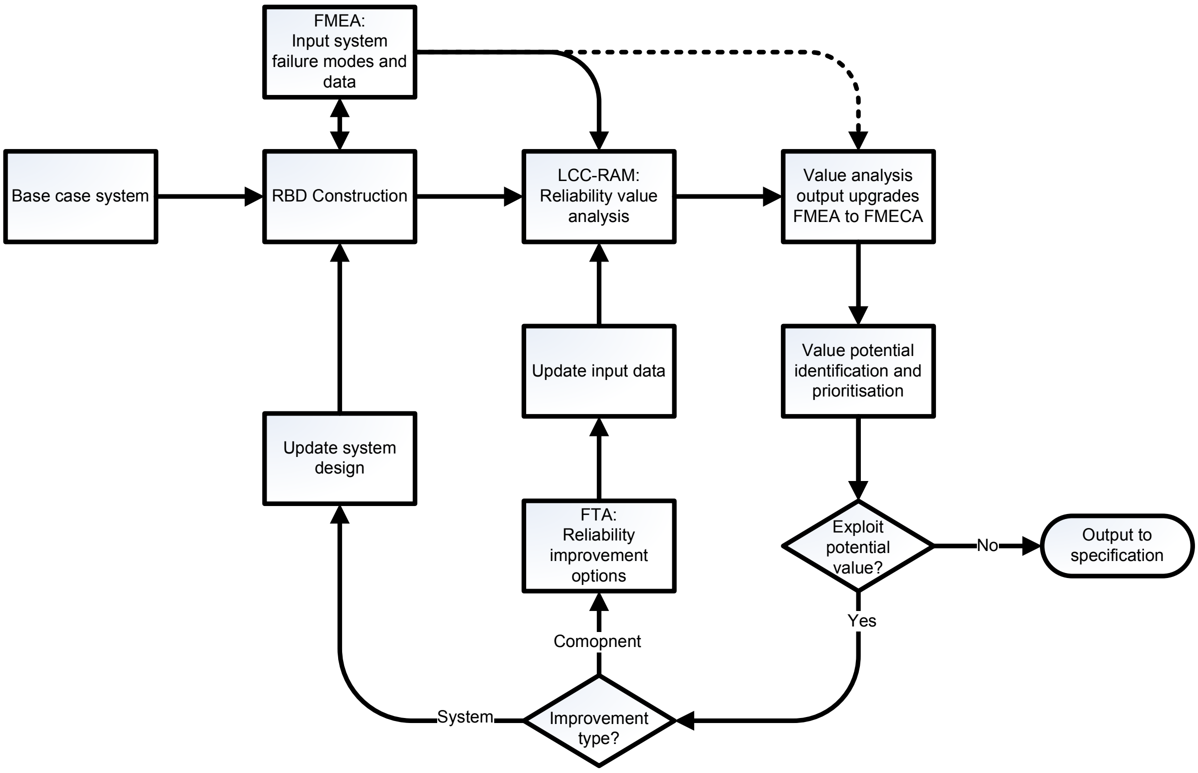


Figure 9-2: Central guidance for the application of reliability analyses.

The decision scenario commences with the development of a technically feasible design option which is treated as the base case. This design feeds into the construction of a reliability block diagram to represent the system reliability logic, which also defines the system failure modes. Based on the system reliability logic defined by the reliability block diagram a failure modes and effects analysis is performed to determine the failure modes, how they propagate through the system and collect the data required for the reliability value index calculation. That is the failure modes identified by the reliability block diagram drives the data collection for reliability centred life cycle costing via a failure modes effect analysis.

The output from the initial analysis is the criticality of the failure modes in terms of life cycle cash flow. Sensitivity analysis is performed to identify where the greatest scope for value improvement exists within the system and this information is fed back into the FMEA, upgrading it to a ‘potential value FMECA’. Here, the ‘criticality’ in failure modes effect and criticality analysis refers to the potential value that could be realised through improving the reliability from the base case, thus prioritising where to focus design improvements. As the criticality is reported in terms of life cycle cash flow, it is not subject to the criticisms of the risk priority number. It is this FMECA, then, that becomes the reporting structure intended to influence a design reaction.

