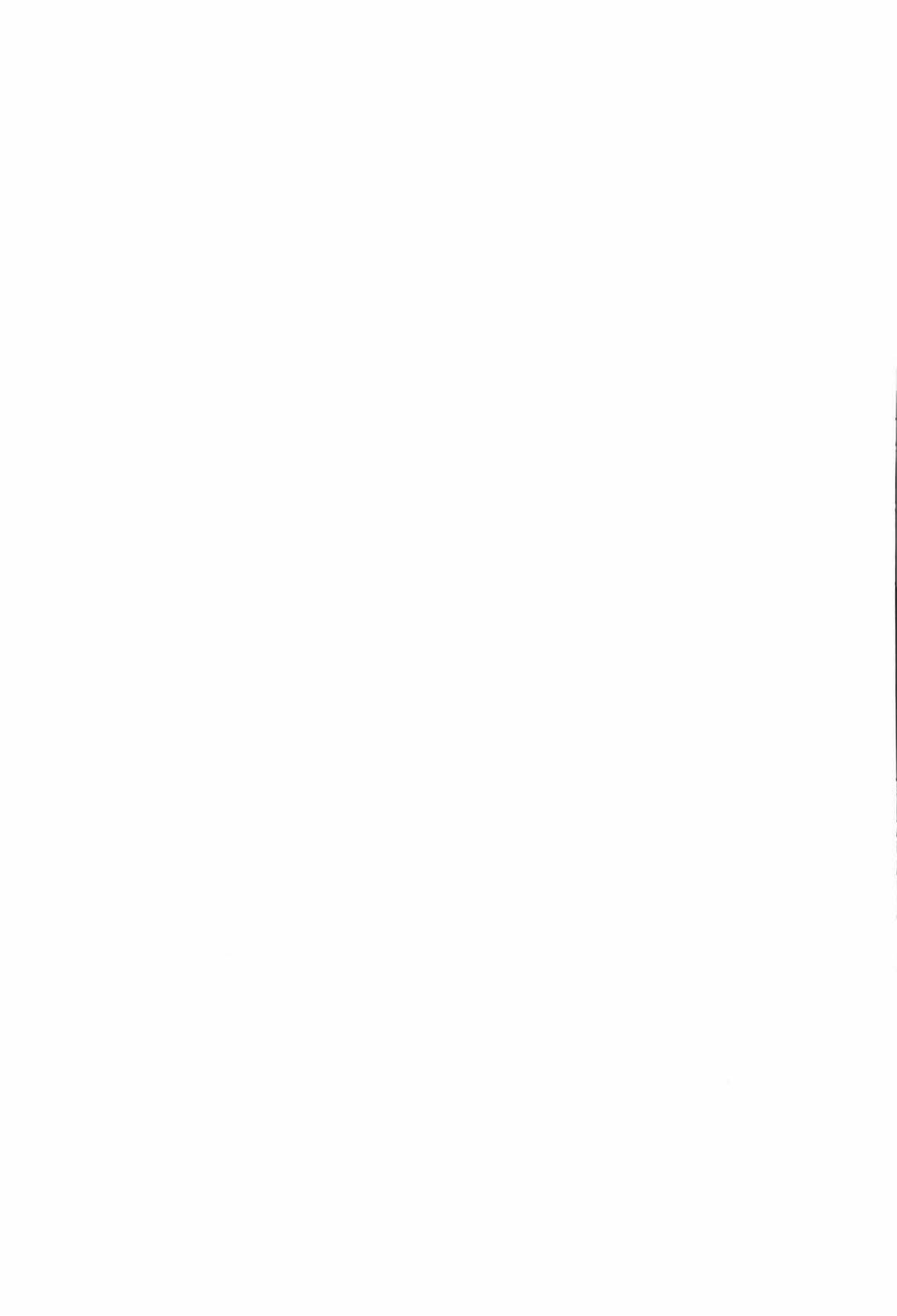# PROCESS DESIGN TESTING USING SIMULATION

A thesis presented in partial fulfilment of the requirements
for the degree of

MASTER
IN
TECHNOLOGY

At Massey University, Palmerston North, New Zealand.

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SUMMARY

Many industries are not getting full use out of their process equipment. Machine downtime due to breakdowns and unscheduled maintenance has been identified by SchemNZ Ltd as a major cause of under utilisation. The ability to schedule programmed maintenance before a breakdown occurs, rather than once something fails, and minimise the chance of breakdown through improved design will allow companies to operate more efficiently.

Improved methods of system design testing and a better knowledge of the types of faults and their causes will allow improved designs to be developed. Therefore, a scheme for design testing has been developed which includes components such as the identification of system and component reliability through data collection and simulation. A tool has been identified (Relex reliability software) that provides some component reliability information and facilities for system reliability modelling and simulation techniques such as Failure Mode Effect Analysis (FMEA).

A strapping machine and the 240-volt single-phase induction motor were chosen as case studies to identify the sorts of results that could be expected from modelling and simulation tools and to assess the feasibility of the design testing scheme.

The case studies resulted in the identification through modelling of a number of components in the strapping machine that have a high level of unreliability and could be the cause of many of the failures associated with the machine. In addition, the predominate failure modes for the induction motor were identified through FMEA models.

These results demonstrate that the design testing scheme can be used to predict the reliability of designs based on the past reliability of components. Furthermore, the most common or critical failure modes can be identified using FMEA allowing these failure modes to be targeted for prediction of prevention.

CONTRIBUTION TO LITERATURE

This chapter presents a summary of what this research contributed to its field of study and what specific documents were published apart from this thesis.

The contributions included:

- The conjecture of a structure for linking together tools such as existing software packages and databases with each other and with the ASK system.

- An introduction to the ASK system. Providing a unique way of linking engineers in the field with remote technical resources through the use of wireless audiovisual technology.

- A methodology was developed to allow existing simulation tools to be used to predict, prevent and identify specific types of mechanical failure in industrial systems. This was applicable both before systems were realised and after commissioning of the systems. The demonstration of how this research could be applied to practical situations.

The specific contributions to literature that were made as part of this research included a short correspondence, a paper presentation and a pair of posters. These are as follows:

- A short correspondence: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2003), Modelling for Predictive Maintenance and the Role of the Tele-expert. J Chin. Inst. Chem. Engrs. 34(6), 661-666.

- A paper presentation: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2002), Maintenance through the Tele-expert. In A Symposium on Maintenance Engineering, (pp. 15-24), New Plymouth, New Zealand: The Maintenance Engineering Society of New Zealand.

- A poster paper: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2002), Modelling for Predictive Maintenance and the Role of the Tele-expert. In 9th APPChE Congress and Chemeca 2002 (#572). Christchurch, New Zealand: The University of Canterbury

- An entry to the Foundation for Research Science & Technology (FRST) 2002 poster competition: Martin, N. K. L.: Design Testing Through Simulation.

In the case of the posters these publications demonstrated the research to a general audience while the paper and correspondence described the technical applications and implications of the research.

PREFACE

PROGRAMME OVERVIEW

The research described here, 'Design Testing Using Simulation,' is part of the larger programme 'Remote Process Performance Monitoring and Process Design Auditing'. The goal of this is to provide SchemNZ Ltd with the expertise and technological capability to remotely (internationally) monitor and diagnose the performance of processing and manufacturing plants. This will permit the client companies to schedule maintenance of equipment rather than react to unexpected equipment failures. In addition, it will allow the client companies to retain trained staff locally rather than attempt to duplicate skills in each international market.

PROJECT DESCRIPTION

Specifically this project investigates the use of process simulation software to audit process designs before construction and in particular, before overseas shipping. By trialing the software on a case study the company will gain confidence in the ability of the software to highlight problems with process designs.

Although the theoretical background for modelling and simulation has existed for some time, the application of these techniques is only becoming widely feasible with the advent of computers. Furthermore, the techniques are not yet as rigorous as those used in more traditional methods.

A large part of this project therefore is concerned with building techniques and systems that will enable further modelling to proceed in a high-quality fashion. The results of the simulation while important, are not the driving factor in this project. Rather the creation of a logical framework that can be applied to additional projects and the validation of the model's usefulness are the primary goals for this research.

This approach will lead to an integration of modelling techniques providing a system that allows useful simulations to be created quickly and easily.

ACKNOWLEDGMENTS

A system is a big black box

Of which we can't unlock the locks,

And all we can find out about

Is what comes in and what goes out

Perceiving input-output pairs,

Connected by parameters,

Permits us, sometimes, to relate

An input, output and a state.

If this relation's good and stable

Then to predict we may be able,

But if this fails us – heaven forbid!

We'll be compelled to force the lid!

Kenneth Boulding

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INTRODUCTION

The purpose of this research project 'Process Design Testing Using Simulation' is to look at ways to improve the efficiency of process systems through increased reliability, realised at the design stage.

The project was completed in partnership with a number of companies, these were: SchemNZ Ltd (industrial technology consultants), Graphpak Services Ltd (engineers to the printing and packaging industry) and Relex Software Corporation (suppliers of Relex reliability software).

Part 2

Software evaluation
Evaluate software and identify how it fits into the process design testing structure

Fault data collection and analysis
Identify where and how faults in mechanical systems commonly occur

Process and system identification and analysis
Based on faults and systems that have been witnessed identify and describe a system for simulation

Part 1

Process design testing method
Establish a standard structure for process design testing

Model development
Create a model of the chosen system using suitable software

Modelling and simulation background
Research into the terms and techniques commonly used for modelling

Figure 1: *Project structure*

The goal of process design testing is to establish new or modified systems that have shortened design and construction cycles and are more reliable; auditing new system designs or proposed changes to existing systems before implementation is one method of achieving this. The auditing techniques developed here rely on modelling and simulation to provide predictions of various aspects of the system under consideration.

The background section describes the practical environment that has made this research necessary. Illustrated here are issues such as the economic importance of the work and the opportunities that exist because of the economic pressures. Some possible products are also suggested that could take advantage of these opportunities.

The practical aspect of this research is described in two major parts as illustrated in figure 1. The first part of the project involves the identification of two processes for use as case studies, which will benefit from design testing and the development of a standard method for process design testing.

The second part of the project is concerned with the development of models for the case studies. This includes the evaluation of a large number of software packages and research into standard modelling techniques and best practices. This is followed by an evaluation of the case study results.

Finally, the conclusions chapter provides an overview of how this project has met its objectives and what knowledge can be drawn from the research. In addition, a section on future work provides direction for further investigation into this subject and describes the issues that are still unresolved or are in need of further investigation.

BACKGROUND

This chapter provides some perspective for the research, describing issues such as the economic importance of the work and the opportunities that exist because of the economic pressures that exist. Products that can be expected to take advantage of these opportunities are suggested here, some of which are explored in detail in later chapters.

ECONOMIC IMPORTANCE

Recent years have seen trends that are placing unprecedented stresses on companies in the industrial sector. These trends are:

- **The globalisation of the marketplace.** New communication technologies and the removal of trade barriers have resulted in market places that are less constrained by location than ever before. Companies often look to markets that may be remote geographically to provide them with sales as well as with resources such as labour or manufacturing capabilities.

- **Increased pace of development.** System complexity has increased much faster than the education sector can cope with, particularly in less developed countries. The growing sophistication of equipment requires highly skilled individuals to perform tasks such as the design, implementation, testing and servicing of equipment. This has resulted in high demand for education and skills that are often not available locally.

- **Global competition.** Globalisation of the market also results in globalisation of the competition. Companies are now required to compete with world class multinational companies and as such they must be willing to move beyond their traditional ways of doing business and look at new and innovative practices if they are to survive.

The pressure exerted by these factors has led to the cost of certain business practices becoming increasingly problematic.

The cost of transporting equipment and staff to remote locations is significant. The equipment must work when it arrives and it must not prematurely fail. The increasing cost of support emphasises the need to check at the design stage for areas where failure will occur sometime after commissioning.

With increased competitiveness comes reduced tolerance for failures and downtime. This often results in the replacement of parts before they fail. This in turn wastes parts and resources and leads to an increase in costs.