Having identified where reliability improvements can add the most value, the decision reaction is defined. These reactions are considered either as system reconfigurations or component reliability growth. Improvements at the component level observe the first feedback loop, whereby the fault tree analysis is performed in order to identify how reliability growth might be achieved. The potential value FMECA is updated to capture the change in cash flow as a result of the reliability growth design reaction. Subsequently the RVI breakdown structure is resolved to determine if the design reaction adds value or to allocate a budget for the reliability achievement. The second feedback loop occurs when the design reaction is system reconfiguration. In this case either the system reliability logic (and hence RBD) is changed and or the FMEA is updated to reflect that the base case has changed in terms of the technology deployed.

This process is unavoidably data intensive and data sensitive. However, with a decentralised reliability function data is collected across the project organization and no one division is solely responsible for the data collection or analysis; more importantly all divisions are involved in the process and acceptance of a decision reaction could be further supported by qualitative discussion of the effects of the design reaction just as much as quantitative assessment.

9.4. The potential value FMECA

Reliability value analysis is intended to facilitate proactive value addition through reliability improvement. This is achieved through conducting sensitivity analysis to identify the major potential value drivers. Figure 9-2 indicates this process in terms of the interaction of the existing reliability analysis toolkit and suggests the use of a FMEA style worksheet to collect and present the data. The FMEA technique is widely used throughout all industries and is perhaps the most accessible component of the design for reliability toolkit. As the organizational structure for decentralised reliability management suggests, many project functions should be involved in the FMEA process. Using a modified FMEA approach to drive the reliability value process facilitates its implementation and increases awareness of the implications of reliability and cost. Appendix C suggests the format for a potential value FMECA worksheet.

While the modified FMEA worksheet can present the component parts of the RVI, without graphical representation, the decision maker can be rendered insensitive to the scale of the investment. To compensate, a value decision matrix (Figure 9-3), is proposes as a replacement for the criticality matrix of the traditional FMECA. The potential value matrix, rather than prioritising high criticality equipment or failure modes, is used to prioritise design reactions.

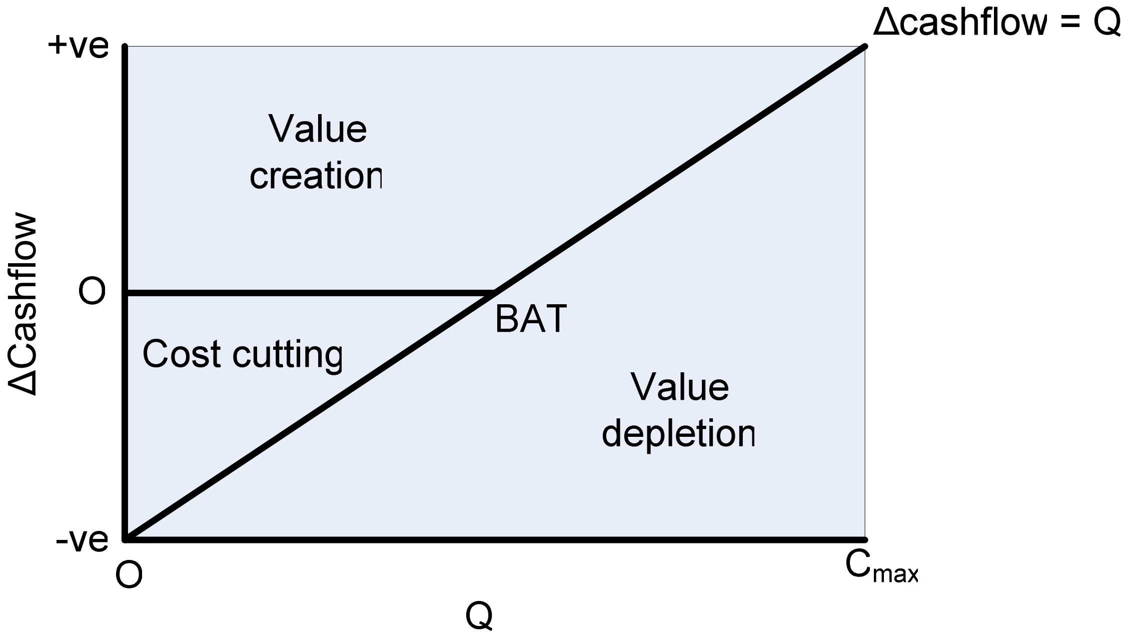


Figure 9-3: Potential value criticality matrix.