These problems have been found by SchemNZ in their experience with industrial commissioning and maintenance, to be becoming increasingly acute as they influence the costs of operation for the supplier and the ability of the supplier to operate effectively. For companies to be successful today and in the future it

is vital that these problems are examined in terms of opportunities for innovation and the chance to gain a competitive edge.

OPPORTUNITIES

The factors described above lead to a number of opportunities, most of which are addressed in the overall programme, 'Remote Process Performance Monitoring and Process Design Auditing'. As a part of this programme, the 'Process Design Testing Using Simulation' project focuses on opportunities that occur at the design stage, while looking to the overall programme for strategic goals and integration of results.

It is suggested that opportunities that exist in the area of design auditing are as follows:

- **Minimisation of design costs**. A well designed modelling system that integrates and automates all of the auditing techniques detailed here, as well as such tasks as reporting and documentation will allow a comprehensive design to be developed with a minimum of resources.

- **Minimisation of construction costs.** Comprehensive designs have obvious benefits in the construction phase, such as fewer unforeseen problems, a clear plan, and documentation of the parts required.

- **Minimisation of post construction testing.** A good model can complement actual testing by pinpointing the areas of need, providing starting points for tuning and developing optimal control strategies.

- **Optimisation of running parameters.** Simulation allows the identification of running parameters that give the most efficient operation of a system, reducing the need for physical trials. This reduction of physical trials in turn reduces the amount of time required for commissioning and therefore the costs at the point of construction.

- **Minimisation of unforeseen failures**. Good auditing and simulation should provide information about what to expect during the actual operation of the system. This should allow prediction and prevention techniques to be focused where they are most required.

- **Minimisation of overall costs.** This can be achieved through effective knowledge management developed over time and applied in a timely fashion.

- **Accurate assessment of risk.** Simulation allows the attachment of accurate values to levels of risk. Good risk assessment is very valuable economically for businesses today as it allows informed decisions to be made. Resources can be allocated to areas of need and risk can be managed more effectively.

Much has been said about the information age and this is an example of how high quality information gained through modelling and simulation of designs can result in real benefits to modern business. Furthermore, companies that take advantage of these opportunities to create actual solutions to the problems described, will not only be well placed to be competitive in the global market place but they will be taking a path of continuing improvement that will serve them well in tomorrows world of fast paced change.

PRODUCTS

This project deals with the research and development of products that will take advantage of these opportunities including:

- **A database of how components fail and the root causes for this failure.** Knowledge of why they fail, the rate of failure and means of predicting and preventing failure would be invaluable for any design. Furthermore, it would provide a starting point for comprehensive FMEA and other techniques to improve reliability. Some information exists on individual component failure but further work is required regarding the presentation and compilation of this data.

- **A database of how systems fail and the root causes for this failure**. Integrated with the component failure database this provides the opportunity for continuous improvement of system designs.

- **System and component loading assessment**. A technique for measuring system and component loading through mathematical representation independent of, or complementary to, physical testing will allow prediction and prevention of failure based on this information.

- **Integration of these elements.** The combination of these aspects will allow failure analysis such as FMEA and Fault Tree Analysis (FTA) to be performed.

These products, while important for process design testing, are also useful at other times in a system's life. The benefits of predictive maintenance have already been touched upon, such as the focusing of resources to areas that have a high risk or cost of failure. Furthermore, design testing will provide clues about what to measure at a component level to prevent specific failures at a system level. Once the system is running comparisons between the model developed for the design testing and the actual system will give an indication of how parts of the system are deteriorating or changing.

The goal of good design is not necessarily to eliminate failure because this is an almost impossible task. A more useful target is to predict more accurately how when and where failure will occur. In addition, the identification of which components are likely to wear out first or often will allow sensors to be chosen to measure the level of wear of these components.

PART I

Part I describes the practical steps that were required to prepare for the modelling task such as fault data collection, documentation and analysis which is covered in the first chapter. The second chapter discusses how systems for the test cases were identified while the third chapter talks about the design of a standard process design testing method.

FAULT DATA COLLECTION AND ANALYSIS

The first step in this work was to accumulate some data first hand on how mechanical systems fail. This chapter describes what classification techniques for faults and their causes are commonly used in industry, how the actual fault data information was collected and the reasoning behind the documentation style used. The results and discussion sections describe the lessons learned and trends observed from this period of practical work that relate both to this project and the overall programme.

LITERATURE REVIEW

Fault cause classification

There seems to be no standard system for classifying the types of fault causes or describing how these causes manifest in industry.

Several authors have focused on how a component or system might fail, such as Thorsen and Dalva (1999) who focus on failures in high voltage induction motors in the petrochemical industry. This type of classification is intended to provide an idea of how basic systems, such as motors, might fail and how these failures might be predicted. Therefore, the focus is on the failure modes of the system and what the various distribution of failures modes is.

Bonnett (1997) has also written a series of papers on how individual parts of AC motors fail, focusing on entities such as the stator, the rotor, bearings and the shaft. This type of classification is more concerned with improving the design of parts of a system and there-fore focuses on the identification of the specific failure type of a component.

Various component manufacturers such as SKF (the bearing manufacturer) have also published information on how their particular components might fail (SKF 1986, 2001). These types of analysis are intended to help consumers get the best possible use out of the component by identifying the common failures and their causes so that the failures can be prevented.

Grothus (1984) takes a broader approach and covers general types of failure such as the breakdown of electrical insulation or parameter deviation and then gives specific component subcategories such as motor winding or heating element. The type of component subcategory is sometimes unique to the general type of failure but some subcategories occur within several failure types. For example, an 'accessible' or 'inaccessible' part occurs in several failure types including corrosion, erosion and pollution. Grothus also provides failure rates over time for the subcategories with the intention of illustrating which types of failure

are more prevalent and may require further attention.

Finally, Zerbst (1981) focuses on gear (sprocket) failures. A list of causes such as material faults or design/construction faults subcategorised with causes such as slag inclusion for material faults or incorrect tooth clearance for design/construction faults. This information is then cross-referenced with symptoms or appearances of the fault. For example, slag inclusion incorporates tooth breaks due to wear, flaking, hardening cracks or material cracks, while incorrect tooth clearance is manifested as erosion or seizure. This approach is very useful for the diagnosis of the root causes of failures and allows engineers to address the true problem rather than repeatedly treating the symptoms of the problem.

It is therefore apparent that there are a number of ways to describe failures. Either from a general framework of types of fault or from a more specific component based analysis. Failures can be described with the intention of either determining the root cause of the fault through analysis of symptoms and related parameters or by trying to determine which faults occur most often in an attempt to prevent or minimise these types of faults.

Rather than focusing on just two relationships, such as symptoms/ appearance, failure category/ failure rate or failure category/ component, as most authors have done, it would be more useful to provide this information in the form of a database. This database can link all these aspects together and provide a full picture of how specific components fail with regard to standard types of failure, at what rate they fail and what root causes exist for the failure. This would provide a firm basis for identifying the failures that are most likely and minimise the appearance of such failures through the reduction or removal of the root causes of failure.

While it is hoped that this short documentation of fault classification techniques will prove useful for identifying the raw data for the 'Process Design Testing Using Simulation' project, the work done should also provide a template for further work in the 'Remote Process Performance Monitoring and Process Design Auditing' programme of which this project is a part.

METHODOLOGY

Described here are the steps taken to identify and document the faults that were witnessed during the time spent at Graphpak Services Ltd and to describe the reasoning behind the documentation style. A template of the documentation record is provided in Appendix 1: Fault Data Collection.

Fault identification

One of the most important parts of this project is the practical identification of faults that actually occur in industry. This helps to build knowledge of how mechanical systems fail. It also ensures that the simulation and modelling aspect of the project is grounded in reality and that it considers the actual problems that are faced by engineers on a day-to-day basis.

The fault identification took place in association with Graphpak Services Ltd. an engineering firm for the printing and packaging industry. When a maintenance job occurred it was attended and assessed on site for suitability for the project. If it was found to be suitable, it was documented.

Fault documentation

As faults were identified and systems repaired, documentation was created recording important features that would help to:

- Identify common types and classes of faults

- Identify root causes of faults

- Identify the true costs of faults

- Identify possible prediction and prevention techniques

Recording the fault data incorporated a number of different techniques for grouping the types and causes of faults. These techniques included a number of categories such as:

- Problem definition

- Service information

- Type of fault

- Cause of fault

- The cost of the fault

- Possible techniques for predicting and preventing the faults

The final form of this documentation was developed through consultation with experienced engineers and the examination of the failure categorisation systems described in the literature review. The aim when designing the documentation was to ensure that all the pertinent information was collected and that it was clearly and unambiguously recorded. The following sections describe the various documentation headings that were actually used in the documentation and what each section was intended to illustrate.

Problem definition and service information

This is generally background information regarding the fault. However, these categories are important for identifying trends and patterns in certain types of fault occurrences, particularly time and event patterns. These categories also contain information such as the type of machine serviced, the symptoms of the fault and where in the system the fault was located.

Many of these types of questions have been adapted from the industrial root cause analysis techniques that focus on looking at patterns to establish the root cause of problems. This technique was developed and taught by Werner Schneider, CEO of SchemNZ Ltd in association with the Institut des Kontaktstudiums at the University of Stuttgart and Hohenheim, and the Fachhochschulen fur Technik Esslingen and Stuttgart (Siede, Keller and Schneider, 1990).

Type of fault

This category is subjective and involves classifying the fault into three classes. By exploring how different faults fit into these classes, the best methods for classification become clear. This in turn will allow data to be gathered more efficiently in the future and provide information that will highlight areas that will benefit from further research and development.

The classifications described here are adapted from Gertler (1998).

Stress rupture or wear out fault

The definition of a stress rupture failure is 'an applied stress directly giving rise to some type of failure'. That is, the application of a specific stress will cause the item to fail every time the stress is applied.

In a wear out situation, the load does not cause immediate failure in the item but repeated applications of the load will cause deterioration in some material property. This causes the eventual failure of the item either through application of the load that is causing the deterioration or through some other load that affects the material property that is being reduced.

Additive or multiplicative process fault

Additive process faults are caused by unknown inputs acting on the plant that, when present, cause a change in the known plant outputs independent of known inputs (as in leaks and loads).

Multiplicative process faults are changes, both abrupt and gradual, in plant parameters. They cause changes in plant outputs proportional to the magnitude of known inputs, for example, deterioration of equipment, surface contamination, clogging and partial or total loss of power.

Sensor or actuator fault

Sensor faults represent discrepancies between the measured and actual parameters of the system. These faults are usually additive faults but may also be multiplicative in nature.

Actuator faults are discrepancies between the input commands to a system and its actual output. Once again, these faults can be either additive or multiplicative.

Causes-stress-symptom

The cause of a fault is often one of the most difficult areas to classify. Frequently the root cause of a fault is not known and only the symptoms are repaired. For example it is very easy to identify that a bearing needs to be replaced, but it can be much more difficult to identify that it is a too tight interference fit on the shaft that is causing the bearing to fail repeatedly. It takes a skilled engineer to be able to identify these root causes and the tendency is to rely on intuition and experience.

A technique for classifying faults and their causes was developed based on experience gained while working with Graphpak and from research into the types of classification found in literature.

The final form of the classification technique as shown in figure 2 is based on the idea of the

root causes resulting in some type of loading which in turn produces the symptoms.
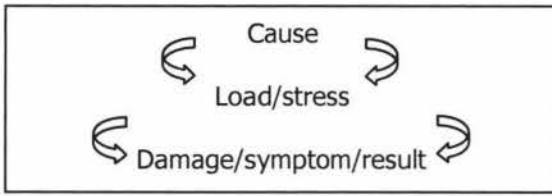
Figure 2: *Fault appearances*

Cause

The underlying origin of the fault is known as the root cause, this can include things such as external influences from the environment like condensation or temperature fluctuations, design faults such as unsuitable material pairing and lubrication faults, for example contamination by solids or liquids.

The elimination of the root causes is a valuable strategy when attempting to increase reliability. The treatment of root causes rather than symptoms prevents the fault from reoccurring and also provides an improved understanding of the factors that influence the operation of a system.

Load/stress

The root causes result in a load or a stress being applied to a system. Examples of the loads and stresses that may be encountered include: thermal stresses such as cycling, electrical stresses such as transient currents and mechanical stresses such as pressure or friction. It is often beneficial to measure these loads and stresses as analysis of the trends can provide valuable information about how and when a system might be expected to fail.

Damage/symptom/result

This is the final expression of the fault. It is often the first thing to be noticed when a failure occurs and as such it is what is most likely to be treated. When a fault continues to reoccur it is generally because the symptoms are treated rather than the root cause. These damage symptoms can include cage wear or noise from bearings, break down of electrical insulation and short circuit or rotor vibration in a motor.

It is important to note that each of the above definitions is interrelated and it is not sufficient to consider each of them independently. If a root cause has been identified and action taken to prevent its reoccurrence, action should also be taken to address the symptoms and loads that may have been developed when the fault occurred. Similarly, while it was said that the measuring of loading is a good way to provide data about the system, the measurement of other variables should not be ignored as they may also provide valuable information.

RESULTS

During the period of practical work with Graphpak Services Ltd. a number of incidents of fault identification and repair were witnessed and recorded. This provided information, about the types of faults that might be encountered in industry and helped to build knowledge in the area of fault identification and repair.

Fault profile summaries

The summaries presented in table 1 were selected from a larger collection of cases to illustrate the conclusions drawn. The summaries focus on the nature of the fault and how it came about. Further information was also collected concerning the company that owned the machine, the costing of the fault and possible suggestions for predicting or preventing the fault. However, this information is outside the scope of this specific project and is therefore omitted. More detailed information about all the faults that were documented can be found in Appendix 1: Fault Data Collection.

	Case 1	Case 2	Case 3
Problem definition	Three sprockets on the chain drive of a Fuji wrapping machine were very worn and needed replacing. No actual fault had occurred, however failure of the chain drive was imminent. This would have caused the feed conveyer to fail and the operation of the wrapping machine to be seriously impaired. The sprockets that had worn were all on the feeder conveyer chain drive. Graphpak first noticed the fault during routine maintenance .	A bearing on a belt-driven shaft on Station II T1 of a 1995 GUK automatic folding machine had collapsed. This caused noisy running and excessive vibration. Left alone the problems would have worsened and the bearing may have seized, possibly causing further damage. The fault first occurred 18 months previous to the date of service and has occurred twice more since then. The failure was regular after the initial episode which occurred approximately four years after the machine was first used.	The clutch on a 1959 Perfecta guillotine was worn. This prevented the motor from properly driving the blade meaning that the blade was going down but not up again This caused procedures to take longer than usual, slowing down operation. The clutch is positioned on the flywheel of the guillotine and the plates on the clutch were worn. It could not be established exactly when the fault first occurred because it was manifested as a gradual deterioration in performance. The problem was intermittent particularly after 20+ cuts and when performing trimming operations, the situation was deteriorating.
Type of fault	Wear out, multiplicative, actuator fault.	Wear out, multiplicative, actuator fault.	Wear out, additive, actuator fault.
Cause-stress-symptom	Overuse (possible lubrication deficiency) - friction - erosion/wear.	Repair process fault specifically, misalignment of the bearing - mechanical stresses - noise, premature fatigue, and bearing cage failure.	Overuse - friction - clutch wear.

Table 1: *Fault profile summaries*

DISCUSSION

Fault trends

The number of wear out faults observed lends credence to the aims of the project because it demonstrates that many systems are failing in a manner that can be easily predicted, that is, through normal wear. This is illustrated in case one where failure was about to occur due to wear. This wear could have been minimised through better maintenance practices. The occurrence and timing of the fault could also have been predicted through reliability measures, such as Mean Time Till Failure (MTTF). This would have allowed more accurate budgeting and scheduling of the maintenance.

The number of faults occurring because repairs were carried out poorly exposes the dangers of New Zealand's 'do it yourself' attitude. As equipment becomes more complex it becomes more and more important to get experts to perform what may seem to be simple repairs to preclude the possibility of worse damage being caused. This is demonstrated in case two where the repeated fitting of the wrong bearing to a shaft caused repeated failure of the bearing.

Faults due to overuse reflect the fact that small companies purchase much of their equipment second hand and as such it is prone to wearing out. It is not known exactly how much of this wear is within the normal parameters of the equipment life or if the equipment is wearing out prematurely due to poor maintenance practices. This is shown in case three where it was not known what the maintenance history of the machine was. These types of subtle wear out faults can be very hard to detect and only periodic assessment can pick them up before they become serious. This makes a good case for the monitoring of variables that may indicate when this failure might be beginning. Simulation can give an idea of how often this assessment should take place and what entities need to be assessed.

It is expected that the application of a classification system, such as the one developed for this project will lead to the identification of wider trends and areas of need. It is also expected that a broad range of manufacturing industries will share the same need for accurate information about failure trends.

Fault classifications

The collection of fault data allowed a number of conclusions to be drawn regarding usefulness of the various types of classifications that were used.

Wear out/stress rupture

The wear out/stress rupture classifications highlight problems with design and operation.

Stress rupture faults occur when a load is applied that will cause a component to fail every time that load is applied. Stress rupture faults are evidence that the strength of the component is insufficient when compared to the magnitude of the load. Therefore, either the strength of the component should be greater or the load should be reduced. These changes can be addressed in design and operation stages respectively, either through designing components that are stronger or through ensuring that the operation of the system is within safe parameters.

Wear out faults on the other hand often appeared to be evidence of either poor maintenance practices or extended use beyond normal life expectancy. For example, in case one it was observed that drive gear erosion had caused failure in a machine that had been in use for a long time, suggesting that the drive gears may have been outside their normal life expectancy. However, it is also considered that regular maintenance of the gears, such as the periodic application of oil and cleaning, could have extended their life considerably.

Additive/multiplicative

Many faults start out as multiplicative and either become, or have the potential to become, additive. For example, in several cases worn clutches were initially producing multi-plicative faults in that they were slowing normal operation. However, in one case this fault progressed to an additive fault as the clutch failed completely and caused the system to break down.

It is suggested therefore that by identifying multiplicative faults early, the more severe additive faults can be avoided. This can be difficult because multiplicative faults can be very subtle, especially over long periods of time. This makes a good case for the recording and analysis of trending data as a tool for fault prediction/prevention.

Causes-stress-symptom

A number of trends became clear using this type of classification for each of the faults that were investigated, these trends were:

- Faults due to overuse were common.

- Difficulty exists in distinguishing between normal wear and wear caused by unnecessary abrasion when long-term records were unavailable.

- Several faults were the result of poor repair processes.

While the size of the sample precludes drawing any concrete conclusions, it is suggested that these trends are representative of the printing industry in New Zealand.

The identification of these trends demonstrates the usefulness of the classifications and demonstrates the sorts of classifications that are required if specific strategies are pursued. For example, if an investigation into how to extend the life of a product is required then wear out/stress rupture categorisation would be useful to identify whether design and general operation should be targeted or if maintenance procedures are more important.

All these types of categorisation and more, should ideally be incorporated into an analysis to provide a complete picture of what is occurring on a wide scale. Limited resources may prevent the use of all the categories, so the identification of the scope of the individual categorisations is an important result.

PROCESS AND SYSTEM
IDENTIFICATION/ ASSESSMENT

This chapter deals with the identification of the systems that are the subject of the practical modelling exercise, the Strapack model S-661 strapping machine and the 240-volt single-phase induction motor. Also discussed are physical aspects of the systems that were identified as being important for the model. This includes a description of what techniques are available for measuring the condition of the motor system.

METHODOLOGY

An important part of this project is the choice of system and entity to be modelled.

For this reason a large amount of time was spent working with Graphpak. This involved personally visiting factories and assisting with fault identification and repair. While this resulted in the attainment of some experience in practical fault finding and repair, it also allowed a large number of systems to be identified as candidates for simulation.

The criteria identified for the choice of system are as follows:

- The entity to be focused on should be widely used and prone to failure.

- The system containing the entity should be simple enough to allow modelling to be performed within the time frame of the project.

- The system containing the entity should be complex enough to allow techniques such as object oriented modelling and multi-domain interaction to be utilised and assessed.

These criteria were chosen to ensure that the work done for this project is applicable to wider research and has industrial value.

Other considerations that were taken into account were the nature of the failures that might be expected to occur in the system that was selected for simulation. Building on experience and intuition, coupled with research into past failure modes of similar systems, predictions can be made for probable failures that can occur in the system under focus. Furthermore, the identification of variables that can predict these types of failure or monitoring techniques that can provide information about whether the specified failure has occurred, or is likely to occur, is seen to be of value.

Once the common failure modes have been identified and an assessment through simulation of the probability of these failures occurring has been made, then recommendations can be prepared as to what sorts of monitoring techniques or maintenance practices are required to predict and prevent the most common or critical types of failure.

RESULTS

The knowledge gained from the period of practical experience allowed an informed decision to be made as to which type of entity should be focused on for the simulation. The entity chosen was the '240 Volt, Single Phase, Induction Motor' shown in figure 3. The system chosen for simulation that contained this entity was the 'Strapack model S-661 strapping machine' shown in figure 4.
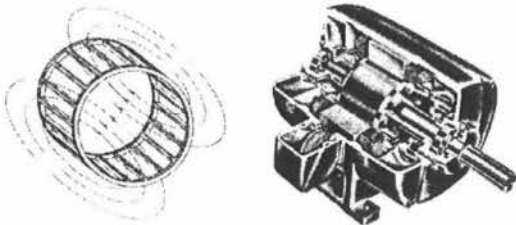
Figure 3: *Induction motor*

The 240-volt motor was chosen because it has been found to be a vital part of modern industry and can be prone to failure. Therefore, a comprehensive model of an induction motor will be useful for a large number of future simulations.

Figure 4: *Strapack model S-661 strapping machine*

The strapping machine was selected because it is widely used in industry and includes complex components such as a clutch, gearbox and motor within a simple system. This will ensure that the simulation techniques used in this project are applicable to further work in this field.

From a survey of literature on motor faults a summary of the types of faults that can be predicted by various techniques was developed, This is shown in table 2. A more complete list of techniques and a description of each is provided in Appendix 3: Diagnosis Techniques for Induction Motors.

Motor faults \ Prediction techniques	Vibration monitoring	Acoustic emission monitoring	Speed fluctuations monitoring	Current monitoring	Temperature monitoring
Magnetic imbalance	✓				
Mechanical imbalance	✓			✓	
Aerodynamic imbalance	✓				
Load imbalance	✓			✓	
Vibration	✓		✓		
Uneven air gap	✓		✓		
Rolling element faults	✓	✓	✓		✓
Stator winding faults	✓				✓
Rotor faults	✓		✓	✓	
Asymmetrical power supply	✓				
Rotor asymmetry			✓	✓	
Misalignment			✓		

Table 2: *Motor fault prediction techniques*

DISCUSSION

The system to be simulated, the Strapack model S-661 strapping machine, is simple enough to be modelled in its entirety but complex enough that the capabilities of the software tools chosen are demonstrated. The specific component chosen for more in-depth analysis is the induction motor which has been described by Smith & Dorf (1992) as the "...the work horse of industry" (p.782). As such, the induction motor has been the subject of extensive research and much of the theory required for the model already exists.

PROCESS DESIGN TESTING METHOD

This section deals with how the process design testing method is structured. The development of the structural plan for the process design testing method is described here. In addition, an examination of what the suggested structural descriptions tell us is covered, as well as the specific resources that have been identified as necessary.

METHODOLOGY

The goal of process design testing is to establish new or modified systems that have shortened design and construction cycles and are more reliable. Auditing new system designs, or changes to existing systems before implementation of the design is one method of achieving these goals. The auditing techniques developed here rely on modelling and simulation to provide predictions of various aspects of the system under consideration.