The potential value matrix plots the cost of the reliability investment against the change in operational cash flow as a result of the reliability improvement. The best available technology (BAT) is centred in the matrix as a point of reference. The diagonal Δcashflow = Q represents the iso-value line of BAT, which indicates the required cash flow performance given any cost to return the same reliability value as that observed by the best available technology (RVI = 1). There are three broad areas covered by the potential value matrix, which have been labelled; 'value depletion', 'value creation' and 'cost cutting'. 'Value depletion' occupies all those instances where the design reaction does not satisfy the RVI acceptance criterion (i.e. all instances where RVI < 1). 'Value creation' represents those instances where the reliability value index decision making criterion is satisfied (RVI > 1).

The final area, ‘cost cutting’ indicates where the reliability value has been improved, but the performance has dropped, relative to BAT, as a result. This is viewed as the wrong objective of the potential reliability value process. Application of the matrix should plot the design alternatives assessed during the second phase of the potential reliability value process to prioritise the reliability improvement activities.

9.5. Concluding Remarks and Future Research Opportunities

Since first stepping offshore in the 1800s, the oil and gas industry has increasingly moved to more remote locations in an attempt to exploit the World’s hydrocarbon reserves. As these reserves are discovered in deeper offshore locations, so the use of traditional technologies for offshore production (i.e. fixed platforms) becomes uneconomical and technically infeasible. The solution is to deploy subsea technology which vastly reduces the capital expenditure compared with the original technology. Trading off the reduction in CAPEX is the risk of high operational expenditures associated with subsea failure. This has spurred the development of reliability strategies aimed at reducing the risk of operational failure through front loading effort and resources to assure that the required or target reliability is observed in service. The implementation of such a strategy is counter to the conventional wisdom of achieving economic feasibility through CAPEX minimisation and as such requires a decision framework to demonstrate how investing in reliability and technical risk management can enhance project value.

The combination of financial appraisal and reliability analysis is not novel; the life cycle costing methodology emphasises the relationship between system reliability and life cycle cost to drive design decisions. However, there is no evidence in the literature of implementing life cycle costing to justify the application of reliability analyses. In response, this research proposes a potential reliability value framework, which offers the following contribution to knowledge.

The primary contribution is the reliability value index and its associated RVI breakdown structure. Central to the potential reliability value framework, the RVI breakdown structure is an advanced life cycle costing application that explicitly considers how reliability analysis affects the remaining project life cycle cash flow as a means to justify reliability analyses based on its potential value addition. Conventional life cycle costing does include reliability analyses, but only as a cost consuming activity. The RVI breakdown structure focuses explicitly on a decision scenario, which commences with reliability analysis and propagates its effects through the remaining project life cycle. The structure is value, rather than cost, based, which avoids the preoccupation with cost. This decision making framework targets improving project value through enhanced reliability.

The RVI breakdown structure identifies that reliability and technical risk management is dependent on the ability with which an organization can locate and mitigate system weakness. That is the potential value generated from reliability analyses is dependent on the cost efficiency with which an organization can both identify potential system weaknesses and improve reliability. The limiting capability, which influences if an organization can improve project value, is defined as the reliability management efficiency frontier. The research has proposed that in order to expand the reliability management efficiency frontier, an organization should adopt a decentralised approach to reliability and technical risk management. Decentralising the reliability management function both reduces the cost of retaining reliability expertise but also exposes the remaining project functions to the field of design for reliability. In doing so, the project organization gains greater awareness of the causes of failure and is potentially more capable of improving the reliability.

Decentralised reliability management is not without its flaws. Without central guidance, decentralised decision making can lead to conflicts of interest and option selection that does not represent the optimum solution for the organization. The final contribution of the potential value framework is its application as common guidance for design for reliability decisions. Specifying the application of reliability analysis, as defined by the decision scenario in the RVI breakdown structure, becomes the central guidance for decentralised reliability and technical risk management. This reduces the effort needed to plan for reliability analyses as the approach taken to assess the value of the initial analyses (as defined by the decision scenario) incorporates all the necessary components of the reliability engineers' toolkit.