The process design testing system has several major sub-functions such as bill of materials analysis, operation auditing and predictive maintenance. In this project, the focus is on predictive maintenance scheduling. This focus was chosen because of its immediate use to industry and because the results from this area will strongly influence other areas of the 'Remote Process Performance Monitoring and Process Design Auditing' programme. In particular, the choice of the process to investigate and which variables are important to monitor will have a strong influence on the work done in this programme.

Two techniques for establishing a picture of how the predictive maintenance scheduling system works and how it fits into the overall project are considered here. The development of a functional diagram and associated functional descriptions is one approach. The other is to create a schematic demonstrating the flow of information. These schemes are complementary rather than contradictory. They demonstrate two alternative ways of describing the same process, and provide a greater variety of solutions and approaches than a single portrayal would.

Aims

The first step in the design of the structure was the identification of what was required from the process design testing method. These requirements were identified as:

- The identification of required inputs

- The identification of required outputs

- The identification of how processes interact and communicate with one another

- The identification of techniques and tools for using the given inputs to produce the required outputs

The first simple description as shown in figure 5 describes the system as a simple black box with inputs and outputs. The inputs were identified simply as:

- A description or listing of the components that are part of the system under study.

- A description of the events or operations that the system performs or is expected to perform.

- Information regarding the attributes of the events and components.

The output of the system is expected to be some kind of measure of the state of the system.
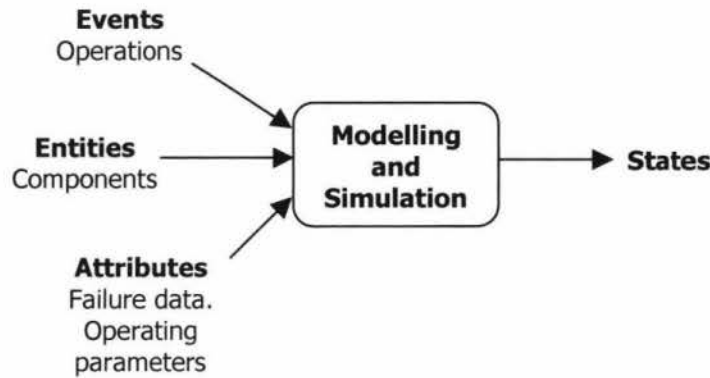
Figure 5: *Design simulation inputs/outputs*

Once the basic black box inputs and outputs had been identified, more thought could be given to the actual contents. Figure 6 describes the simulation structure in more detail and splits the modelling part into quantitative and statistical components dealing with physical and reliability states respectively. Also demonstrated is the requirement of information from the actual system for validation purposes.
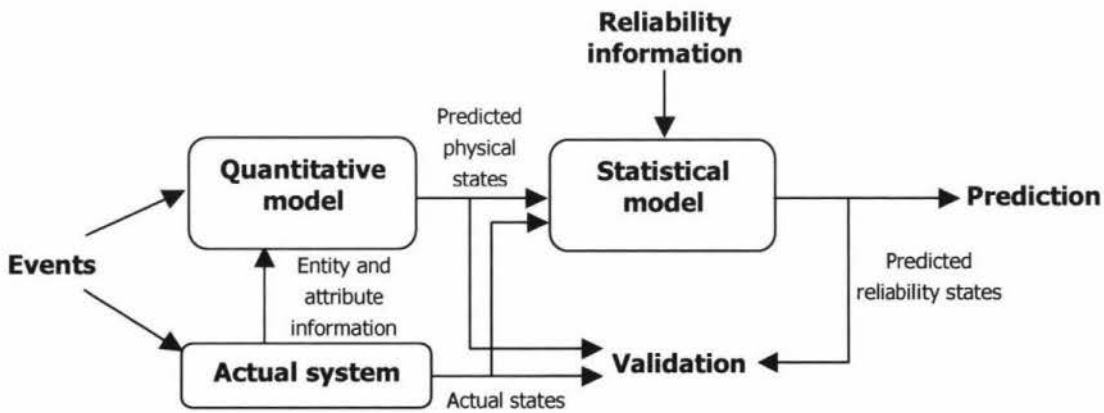
Figure 6: *Model types and validation*

It can be seen that there are three major aspects of the system. The first is a quantitative model that predicts the physical states of the system based on events. The second part which also deals with the identification of physical states in the system, is the measurement of the actual system states. Both of these physical state measures can then be used by the third part of the method to predict reliability states. This duplication of the actual system by a quantitative model allows information that cannot be gained from the actual system to be simulated, while the actual system allows the quantitative model to be vali-

dated. It should be noted that in a design test of a completely new system the actual system will not be available so validation of the model cannot be undertaken until some construction is carried out. However in many cases some kind of actual system will exist that can be used for validation purposes.

The statistical model uses both physical state information regarding the system and reliability information regarding specific components to produce a prediction of the system reliability.

Functional divisions

These concepts were further refined to produce a functional diagram as shown in figure 7. The functional approach involves identifying and describing the major overall function of the scheme and then breaking these functional descriptions into sub functions. This process is repeated until a complete description of all the functions in the scheme is identified. This allows critical functions to be targeted as well as identifying which functions operate together to achieve specific results.

Information flow

Another approach that was used to establish the structure of the scheme was that of identifying how information flows through the scheme, from a large number of individual entities such as part manufacturers through to the final compilation of system failure information. This demonstrated what communication schemes are required and how the scheme needs to be organised for efficient interaction.

RESULTS

Using the techniques described above, two separate but complementary descriptions of the process design testing method were established.

Functional approach

The functional approach resulted in a branched structure with detailed descriptions of the separate functions of the scheme and how these functions fit together to describe higher-level functions. The functional diagram, figure 7, provides a representation of this structure.

Detailed descriptions of the functions considered are provided below.

Process design testing

As the overall function, process design testing incorporates a number of sub-functions that are not explicitly included in this project, such as shortened design and construction time through operation auditing and bill of materials analysis. However, it is useful to have an understanding of what these other functions are so that this project can fit into the overall scheme.

The focus of this project is to improve reliability, specifically through the scheduling of predictive maintenance. Therefore, this is the main sub function considered in this analysis.

Improve reliability

There are several ways to improve reliability in the design-testing phase such as, improved operational strategies or by more reliable design and component selection. Predictive maintenance scheduling, however, provides tools for both these functions. Scheduling of predictive maintenance can provide the optimum maintenance strategy while comparison of the system reliability for different designs can provide a measure of how reliable each design is and allow the most appropriate design to be selected.
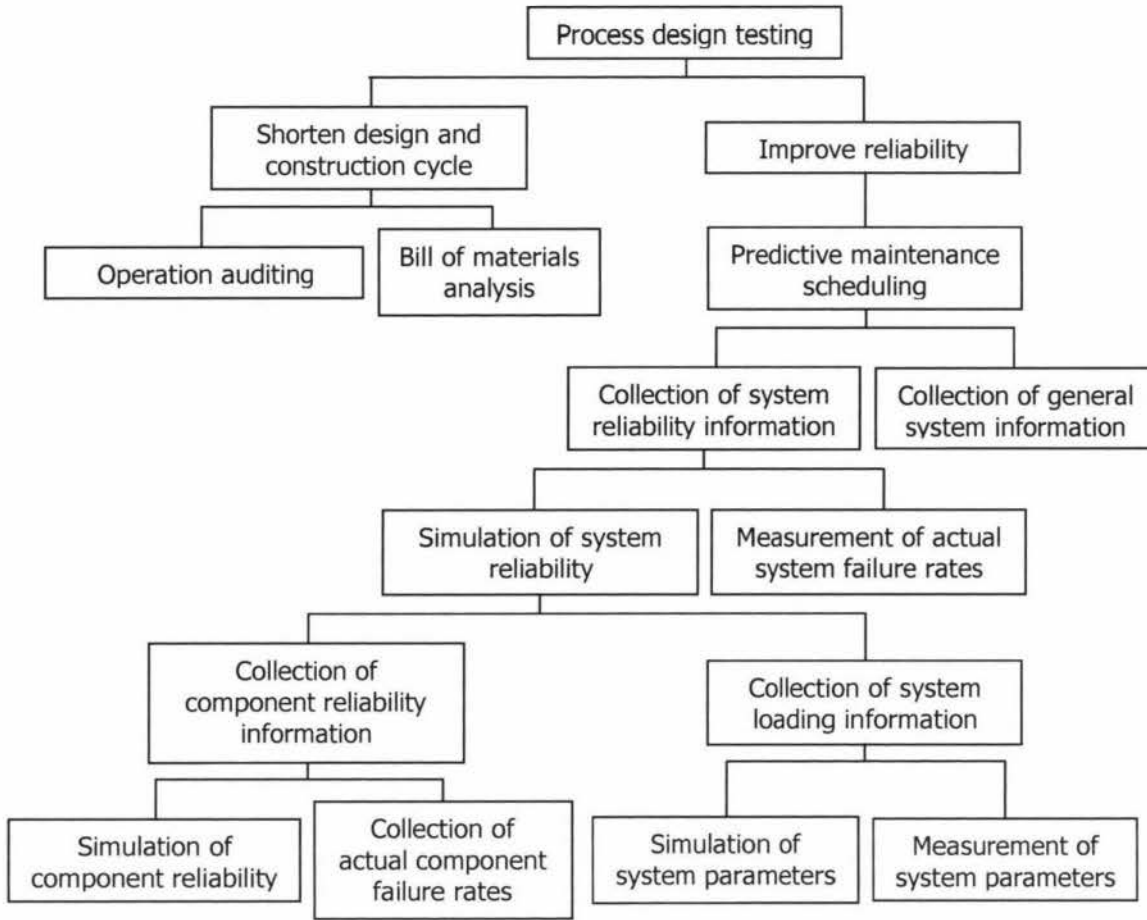
Figure 7: *Functional diagram*

Predictive maintenance scheduling

Predictive maintenance scheduling is the ability to plan efficient maintenance strategies based upon predicted time until system or component failure and operational information about the system. This minimises unplanned system downtime.

Collection of general system information

This includes information about what the best times for maintenance are, what resources are available for maintenance, how to carry out the maintenance and what the Mean Time To Repair (MTTR) for each component or system is.

The operational information combined with the system reliability information provides the basis for predictive maintenance scheduling.

Collection of system reliability information

Reliability simulation and actual system failure rates provides the data required to build a full picture of system reliability. However, because of the predictive nature of the maintenance system initially only predicted system reliability information will be available, rather than the actual failure rates of the working system. However, comparison of the simulated reliability analysis with the actual failure rates where possible is required for validation purposes.

Simulation of system reliability

The simulation described here provides data regarding the reliability of the system in question. Simulation of system reliability incorporates information concerning component reliability, both actual and simulated, and system

loading information, both real and simulated, to create a representation of the system reliability as a whole under specific loading conditions.

While system information can include the types of analysis described above such as Mean Time Between Failures (MTBF) or availability, systems also have a number of other tools for describing their behaviour from a reliability standpoint. These tools include FTA and FMEA

Measurement of actual system failure rates

The information measured here demonstrates the actual reliability of the system. Comparison of this information with that developed through simulation of system reliability will validate the simulation and provide indications of where the model may be lacking or requires improvement.

Collection of actual component failure rates

Actual failure rate information for individual components can come from two main sources, the manufacturer or the final user. This data should complement the failure information gained through simulation. Actual component failure rates are more useful when the component has been around for some time and a large amount of data exists for it. This is because failure information is by nature statistical and therefore larger samples provide a greater level of confidence.

In addition, failure rates of existing components can provide models for use in simulation of components that are operating under specific circumstances.

There are a number of databases that contain failure rates for actual components. These include the Electronic Parts Reliability Data (EPRD), the Non-electric Parts Reliability Data (NPRD), the Offshore Reliability Data (OREDA), and the European Industry Reliability Database (EIREDA) to name a few. Appendix 4: Models and Databases describes further details of these data sources.

Simulation of component reliability

The information concerning the reliability properties and behaviours of individual components can come from a number of sources including:

- The part manufacturer
- The part user
- Component modelling

Component modelling can fill the gaps in the information collected from manufacturers and users of components. Such gaps exist for new components or components that are under specific types of loading that may be uncommon.

Collection of system loading information

This gives a measure of the loads that are experienced, or are expected to be experienced, by the components within the system.

The complete reliability analysis of a system requires some information about the predicted or actual operation and loading of the system. This information includes:

- Loading levels over time
- Length of operation time
- Number of operation cycles

This data should be given both for the overall system and for individual components.

The collection of this data can take two forms. Either through direct measurement of the actual system or, in cases where the system is not available, such as in the design stage, through the modelling of the system.

The system loading information combined with component reliability information allows the reliability of a system for particular circumstances to be evaluated through simulation.

Simulation of system parameters

This is the prediction of system and component loading levels through modelling and simulation. It is required for systems that are still in the design phase or for proposed changes to an existing system.

Measurement of actual system parameters

This is information taken directly from the system concerned, such as through direct sensing of loads.

Information flow

The processing steps that need to be undertaken and what information needs to be obtained is demonstrated by the information flow diagram in figure 8. It shows the data sources as parallelograms and the information processing steps rectangles.

```
                          ┌──────────────┐
                         ╱  Part        ╱
                        ╱  manufacturer╱
                       └──────────────┘
                              │
                              ▼
┌──────────────┐      ┌──────────────────────┐      ┌──────────┐
╱ Component   ╱  ──▶ │ Component failure      │ ◀── ╱ Part    ╱
╱ simulation ╱        │ information            │     ╱ user   ╱
└──────────────┘      │ Failure rates over time│     └──────────┘
                      │ and number of cycles,  │
                      │ Weibul plots, MTTF,    │
                      │ loading limits etc.    │
                      └──────────────────────┘
┌──────────────┐                  │
╱ Actual system╱                  │
╱ parameters  ╱                   │
└──────────────┘                  │
       │                          ▼
       ▼                  ┌──────────────┐
┌──────────────────┐     ╱ Reliability ╱
│ System loading   │ ──▶ ╱ analysis    ╱
│ information       │     └──────────────┘
│ Loading levels    │            │
│ over time, length │            ▼
│ of operation time,│     ┌──────────────────────┐
│ number of         │     │ System reliability    │
│ operation cycles  │     │ information            │
└──────────────────┘     │ Failure rates, Weibul  │
       ▲                  │ plots, MTTF, FTA,      │
┌──────────────┐         │ Failure Mode and       │
╱ System      ╱          │ Effects Analysis       │
╱ simulation  ╱          └──────────────────────┘
└──────────────┘                  │
┌──────────────┐                  ▼
╱ Operational ╱          ┌──────────────┐
╱ information  ╱         ╱ Predictive   ╱
└──────────────┘        ╱ maintenance  ╱
       │                ╱ scheduling   ╱
       ▼                 └──────────────┘
┌──────────────────┐           ▲
│ System           │ ──────────┘
│ information       │
│ MTTR, existing    │
│ resources,        │
│ maintenance       │
│ times etc.        │
└──────────────────┘
       ▲
┌──────────────┐
╱ Inventory   ╱
╱ information  ╱
└──────────────┘
```
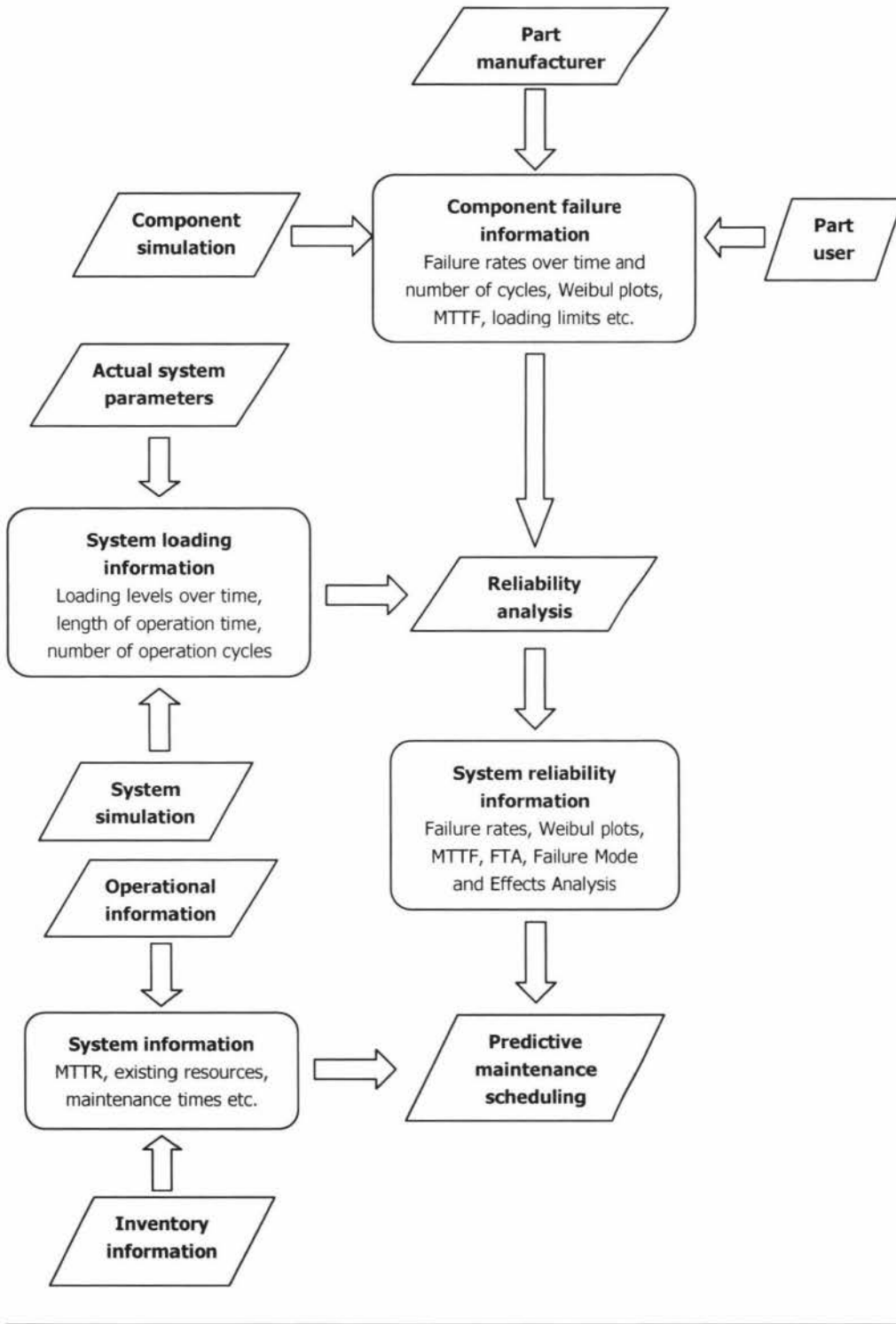
Figure 8: *Information flow diagram*

Component failure information

This type of information can be sourced from manufacturers that perform in house testing of components and can provide a variety of information about how components might fail in specified situations. This type of information is useful for broad classes of situations, such as high temperature or high vibration levels.

The users of components can also supply component failure information (if they keep good records), which can provide an insight into how a component might fail when used in a specific location or manner. While the individual user can only provide a small amount of information about a component, when many users compile their collective experience, a broad picture can be built up of how a component may fail.

Component modelling fills in the last part of the description. Through statistical analysis of manufacturer and user failure information, models can be created that interpolate and extrapolate from what is known. This data can be applied to very specific operating conditions.

Once this component information is compiled, it provides one of the resources that are required for reliability analysis.

The component failure information will generally come in a standard statistical form such as MTBF, failure rate or failure distribution.

Examples of some sources of component failure information are described in Appendix 4: Models and Databases.

System loading information

The other resource that is required for system reliability analysis is information concerning system loading.

This can come from either the measurement of the parameters of actual system or from the modelling of system parameters.

These two techniques should ideally work together, the modelling stage providing a starting point for actual measurement. Each method can then be used for the validation of the other.

This loading information can be expressed as maximum and minimum values, loading distributions and loading over time. It can also express any number of loading types, such as temperature, operating time and stress.

System reliability information

The two main information entities that are required for reliability analysis are system operation information and component failure information. Between them, they contain the data required for reliability analysis, which in turn, provides information about system failure. This information about system failure then provides the tools necessary to identify and perform predictive maintenance scheduling.

This data can be expressed in a number of ways including MTTF, Weibull plots and failure rates. Other information that can be included in the system reliability simulation is analysis techniques such as FTA and FMEA.

DISCUSSION

The previous results show that the important features of the process design testing method can be expressed in a number of ways. These ways complement each other and provide illumination of different aspects of the scheme.

For example, the information flow strategy highlights the sources of information that need to be cultivated for Process Design Testing to be valid for real life problems. On the other hand the functional descriptions give a much clearer picture of how each part of the scheme works and what tasks must be integrated to achieve the overall objective of improved reliability.

The development of information sources is vital for the predictive maintenance scheme if it is to be applicable to real problems. It is important not just to have a modelling and simulation system in place but also to utilise accurate information pertaining to real systems.

This information can come from a number of sources, some external to the scheme such as the part manufacturers and users, others are incorporated within the scheme such as reliability analysis and predictive maintenance scheduling.

The identification of the components required by the process design testing method is possible using these schematics. These components include:

- A tool for the simulation of component reliability

- A collection of actual component failure rates

- A tool for the simulation of system parameters

- A technique for the measurement of actual system parameters

- A procedure for the collection of general system information

Furthermore, it is also shown how these components must interact, either through the passing of information from one to the other, or through integration of functions to produce a more powerful higher-level function.

The large number of separate components that must be incorporated into the overall scheme also suggest that compatibility between the tools used will be of the utmost importance.

Another crucial point when establishing a design testing scheme is to ensure that industrial standards are met. A number of groups exist that have produced industrial reliability modelling techniques that can be incorporated into the proposed methods, such as the MIL-HDBK-217, Bellcore, NSWC 94/L07, and PRISM standards. The relative merits of these standards are described in Appendix 4: Models and Databases.

It may be relevant in some cases to attempt to combine the two techniques described here into one overall picture, perhaps a functional description with lines demonstrating the flows of information. However, it is deemed unnecessary for this project as a clear understanding of how the scheme fits together can be gained from the present configuration.

PART II

Part II of the project is more directly concerned with the actual modelling task. The first chapter includes such things as background information regarding definitions and techniques important to modelling and simulation. The second chapter is an evaluation of a large number of different software packages for suitability at various parts of the process design testing system. The third chapter contains a description of the actual modelling and simulation tasks and the results of these.

MODELLING AND SIMULATION BACKGROUND

This section is intended to provide a short description of some of the concepts that are used when discussing modelling and simulation.

Explanations and examples are given for the terms model, systems and simulations. Other definitions are specified such as environment, verification, validation and a number of reliability terms used to describe how and when entities fail. Common methods of dealing with time in simulations are also examined.

Finally, a short description of current practices regarding the modelling of process designs is provided.

LITERATURE REVIEW

Model

According to Friedman (1996) a model is the "...*representation* of a real-world entity but not the 'real thing' itself" (p.1).

Or as defined by Neelamkavil (1987) "A model is a simplified representation of a system (or process or theory) intended to enhance our ability to understand, predict, and possibly control the behaviour of the system" (p.30).

From these definitions of a model we can then go further and define modelling as "the process of developing an internal representation and set of transformation rules which can be used to predict the behaviour and relationships between the set of entities composing the system" (Franta, 1977, p.1).

Or stating the primary goals of modelling as being "...to achieve a simplified model which does not include all the details known about the real system and yet has sufficiently similar behaviour. (Payne, 1982, p.226).

It appears that these definitions agree on two main points. One is that a model must be representative of an entity or system and the other is that the model is a simplified yet sufficiently similar version of that which is being modelled.

A description of the various types of models that exist is described in Appendix 6: Types of Models.