The application of the potential reliability value index to specify a budget for reliability improvement and the implementation of a decentralised reliability and technical risk management function introduces some interesting opportunities for further research. Of note is the use of specifying a reliability improvement budget as a tool to provide financial incentives to suppliers to improve the reliability of their hardware based on a rank order tournament game theory model. Lazear and Rosen (1981) introduced the tournament model as a compensation scheme, which pays out based on rank order rather than output level and has been used to influence supplier selection based on quality (Deng and Elmaghraby, 2005). The game theory model classifications (Wang and Parlar, 1989) are briefly addressed below as a starting point for research in reliability based supplier selection tournaments.

- **Number of players:** There are four players in a tournament model; two suppliers of subsea hardware and two operators. The operators represent an oil major and a smaller operator (or collection of smaller operators). Expansion of the supply base provides further scope for the possible development of the model.
- **Nature of the payoff function:** The tournament is a nonzero-sum game, all participants are assumed to realise a profit. However, this application is interested in level of incentive required to generate a suitable improvement in product reliability for the oil major.
- **Pre-play negotiation:** It is assumed that the suppliers are not colluding; therefore, this is a non-cooperative model.
- **State of information available:** Each supplier knows the (historical) industry MTTF as per the ORDEA database; that this is the base case reliability offered by supplier.
- **Involvement in time:** In practice, the tournament should be repetitious but in the first instance, this should be treated as a static game. This would provide significant scope for further development of the model should the proof of concept be successful.

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Appendix A – Example RBD Visio Report

Master Name	*Shape ID*	*Name*	*BeginX*	*BeginY*	*EndX*	*EndY*	*Connection1X*	*Connection1Y*	*Connection2X*	*Connection2Y*	*Connection3X*	*Connection3Y*	*Connection4X*	*Connection4Y*	*Cost*	*MTTF*	*MTTR*
Connection	15		0.71	10.83	1.08	10.83											
Connection	16		2.07	10.83	2.36	10.83											
Connection	17		3.35	10.83	3.67	10.83											
Connection	18		4.66	10.83	5.01	10.83											
Connection	19		5.99	10.83	6.38	10.83											
Connection	20		6.87	10.53	6.87	10.04											
Connection	21		6.87	9.45	6.87	8.96											
Connection	22		6.87	8.37	6.87	7.68											
Connection	23		6.87	7.09	6.87	6.54											
Connection	24		6.87	5.94	6.87	5.36											
Connection	25		6.87	4.77	6.87	4.46											
Connection	26		6.87	3.87	6.87	3.52											
Connection	27		6.87	2.93	7.48	2.07											
RBD block	2	Umbilical					1.08	10.83	2.07	10.83	1.57	10.53	1.57	11.12	2030000	26.5	32
RBD block	3	Subsea Control					2.36	10.83	3.35	10.83	2.85	10.53	2.85	11.12	715000	2.3	20.5
RBD block	4	Subsea Distribution					3.67	10.83	4.66	10.83	4.16	10.53	4.16	11.12	730000	3.2	21
RBD block	5	Topside control					5.01	10.83	5.99	10.83	5.5	10.53	5.5	11.12	50000	1.33	0.5
RBD block	6	Pipe					6.38	10.83	7.36	10.83	6.87	10.53	6.87	11.12	8250000	285.19	90
RBD block	7	Subsea isolation system					6.38	9.74	7.36	9.74	6.87	9.45	6.87	10.04	745000	380.5	21.5
RBD block	8	Riser elements					6.38	8.66	7.36	8.66	6.87	8.37	6.87	8.96	745000	36.8	33
RBD block	9	Flowbase					6.38	7.38	7.36	7.38	6.87	7.09	6.87	7.68	2055000	24.27	30.5
RBD block	10	Wellhead					6.38	6.24	7.36	6.24	6.87	5.94	6.87	6.54	2000000	1140	30.5
RBD block	11	XT					6.38	5.07	7.36	5.07	6.87	4.77	6.87	5.36	2000000	5.14	21.5
RBD block	12	Tubing hanger					6.38	4.16	7.36	4.16	6.87	3.87	6.87	4.46	750000	167.8	60.5
RBD block	13	Pump					6.38	3.23	7.36	3.23	6.87	2.93	6.87	3.52	5500000	3.5	23
RBD end node	14						7.48	2.07									
RBD start node	1										0.71	10.83					

Appendix B – VBA Code for Reliability Value Analysis

```
Option Explicit
Option Base 1

'Reference variables with set integer values (e.g. the number of blocks in the RBD)
Dim NCols As Integer, NRows As Integer, Items As Integer, Links As Integer, Blocks As Integer
Dim RBDBlocks As Integer, SysStates As Integer, TTBlocks As Integer, StartNode As Integer
Dim EndNode As Integer, SBlockOffset As Integer, EBlockOffset As Integer, StartOffset As Integer

'Valirables used in the system assessment simulation (e.g. time to failure)
Dim OpsLife As Single, EventTime As Single, eventcost As Single, eventDT As Single, EventYear As Integer
Dim LCC As Single, unavailability As Single, discRate As Single

'Variables for counting through loops
Dim i As Integer, p As Integer, n As Integer, x As Integer, y As Integer, z As Integer
Dim a As Integer, b As Integer, c As Integer, d As Integer, e As Integer
Dim counter As Integer, xcounter As Integer, ycounter As Integer, sim As Integer

'Boolean variables
Dim path As Boolean, Found As Boolean, SysFailed As Boolean, StopSim As Boolean

'Arrays
Dim CNexLink() As Integer, CNexMatrix() As Integer, SysCNex() As Integer
Dim cost() As Single, mttf() As Single, mttr() As Single, random(500) As Single
Dim sysmttf() As Single, faileditem() As Integer, syscost() As Single, sysDT() As Single
```

```
Dim LTCost(10000) As Single, LTAvailability(10000) As Single

Sub FormatVisoReport()

    'Rows("1:1").Select
    'Selection.Delete Shift:=xlUp
End Sub


Sub GetOpsLife()
'User iput to define the operational lifetime of the field in years
Sheets("Visio Report").Select

With Range("A1")
    NRows = Range(.Cells(1, 1), .End(xlDown)).Rows.Count
End With

Range("A1").Offset(NRows + 2, 0).Name = "OpsLife"

Range("OpsLife").Value = InputBox("What is the operational liftime, in years?")

Range("A1").Offset(NRows + 3, 0).Name = "DiscountRate"

Range("DiscountRate").Value = InputBox("What is the discount rate, as a decimal?")

Range("A1").Offset(NRows + 4, 0).Name = "Availability"
Range("A1").Offset(NRows + 5, 0).Name = "LCC"

Range("A1").Offset(NRows + 4, 1).Formula = "=RiskOutput(""Availability"")+Availability"
Range("A1").Offset(NRows + 5, 1).Formula = "=RiskOutput(""LCC"")+LCC"
```

```
End Sub
Sub SystemAssess()

Sheets("Visio Report").Select

With Range("A1")
   NCols = Range(.Cells(1, 1), .End(xlToRight)).Columns.Count
   NRows = Range(.Cells(1, 1), .End(xlDown)).Rows.Count
End With

   'Range(Range("A1"), Range("A1").Offset(NRows - 1, NCols - 1)).Select
   'Selects the range that houses the Viso Report

   Items = NRows - 1

   'MsgBox "There are " & Items & " items in the RBD"

   Links = 0
      For i = 1 To Items
         If Range("A1").Offset(i, 0).Value = "Connection" Then Links = Links + 1
      Next

   'MsgBox "There are " & Links & " links in the RBD"

   Blocks = 0
      For i = 1 To Items
         If Range("A1").Offset(i, 0).Value = "RBD block" Or _
         Range("A1").Offset(i, 0).Value = "RBD start node" Or _
         Range("A1").Offset(i, 0).Value = "RBD end node" Then Blocks = Blocks + 1
      Next
```

```
RBDBlocks = 0
   For i = 1 To Items
      If Range("A1").Offset(i, 0).Value = "RBD block" Then RBDBlocks = RBDBlocks + 1
   Next

'MsgBox "There are " & Blocks & " Blocks in the RBD"

   Found = False
      For a = 1 To NCols
         If Range("A1").Offset(0, a).Value = "BeginX" Then
            Found = True
            Exit For
         End If
      Next

   If Found = True Then Range("A1").Offset(0, a).Name = "BeginX"

   Found = False