System

The basis of a model is a system, either real or imagined. Consequently, the definition of a system also requires some discussion. This is difficult however because the term is used in such a wide variety of ways to mean very specific but very different things. Presented here

are some interpretations of the definition of a system.

According to Neelamkaivl (1987) "A system can be defined as a set or assemblage of entities (elements or components) interrelated to each other and to the whole so as to achieve a common goal" (p.19).

Or from Payne (1982) "The term *systems* is used here to mean a group of units which operate in some interrelated manner..." (p.2).

Alternatively, "A system is defined as an aggregation or assemblage of objects joined in some regular interaction or inter dependence" (Gordon, 1969, p.1).

The underlying theme of these discussions is that a system is a group of entities that act in an interrelated matter. For this project the focus is on mechanical systems, specifically, systems for industrial processing.

Simulation

The focus of this project is of course simulation and many of the definitions of simulation rely on the previous definitions of systems and models.

"...experimenting with an abstract (i.e., mathematical or flow chart) model over time..." (Naylor, T. H., Balintfy, J. L., Burdick, S. D., & Chu, K. 1966, p.3).

"*Simulation* is a method used to study the dynamics of systems... Simulation provides a description of system behaviour as it evolves over a period of time" (Payne, 1982, p.2).

"Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set criteria) for the operation of the system" (Shannon, 1975, p2).

The common thread with these definitions seems to be the formulation of experiments that use some type of model to demonstrate how a system evolves over time.

Verification and validation

One of the most vital steps in computer modelling and simulation is the verification of the model and the validation of the simulation. These steps ensure that the model does what

it is supposed to and is a viable representation of the system being modelled. A description of the distinction between verification and validation is given below.

Verification

"The purpose of verifying the program is to determine whether or not the model is properly programmed; that is, does the program behave as the model is intended to behave?" (Payne, 1982, p.228).

"Verification is a procedure to ensure that the model is built according to specifications and to eliminate errors in the structure, algorithm, and computer implementation of the model" (Neelamkavil, 1987, p.76).

To summarise, verification is the process of ensuring that the model produced does what it was designed to do. This may involve such things as checking for programming errors and failures in logic, consulting with third parties and checking for ill conditioning, convergence, accuracy and robustness. The important point is to determine whether the model has been correctly solved.

Where validation is concerned with comparing the system with the simulation, verification has little to do with the actual system or any specific simulation, it is more concerned with self-consistency and how the model works.

Validation

"The objective of the validation stage is to ensure that the simulation program is a proper representation of the system being studied, so that the results to be obtained from the experiments will be the results which would be obtained from the real system" (Payne, 1982, p.225).

"Model validation can be defined as the process of substantiating that the model within its domain of applicability is sufficiently accurate for the intended applications" (Neelamkavil, 1987, p.76).

Validation is essentially a process of determining how well the simulation represents the system that it is intended to model. Validation is a method of attaching some degree of confidence to the simulation, to allow meaningful insights to be drawn. Does the model represent the system to the accuracy or resolution required?

Summary

These definitions are necessarily broad and cover a wide range of topics not covered by this thesis. For our purposes, a system is a set of entities that act in an interrelated manner. A model is a (computer) representation of a system that predicts its behaviour to a level of accuracy that is detailed enough to be useful (and simple enough to be practical). A simulation is the use of this model through experimentation to give insight into future events.

OTHER MODELLING DEFINITIONS

Other terms and concepts that are used in this document that may not be sufficiently understood are described here. These are the concepts of environment, how the passage of time may be dealt with in a simulation and finally some of the common terms and techniques of reliability such as failure rate, MTBF, reliability and availability, failure distribution, FTA, FMEA as well as a short description of the current practices.

Environment

The concept of environment is very important and is an area where misinterpretations of what qualifies as the systems environment can lead to serious design flaws.

Elements that lie outside the system and that cannot be manipulated by the system but that exert a significant effect on the system are included in the environment.

Exogenous activities are those activities that occur in the environment that effect the system and *endogenous* activities are those activities that occur within the system.

A closed system is one in which the environment exerts no effect on the system. In practice, these systems are hard to find and almost all real systems are open systems that interact with their environment.

A common mistake is to assume closed systems when in fact they are susceptible to many environmental effects such as temperature changes, humidity and dust.

Dealing with time in system simulations

System simulations can be described as either having continuous, discrete or hybrid time. The choice of which of these methodologies is used is vital for managing the complexity of the system.
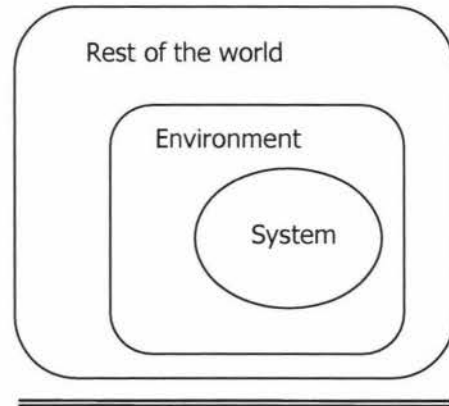
Figure 9: *System, environment and world relationship*

Continuous time system simulation

The defining characteristic of continuous systems is that changes occur in a smooth fashion. Modelling these changes often requires the use of differential equations. Continuous time variables are defined for any value of time.

Discrete time system simulation

Most real world systems are continuous, however they are often simplified as discrete models. This is particularly the case with factory models where the division of processes into discrete steps is easily realised.

Discrete time methodology breaks up the time scale into discrete steps, of either constant or varying sizes. Algebraic equations are typical of this type of model.

Discrete systems simulation is described either by an interval based, linear time scale, or by using events to determine the passage of time. These techniques are known as interval-oriented simulation and event-oriented simulation respectively. Event oriented simulation can be further broken down into event scheduling, process interaction and activity scanning depending on how events are described.

- **Interval-Oriented Simulation.** Simulation takes place at specific time intervals. The advance of time is restricted to the clock intervals. This technique is more suited to continuous systems and systems with large numbers of state variables.

- **Event-Oriented Simulation.** Event scheduling takes a global view of the system, with a complete description of everything that happens in the model when an individual event occurs. Scheduling of events is described by specifying the time of occurrence. Time is advanced to the occurrence of the next event and simulation is carried out by the execution of ordered event sequences.

- **Process Interaction.** A process, described by Neelamkavil (1987) as "...an *entity* and the sequence of actions it experiences during its life in the model" (p.152). This is the basis for the process interaction strategy. The description of the system is a set of processes, which consists of a set of mutually exclusive activities. Processes may interact and overlap but may not start more than one activity at any one time. The basis of process interaction is the flow of entities through the model. A list of processes and the occurrence of the next event in each process is maintained and this collection of event sequences describes all the events that occur in the system.

- **Activity Scanning.** The definition of activities given by Neelamkavil (1987) is "The state of an entity over an interval. (An activity is bound by any two successive events which need not be related to the same entity.)" (p.135). Any change in the state of the system is caused by an activity. A list of activities is maintained and an associated true-false condition is coupled with these activities, depending on the simulation time and the overall state. Events are implicitly rather than explicitly scheduled.

Reliability

An important feature of the model for this project is that it expresses reliability in a stochastic fashion. For this reason, presented here are some basic reliability concepts and terms.

Failure rate

This is a description of the number of failure expected over a certain time scale. Commonly described as

$$\text{Failure rate } (\lambda) = \text{failures/hours}$$

or

$$\text{Failure rate } (\lambda) = \text{failures/cycles}$$

These measures are often given per million or per billion hours or cycles.

It is important to look carefully at the units used to measure time and to relate this to the component being measured. For example components that run at variable speeds may be better suited to measurement by number of cycles, however components that are in continuous operation may be better described by number of hours.

A further distinction is also be made between the total hours in service and the number of hours of operation. For components that have a chance of failure while not operating, say through corrosion or the like, consider total hours. Measure other components however by only the number of hours in operation. In some cases both measures may be required.

Mean Time Between Failures (MTBF)

This is the inverse of failure rate and provides a measure of the average time between failures. It is expressed as

$$\text{MTBF} = 1/\text{failure rate}$$

Reliability and availability

Reliability and availability calculations are represented by a probability value. Reliability is the probability that an item will perform a required function without failure under stated conditions for a stated period.

$$\text{Reliability} = e^{-\lambda t}$$

Where λ is the failure rate per hour and t is the total time.

Availability is the probability that an item is in an operable state at any time.

$$\text{Availability} = \text{MTBF}/(\text{MTTR} + \text{MTBF})$$

MTTR is the Mean Time To Repair.

Failure distributions

This is a plot of the failure rate versus time. It can come in a number of forms such as normal or exponential distribution.

A common type of failure distribution is the Weibull plot or bathtub curve as shown in figure 10. It characterises the typical life of a mechanical or electrical component.
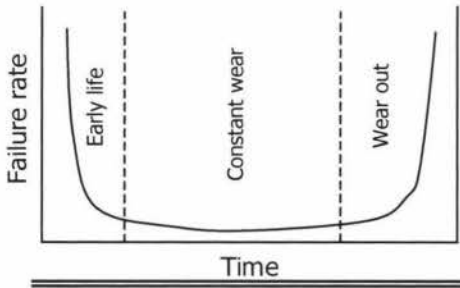
Figure 10: *Weibull plot or bathtub curve*

The initial phase is known as the early life, infant failure or burn in period where the chance of failure is initially high but then drops off as defective components are weeded out.

The middle phase is the constant wear phase, where the chance of failure is constant.

The final phase is the wear out period and is characterised by an increasing chance of component failure.

Fault Tree Analysis (FTA)

FTA is a top down approach to assessing a systems reliability, that is, this technique starts from a system level and moves to a component level. FTA identifies an undesirable system level event and then calculates the statistical possibility of this event occurring and how it might occur based on the probability of the associated causes occurring at a component level.

Failure Mode and Effects Analysis (FMEA)

This technique is also known as Failure Mode and Effects Criticality Analysis (FMECA) and involves identifying which components in a system can fail, how this failure might occur and what the effects of this failure will be on the overall system. This is a bottom up technique as it starts from a component level and moves to a system level.

Current practices

FMEA and FTA are widely used in the automotive industry and for critical applications where unexpected failure would be catastrophic, such as the aerospace industry. Many products are coming onto the market to aid in the development of these types of analysis.

Failure rates, MTBF, reliability, availability and failure distributions are all well known techniques for describing the dependability of components and systems.

Other analysis techniques such as Finite Element Analysis (FEA) are becoming widely used to develop better understanding of how components react under loading and there are a number of tools to facilitate this.

The overriding trend however is for these techniques to be applied to the components being manufactured and very rarely to the plants and processes themselves.

SOFTWARE EVALUATION

This chapter describes how the software used for the modelling and simulation tasks was identified. Initially a review is made of specifications that are deemed important by other authors. From this review, a set of specifications to be used for software assessment purposes is described.

Reviews of software packages and analysis of how they meet the specifications is given and the division between reliability simulation software and parameter simulation software is explained.

Finally, the choice of the software to use is discussed and the reasons for this choice are given.

LITERATURE REVIEW

Several authors have discussed the features that make a computer language suitable for modelling. A few of these ideas are presented here to try to clarify which things are commonly thought of as being important when comparing languages.

According to Neelamkavil (1987) in addition to the normal requirements for programming languages, languages for simulation should

"...provide efficient mechanisms for:

- Describing the system being modelled

- Keeping track of events, activities, and process interactions

- Generation of stochastic variates from appropriate distributions

- Interactive graphical simulation

- Collection, analysis, and presentation (flexible reports, colour graphics, animation) of results

- Self-documentation (listing must be understood by analysts who are not programmers..." (p.155).

Many of the features described by Neelamkavil are provided in all modern modelling tools and have been omitted. However, some features are still worthy of note, such as the method of describing the system being modelled. That is, the structural description should be clear and readable even by someone with no knowledge of the underlying code.

Presentation of results is also important, for what good is a simulation if the results are hard to understand or unusable?

In addition, documentation is also valuable to help users who may not be initially familiar with the model understand how the model works.