      For b = 1 To NCols 'Rows
         If Range("A1").Offset(0, b).Value = "Connection1X" Then
            Found = True
            Exit For
         End If
      Next

   If Found = True Then Range("A1").Offset(0, b).Name = "Connection1X"

   Found = False
      For c = 1 To NRows
```

```
      If Range("A1").Offset(c, 0).Value = "Connection" Then
         Found = True
         Exit For
      End If
   Next

If Found = True Then Range("A1").Offset(c, 0).Name = "Link"

Found = False
   For d = 1 To NRows
      If Range("A1").Offset(d, 0).Value = "RBD block" Then
         Found = True
         Exit For
      End If
   Next

If Found = True Then Range("A1").Offset(d, 0).Name = "RBD_Block"

Found = False
   For d = 1 To NRows
      If Range("A1").Offset(d, 0).Value = "RBD start node" Then
         Found = True
         Exit For
      End If
   Next

If Found = True Then Range("A1").Offset(d, 0).Name = "Start_Node"
StartNode = Range("Start_Node").Offset(0, 1).Value

Found = False
```

```
      For d = 1 To NRows
         If Range("A1").Offset(d, 0).Value = "RBD end node" Then
            Found = True
            Exit For
         End If
      Next

   If Found = True Then Range("A1").Offset(d, 0).Name = "End_Node"
   EndNode = Range("End_Node").Offset(0, 1).Value

   Range("Link").Offset(0, a).Name = "StartBeginX"
   Range("Link").Offset(0, a + 2).Name = "StartEndX"
   Range("RBD_Block").Offset(0, b).Name = "StartConnectOne"
   Range("RBD_Block").Offset(0, b + 2).Name = "StartConnectTwo"
   Range("RBD_Block").Offset(0, b + 4).Name = "StartConnectThree"
   Range("RBD_Block").Offset(0, b + 6).Name = "StartConnectFour"
   Range("RBD_Block").Offset(0, b + 8).Name = "Cost"
   Range("RBD_Block").Offset(0, b + 9).Name = "MTTF"
   Range("RBD_Block").Offset(0, b + 10).Name = "MTTR"


'create array for connection list
ReDim CNexLink(2, Links)

'Finding connection point of block that corresponds to starting point of link and put in array
For c = 1 To Links
   For d = 0 To Blocks - 1

      If Range("StartBeginX").Offset(c - 1, 0).Value = Range("StartConnectOne").Offset(d, 0).Value And _
         Range("StartBeginX").Offset(c - 1, 1).Value = Range("StartConnectOne").Offset(d, 1).Value Then
```

```
        CNexLink(1, c) = Range("RBD_Block").Offset(d, 1).Value
        Exit For

    ElseIf Range("StartBeginX").Offset(c - 1, 0).Value = Range("StartConnectTwo").Offset(d, 0).Value And _
      Range("StartBeginX").Offset(c - 1, 1).Value = Range("StartConnectTwo").Offset(d, 1).Value Then

        CNexLink(1, c) = Range("RBD_Block").Offset(d, 1).Value
        Exit For

    ElseIf Range("StartBeginX").Offset(c - 1, 0).Value = Range("StartConnectThree").Offset(d, 0).Value And _
      Range("StartBeginX").Offset(c - 1, 1).Value = Range("StartConnectThree").Offset(d, 1).Value Then

        CNexLink(1, c) = Range("RBD_Block").Offset(d, 1).Value
        Exit For

    ElseIf Range("StartBeginX").Offset(c - 1, 0).Value = Range("StartConnectFour").Offset(d, 0).Value And _
      Range("StartBeginX").Offset(c - 1, 1).Value = Range("StartConnectFour").Offset(d, 1).Value Then

        CNexLink(1, c) = Range("RBD_Block").Offset(d, 1).Value
        Exit For

    End If

  Next d

Next c

'Finding connection point of block that corresponds to end point of link
For c = 1 To Links
```

```
For d = 0 To Blocks - 1

  If Range("StartEndX").Offset(c - 1, 0).Value = Range("StartConnectOne").Offset(d, 0).Value And _
    Range("StartEndX").Offset(c - 1, 1).Value = Range("StartConnectOne").Offset(d, 1).Value Then