Also, when choosing a modelling tool consideration should be given to:

1. "Nature of the problem under study

2. The availability of the language

3. Ease of installation and use

4. Understanding of simulation concepts and ease of learning the language by the local staff

5. Accuracy of simulation results

6. Facilities for collection, analysis, and display of results

7. Availability of user-friendly documentation

8. Features that reduce cost of programming and simulation

9. Cost-effective maintenance and enhancements facilities"

(Neelamkavil, 1987, p.157)

Once again, the presentation of results is seen as being important as well as documentation. Other considerations such as cost, usability and efficiency are also covered

In Frantas opinion (1977) simulation languages are designed:

1. "To aid the model builder by presenting a conceptual framework for precise thinking. The elements of the language are abstractions which apply to a wide class of phenomena. Their application consists of identifying and describing the system being modelled in terms of the given language concepts

2. To provide a notation for the description of dynamic behaviour

3. To serve as a programming aid; to facilitate the detection and correction of logical errors

4. To facilitate the generation of stochastic variates. This implies multiple random number stream and variates generators

5. To aid in the dynamic collection, analysis, and display of statistical data

6. To efficiently trace the dynamic behaviour of model programs" (p.15).

These concepts focus on how the modelling tool structures and presents the model as well as the results.

Gordon (1967) does not spell out specific attributes that a modelling program should have but rather proposes guiding principles, which are summarised here.

Block Building

The description of the system should be organised in a series of blocks or subsystems. With just a few simple inputs and outputs.

Relevance

The model should only include those aspects of the system that are relevant to the study objectives. Irrelevant information does no harm but should be discarded to reduce the complexity.

Accuracy

The accuracy of the information gathered should be considered, keeping in mind the objectives of the model. Higher than necessary accuracy will result in an unwieldy model, while insufficient accuracy will give meaningless results.

Aggregation

The extent to which the number of individual entities can be grouped together into larger entities. The more general the model, the easier it is to use but less useful information can be extracted.

The various concepts described here highlight a number of different approaches to defining what software should do, what must be considered and guiding principles that should be adhered to. These differing approaches result in a number of basic functions of the software tools that are important. These functions are described below.

METHODOLOGY

When choosing software for any modelling task it is important to have a clear idea of what is going to be modelled and what the requirements of the model will be for successful simulation. In this case the strapping machine and the induction motor are the entities under study and the models will be required to output reliability and failure information for individual components, such as the shaft, the windings and the bearings, as well as for the entire system.

It was found that the process design testing scheme requires two very different types of simulation.

One type of simulation is the modelling of reliability information, with data sets such as

failure rates and MTBF as well as reliability prediction techniques for building industry standard models of reliability for components and systems.

The other modelling approach is that of modelling loading parameters for systems and components, such as the amount of torsion on a shaft and the level of loading it experiences.

The integration of these two approaches gives a complete picture of the system reliability. That is, the predicted failure rate under specific loading conditions.

Furthermore, it is required that any outputs from the modelling and simulation software be in a form such that they will be available for further analysis, possibly through the use of a separate software tool, such as MatLab or Excel.

The chapter on process and system identification and assessment gives a more in depth explanation of exactly what components and parameters are covered but it is suffice to say here that the model will incorporate the integration of mechanical, electrical and magnetic components in one entity that can be used as part of future models which build on this work.

Building on the philosophies described in the literature review, a set of preferred attributes for the software was developed.

The most important factors in assessing the suitability of the software for the chosen task are those influencing its ability to quickly produce relevant and useful models that meet the requirements of the simulation. These include:

- An object-oriented philosophy to produce a modular design that utilises reusable components and subsystems. This allows efficient generation of models and permits future work to be built upon previous efforts.

- A built in library of useful components, appropriate to the modelling task. This increases the efficiency of the modelling process. If standard components that can be dropped into the model either as is or with slight modifications, are available then changes and developments to the model are much easier to make.

- The ability to handle interaction between multiple domains, such as electrical, mechanical and magnetic components. Most of the entities that will be modelled have properties from different domains. For models to be accurate, all these properties need to be included in the same model and considered working together.

- Compatibility with other programs is also considered an important factor. The ability to output results or communicate directly with other applications means that the flexibility of the simulations is much higher. Furthermore, other techniques such finite element analysis can be incorporated into the model using tools more suited to the task than a general modelling program.

Other factors that are important from a practical point of view are the cost of the software, how easy it is to use and what types of support services are available.

It must also be kept in mind that general-purpose languages provide little framework and insufficient tools for efficient model development while more specialised languages tend to restrict the model and provide little latitude for creative solutions not anticipated by the language developers.

Once these desirable attributes had been determined a large number of software titles was initially listed for further consideration. This list was made up though consultation with engineers, literature reviews and internet searches. This initial listing was then sorted to identify the software that seemed to be the most promising through the identification of the main features. Finally, any software that met all the initial criteria was obtained as a demo version and reviewed in depth.

Complete documentation of the software reviews, main features of other software and the initial software listing can be found in Appendix 5: Software Evaluation.

REVIEWS

Reliability simulation software

Software that models reliability information, such as the Item ToolKit suite from Item Software, Relex Software suite from Relex Software corporation and @Risk from Palisade corporation, were identified as the most promising candidates from a longer list of possible solutions which are described in Ap-

pendix 5: Software Evaluation. Reviews of demo versions of these software packages provided knowledge about the individual strengths and weaknesses of each package. Table 3 summarises some of these attributes.

	Item ToolKit	Relex	@Risk
Library of relevant components	✓	✓	
Object Oriented	✓	✓	
Multiple domain interaction	✓	✓	
Compatible with MatLab			
Compatible with Excel	✓	✓	✓
Easy navigation	✓	✓	
Hierarchy tree	✓	✓	
3D visualisation			

Table 3: *Reliability modelling software*

Item ToolKit software

The Item Toolkit Software is a reliability-modelling tool specifically designed for use with mechanical and electrical systems.

The software includes powerful, easy to use tools for FTA, FMECA, and RBD analysis. Also provided are extensive libraries containing failure information for electro and mechanical parts.

Import and export facilities exist for use with many different formats.

The only problem discovered was that the tutorial in the manual was a little hard to follow.

Relex software

Relex is a reliability analysis tool with a range of supported techniques such as reliability prediction, block diagrams, FMEA/FMECA, fault tree, failure data analysis, maintainability prediction and life cycle cost.

Relex appears to be very easy to use and very powerful allowing import and export to Microsoft Access, Microsoft Excel, Microsoft FoxPro, dBASE, Lotus and Paradox. It can

also give outputs in the form of automated reports and charting.

The parts library appears to be comprehensive but is focused mainly on electronic components, although it does support some mechanical components. The components include default failure and reliability data and can be set to specified values by the user, the user can also define the minimum and maximum stress values for each component.

Relex is Both ISO 9001:2000 and TickIT 2000 accredited.

@Risk software

This program is an Excel add-in and is designed to evaluate the risk inherent in certain activities based on the risks of subtasks. Primarily designed to evaluate business risks it is expected that it may be applied to a mechanical situation to deal with failure rates and failure distributions.

@Risk is very good at dealing with a variety of different distributions and is very flexible in this regard. However, @Risk does not specifically have ways of dealing with time series data such as changing loads although it may be possible to build this in through Excel.

Furthermore, @Risk does not incorporate some of the tools that are common with other failure analysis packages such as FTA and FMEA amongst others. This work could be done by hand however this approach may be unwieldy for large problems.

Consultation with HRS, the suppliers of the @Risk software has indicated that the Precision Tree software product from Palisade Corporation may be able to add extra functionality to @Risk.

Parameter simulation software

Software was investigated and reviewed that could be used to simulate the physical parameters of a model such as loading or number of cycles per hour. The most promising software packages were short listed and given a more detailed examination. A summary of this review process is presented in table 4.

20Sim software

The major selling point of the 20Sim software is its support of a number of different techniques for entering relationships between entities, for example models can be entered us-

ing equations, block diagrams, bond graphs or ionic diagrams. This allows great flexibility when combining systems that work in several domains, such as mechanical and electrical.

3D graphical animations can be easily linked to the models, with a good range of tools available for this. The animation did tend to be a little jerky however.

Tight integration with MatLab means that functionality can be easily expanded through the transfer of variables between the two systems.

Editing models was relatively easy with smart block connections that move around the block to make the shortest line. Hierarchy navigation is simple with up down buttons and a visual representation of the model tree. Icon graphics can be defined by the user giving clear model representations.

	20Sim	WinGems 5.0	TaylorEd 2000	Simprocess	Simulink	VisSim	Dymola
Library of relevant components	✓						✓
Object Oriented	✓		✓	✓	✓	✓	✓
Multiple domain interaction	✓				✓	✓	✓
Compatible with MatLab	✓				✓	✓	✓
Compatible with Excel		✓	✓			✓	
Easy navigation	✓		✓		✓	✓	
Hierarchy tree	✓		✓		✓	✓	
3D visualisation	✓		✓				✓

Table 4: *Parameter simulation software*

A wide range of simple components is available in the demo version such as electrical, mechanical (rotation & translation), signals (linear and non-linear blocks, continuous and discrete controllers, discrete and logical signals and signal sources) and system blocks. More complex components can be found in the professional version, specifically in the mechatronics libraries.

Some of the problems found with the demo version were a lack of support for some of the

standard windows editing features such as Ctrl-Z for undo and no use of SHIFT for multiple selections. It was also not possible to delete items from the model tree. Other small issues were that some of the tutorials contained errors and some menus disappeared off screen.

Dymola

Dymola provides a large number of well documented libraries including: Mathematical and physical constants, mathematical functions, SI-unit type definitions, input/output blocks, electric and electronic components, 1D-rotational and 1D-translational mechanical components, 3D-mechanical systems, components to model state machines and Petri nets, linear interpolation in one and two dimensions.

'Acausal modelling' is supported with two-way interactions between blocks. In addition, hybrid modelling of both discrete and continuous systems is possible. The scripting language used is based on Modelica.

The main problem with this program is the difficulty in navigating the model hierarchy. There does not appear to be any kind of map or tree and opening entity after entity is both tedious and results in a large number of windows being opened cluttering the workspace.

Other problems were that some demos do not work in the evaluation version and the animation speed could not be adjusted.

VisSim

The basis of VisSim modelling format is the block diagram. Hierarchy navigation makes use of a navigation tree and movement between layers requires just a simple mouse click. Blocks available are simple including animation, annotation, arithmetic, Boolean, DDE, integration, linear systems, MatLab interface, matrix operations, non-linear, optimisation, random generator, signal consumer, signal producer, time delay, transcendental. Algebraic expression and user defined function blocks are also available.

Scripting can be done using the C programming language. A variety of plots and graphs can be used to view the results of a simulation. Animations are also available to aid visualisation but are limited to bitmap manipulation.

Simulink

Navigation in Simulink is very easy with block diagrams and hierarchy trees showing system layout.

A wide range of continuous and discrete mathematical and control functions, including fuzzy logic, neural network functions are included with the package. Both continuous and discrete functions are supported. Simulink also uses the standard Matlab scripting language and new blocks are easily defined.