      CNexLink(2, c) = Range("RBD_Block").Offset(d, 1).Value
    Exit For

  ElseIf Range("StartEndX").Offset(c - 1, 0).Value = Range("StartConnectTwo").Offset(d, 0).Value And _
    Range("StartEndX").Offset(c - 1, 1).Value = Range("StartConnectTwo").Offset(d, 1).Value Then

      CNexLink(2, c) = Range("RBD_Block").Offset(d, 1).Value
      Exit For

  ElseIf Range("StartEndX").Offset(c - 1, 0).Value = Range("StartConnectThree").Offset(d, 0).Value And _
    Range("StartEndX").Offset(c - 1, 1).Value = Range("StartConnectThree").Offset(d, 1).Value Then

      CNexLink(2, c) = Range("RBD_Block").Offset(d, 1).Value
      Exit For

  ElseIf Range("StartEndX").Offset(c - 1, 0).Value = Range("StartConnectFour").Offset(d, 0).Value And _
    Range("StartEndX").Offset(c - 1, 1).Value = Range("StartConnectFour").Offset(d, 1).Value Then

      CNexLink(2, c) = Range("RBD_Block").Offset(d, 1).Value
      Exit For

  End If

Next d
```

```
Next c

'create a reference connectivity matrix
ReDim CNexMatrix(Blocks + 1, Blocks + 1)

For c = 1 To Blocks
   CNexMatrix(1, c + 1) = Range("RBD_Block").Offset(c - 1, 1).Value
Next c

For c = 1 To Blocks
   CNexMatrix(c + 1, 1) = Range("RBD_Block").Offset(c - 1, 1).Value
Next c

For i = 1 To Links
   For c = 1 To Blocks
      If CNexMatrix(c + 1, 1) = CNexLink(1, i) Then ycounter = c + 1
   Next c

   For c = 1 To Blocks
      If CNexMatrix(1, c + 1) = CNexLink(2, i) Then xcounter = c + 1
   Next c

   CNexMatrix(xcounter, ycounter) = 1
Next i

For c = 1 To Blocks + 1
   If CNexMatrix(c, 1) = StartNode Then StartOffset = c
Next c

'redefines all arrays
```

```
    ReDim sysmttf(RBDBlocks)
    ReDim mttf(RBDBlocks)
    ReDim mttr(RBDBlocks)
    ReDim cost(RBDBlocks)
    ReDim faileditem(RBDBlocks)


    'populate reference arrays (cost, mttr and mttf)
    For z = 1 To RBDBlocks
        mttf(z) = Range("mttf").Offset(z - 1, 0).Value
        mttr(z) = Range("mttr").Offset(z - 1, 0).Value / 365.25 'coverted from days to years
        cost(z) = Range("cost").Offset(z - 1, 0).Value
    Next z

    'get the operational lifetime and redifine system cost and downtime arrays to operational lifetime
    OpsLife = Range("OpsLife").Value
    discRate = Range("DiscountRate").Value
    ReDim syscost(OpsLife)
    ReDim sysDT(OpsLife)
For sim = 1 To 10000
    counter = 0
        For n = 1 To RBDBlocks
            counter = counter + 1
            sysmttf(n) = -mttf(n) * Log(Rnd)
        Next n


    LCC = 0
    unavailability = 0
    StopSim = False
```

```
Do Until StopSim = True 'system life is greater than operational life
'take first n blocks of random numbers and multiply by component mttfs and put in sysmttf array

'find smallest non zero time
    EventTime = OpsLife + 1
    For n = 1 To RBDBlocks - 1
        If sysmttf(n) = 0 And sysmttf(n + 1) <> 0 Then
            EventTime = sysmttf(n + 1)
        ElseIf sysmttf(n) <> 0 And sysmttf(n + 1) = 0 Then
            EventTime = sysmttf(n)
        ElseIf sysmttf(n) <> 0 And sysmttf(n + 1) <> 0 And sysmttf(n) > sysmttf(n + 1) And sysmttf(n + 1) < EventTime Then
            EventTime = sysmttf(n + 1)
        ElseIf sysmttf(n) <> 0 And sysmttf(n + 1) <> 0 And sysmttf(n) < sysmttf(n + 1) And sysmttf(n) < EventTime Then
            EventTime = sysmttf(n)
        Else
        End If
    Next n

    EventYear = Int(EventTime) + 1
    'MsgBox ("year of failure is " & EventYear & "")

    If EventYear > OpsLife Then
        StopSim = True
        Exit Do
    Else
    End If

'determine which component has failed and put in failed item array
    For n = 1 To RBDBlocks
        If sysmttf(n) <= EventTime Then
```

```
         faileditem(n) = 1
      Else
         faileditem(n) = 0
      End If
   Next n

   'MsgBox ("time to first failure is " & EventTime & "")

'send component states through the connectivity matrix to determine system state
'Create system state connectivity matrix
   ReDim SysCNex(Blocks + 1, Blocks + 1)

   For c = 1 To Blocks + 1
      For d = 1 To Blocks + 1
         SysCNex(c, d) = CNexMatrix(c, d)
      Next d
   Next c

'copy failed components onto system state connectivity matrix

      For n = 1 To RBDBlocks
         If faileditem(n) = 1 Then
            For d = 1 To Blocks
               SysCNex(n + 1, d + 1) = 0
               SysCNex(d + 1, n + 1) = 0
            Next d
         Else
         End If
      Next n
```

```
'check system state connection matrix, paste into excel - take out of final code
    'Sheets("Visio Report").Select
    'For c = 1 To Blocks + 1
        'For d = 1 To Blocks + 1
            'Range("a22").Offset(d, c).Value = SysCNex(d, c)
        'Next d
    'Next c


'Path deterioration algorithm for assessing system state
    SysFailed = False
    x = StartOffset
    For y = 1 To Blocks
        If SysCNex(y + 1, x) = 1 Then
            x = y + 1
            If SysCNex(x, 1) = EndNode Then
                SysFailed = False
                Exit For
            Else
                y = 0
            End If
        Else 'SysCNex(y + 1, x) = 0
            If y >= Blocks And SysCNex(1, x) = SysCNex(1, StartOffset) Then
                SysFailed = True
                Exit For
            ElseIf y >= Blocks Then
                For d = 1 To Blocks
                    SysCNex(x, d + 1) = 0
                Next d
                x = StartOffset
```

```
         y = 0
      Else
      End If
   End If
Next y

eventcost = 0
eventDT = 0
'MsgBox ("counter = " & counter & ".")
If SysFailed = True Then
   For n = 1 To RBDBlocks
      If faileditem(n) = 1 Then
         eventcost = eventcost + cost(n) 'add repair cost for nth failure item
         eventDT = eventDT + mttr(n) 'add repair time for nth failed item
         counter = counter + 1
         'MsgBox ("counter = " & counter & ".")
         sysmttf(n) = EventTime + eventDT + (-mttf(n) * Log(Rnd)) 'get new component mttf from system mttf array
      Else
      End If
   Next n

   For n = 1 To RBDBlocks
      If faileditem(n) = 0 Then
         sysmttf(n) = sysmttf(n) + eventDT
      Else
      End If
   Next n
Else
   For n = 1 To RBDBlocks
      If faileditem(n) = 1 Then
```

```
          sysmttf(n) = 0
        Else
        End If
      Next n
    End If

    ReDim Preserve sysDT(OpsLife)
    ReDim Preserve syscost(OpsLife)
    sysDT(EventYear) = sysDT(EventYear) + eventDT
    syscost(EventYear) = syscost(EventYear) + eventcost
    unavailability = unavailability + eventDT

Loop


LTAvailability(sim) = (OpsLife - unavailability) / OpsLife

For n = 1 To OpsLife
  syscost(n) = syscost(n) * (1 / (1 + discRate) ^ n)
  LCC = LCC + syscost(n)
Next n

LTCost(sim) = LCC

Next sim

Sheets("Results").Select

For sim = 1 To 10000
  Range("a1").Offset(sim, 0).Value = LTCost(sim)
```

```
    Range("a1").Offset(sim, 1).Value = LTAvailability(sim)

Next sim
End Sub
```

Appendix C – Potential value FMECA Worksheet

Component	ID	Failure mode	Failure cause	Reliability parameters		Consequences			Potential losses	Potential value		
				η	β	MTTR	Vessel Req.	Repair cost		ΔReliability	ΔCashflow	Q