DISCUSSION

A large number of software tools have been identified and the most promising of these have been reviewed. This provides a useful resource for future modelling and simulation tasks because suitable software for specific tasks can be easily identified. Furthermore, a large amount of experience has been gained through the use of trial versions of software. This experience will prove useful when identifying the types of tasks suitable for simulation and the software tools most suitable for the task.
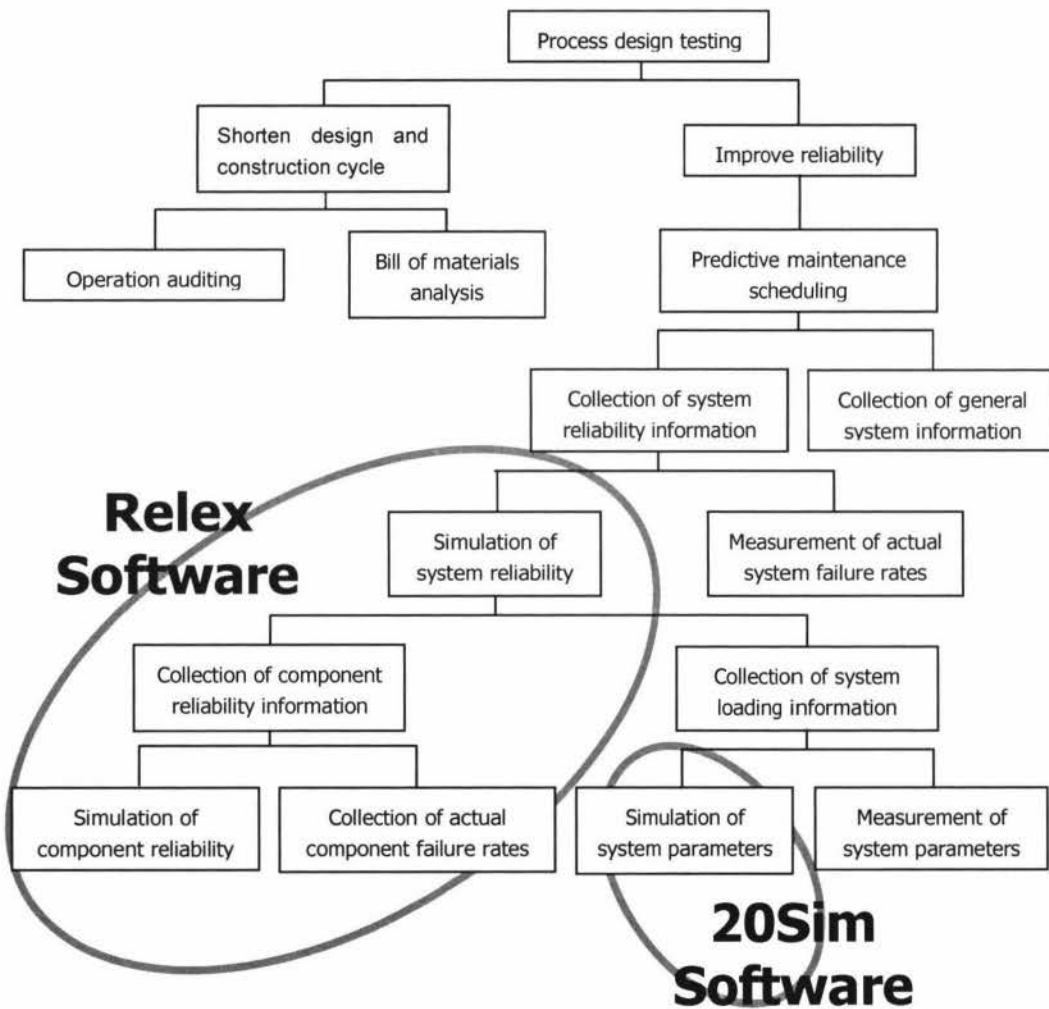
Figure 11: *How Relex and 20Sim fit into the process design testing method*

For the purposes of this project two software packages stood out, these being Relex software and 20Sim. Relex is a reliability modelling tool suitable for the component reliability tasks and providing a framework for the simulation of the system reliability. 20Sim on the other hand is more suitable for the simulation of system parameters. Therefore both fit into

the process design testing scheme in different places. How each software package fits into the process design testing method that was established is demonstrated in figure 11.

Relex choice

The choice to use Relex was mainly due to the large library of industrial standard reliability information for both mechanical and electrical parts. This means that the chore of collecting the basic reliability data for individual components has largely been done. Furthermore, these databases are updated regularly, ensuring that the part information is kept up-to-date.

Also industry standard modelling techniques are used. This ensures that quality standards can be met and that work produced using the Relex software will be widely recognised as being valid.

Another reason that the Relex software suite was chosen for use was the wide range of import and export capabilities that it has with other software. This ensures that it will fit into the overall scheme with a minimum of difficulty.

Relex was also easy to use. The software is modular so that it can be customised to specific needs, minimising the overall cost.

20Sim choice

The factor that most strongly influenced the decision to choose 20Sim as the modelling tool was its large selection of mechanical and mechatronic components, these include entities such as various motors, drive trains and transmissions. Programs such as Simulink and VisSim while powerful and flexible did not have these built in components meaning that building up complex models incorporating multiple entities is a time consuming chore. 20Sim on the other hand allows these standard components to be used or modified for use as needed.

Furthermore, 20Sim was easy to use, providing a number of options to simplify model visualisation, such as editable entity representations, 3D animations and a hierarchy tree.

Another major advantage of 20Sim is the languages compatibility with MatLab and Simulink. This provides for further analysis and the possible incorporation of 20Sim models into future simulations. This compatibility also allows expansion of functionality should it be required and compatibility with other useful aspects of these languages such as the control or FEA toolboxes.

20Sim also has a variety of resources available to the new user, including reference manuals and papers on the design of mechatronic systems other points of contact include consultancy, on site assistance, telephone assistance and training.

MODEL CASE STUDIES

This chapter describes the creation and simulation of computer models, for both the strapping machine and the induction motor using the Relex software.

The steps that were taken during the creation of the model and some of the problems and strategies discovered during the modelling process are recounted. In addition, a description of the results obtained from the simulation and a discussion of the significance of the results is provided.

LITERATURE REVIEW

This section reviews the current state of knowledge regarding how motor failures occur and how components specific to motors tend to fail. This is important because once the common failure modes of a system have been identified then resources can be focused on predicting and preventing these failures.

Furthermore, the information presented here provides the raw data, such as failure rates and modes, that were used to produce the models for the cases studies.

How motor system failures occur

Thorsen and Dalvas (1999) analysis of high voltage induction motors in the petrochemical industry regarding the predominant failures of induction motors is described in table 5.

Bonnett (2000) describes motor failures as being caused by stress categories such as:

- Thermal

- Electric/dielectric

- Mechanical

- Dynamic

- Shear

- Vibration/shock

- Residual

- Electro-magnetic

- Environmental

The Non-electric Parts Reliability Data (NPRD) describes motor failure modes as shown in table 6.

Thorsen and Dalvas have the most specific categorisation of failures by causes including initiators, contributors and underlying causes. Although the authors do not define exactly what these three causes are, the interpretation used for this research is as follows. Initiators are the events that cause the final failure, contributors are the long term loads on the component that degrade the ability of the component to endure the initiators and the underlying causes are the sources of the initiating and contributing causes. This is very similar to the wear out (contributors) and stress rupture (initiators) failures described

earlier. Also included are statistics describing the proportion of each cause occurring. This is very useful for prediction purposes.

Causes of failure for motor system

Initiators	
Transient over voltage	2.4%
Overheating	4.8%
Insulation breakdown	9.6%
Mechanical breakage	66.4%
Electrical faults or malfunction	13.6%
Stalled motor	0.4%
Not specified	2.8
Contributors	
Persistent overloading	4%
High ambient temperature	0.8%
Abnormal moisture	11.6%
Abnormal voltage	2.4%
Abnormal frequency	0%
High vibration	32.4%
Aggressive chemicals	0%
Poor lubrication	14.4%
Poor ventilation or cooling	1.6%
Normal deterioration from age	10.4%
Not specified	22.4%
Underlying causes	
Defective components	37.6%
Poor installation/testing	4.8%
Inadequate maintenance	11.2%
Improper operation	1.6%
Improper handling/shipping	0.4%
Inadequate physical protection	12
Inadequate electrical protection	4.8%
Personnel error	4.8%
Outside agency – not personnel	1.2%
Motor – driven equipment mismatch	4%
Not specified	17.6%

Table 5: *Motor failure causes and frequency, Thorsen and Dalva*

Bonnet on the other hand describes only stress categories and does not attribute rates of occurrence to each category. While this sort of classification is useful for identifying the causes of a fault, it is unhelpful when trying to predict the likelihood of specific faults occurring.

Finally the NPRD data describes the various modes of motor failure and the percent occurrence of the said failure mode. This data is not terribly helpful for identifying the causes or types of failure because the bulk of motor failures are classed as 'no movement' or 'noisy' which could cover any number of failure types.

FMEA Part (AC motor, poly phase)

Displaced	1%
False response	3%
No movement	42%
Noisy	24%
Opened	4%
Out of adjustment	3%
Out of specification	4%
Overheated	9%
Shorted	3%
Vibrating	1%
Other	2%

Table 6: *Motor failure modes and frequency, NPRD*

The description of the failure modes of specific motor components (bearings) is also examined. Specific components that are part of the induction motor system and that are prone to failure were found by Thorsen and Dalvas, Bonnet and O'Kane and Sander (2000) examined to be:

- Bearings

- Stator windings

- Rotor assembly

- Shaft or coupling

Different authors described the failure modes of these components in a number of ways. These are presented below for the specific case of bearing failure to give a feel for the different approaches taken. Complete failure mode descriptions are given in Appendix 2: Failure Modes for Induction Motors.

Component failure modes in the petrochemical industry were described by Thorsen and Dalvas (1999) as:

- **Bearing faults** can be caused by improper or insufficient lubrication, heavy radial and axial stresses due to shaft deflection, improper mounting, alignment or foundation. Such stresses may lead to vibrations and, thereby, increased wear and tear. Bearing faults are best detected by vibration, shock pulse, and acoustic emission monitoring.

This description demonstrates how the failures occur but does not provide any information regarding the frequency of occurrence. This information is useful therefore for identi-

fying the causes and effects of specific failures but not the actual chance of such a fault occuring.

Bonnett (2000) examines the stresses that, when applied to motor components, cause failure. These results, also taken from the petrochemical industry, are summarised in table 7 for the case of bearings.

Bearing Stresses

Dynamic and static loading	Electrical currents
Radial	Rotor dissymmetry
Axial	Electrostatic coupling
Pre-load	Static charges
Thermal	AFD's
Friction	**Environmental**
Lubricant	Condensation
Ambient	Foreign Materials
Vibration and shock	Excessive Ambient
Rotor	
Driven equipment	
System	

Table 7: *Bearing stresses, Bonnett*

Furthermore, Bonnett (2000) also suggests that failure mode and pattern are also relevant, describing them for motor bearings as shown in table 8.

Failure mode/class	Failure pattern
Fatigue	Thermal
Fretting	Vibration & noise
Smearing	Lubricant quality
Skidding	Mounting/fits
Wear	Contamination
Lubricant failure	Mechanical damage
Electric pitting	Electrical damage
Flutting	Load pattern
Cracks	
Seizures	

Table 8: *Bearing failure modes and patterns, Bonnett*

This data is useful for the identification of failure modes and stress that occur in individual components and helps to build up a picture of how entities fail but neglects to deal with the frequency of failure.

The NPRD has compiled information about the common failure modes of bearings, which is described in table 9.

Mechanical part (Bearing)	
Bent	1%
Binding	12%
Clogged	2%
Cracked/fractured	1%
Dented	2%
Jammed	2%
Loss of Lubrication	9%
Pitted	3%
Scored	5%
Seized	2%
Sticking	5%
Vibrating	3%
Worn out	53%

Table 9: *Bearing failure modes and frequency, NPRD*

The NPRD data while having information regarding frequencies of each failure category is not very specific. The actual classification focuses more on the failure modes rather than the causes of failure. This can be useful for the prediction of specific failure modes but is less useful for prevention.

O'Kane and Sander (2000) working for U.S. Electrical Motors have found that the stresses causing failure of motor bearings can be described as shown in table 10.

The information from Bonnet and O'Kane and Sander is of little use because it does not provide any description of how the failures are distributed between the various failure categories. However, it does provide some understanding of the stresses that occur within bearing entities.

SKF are bearing manufacturers that have also gathered data on how bearings commonly fail. Their collected failure mode percentages are presented in Appendix 2: Failure Modes for Induction Motors. The focus of the data provided by SKF is on how faults are caused and how they can be prevented.

This review of failure modes for induction motors and their components demonstrates some of the differences between the analysis of

equipment users and the analysis of equipment manufacturers, with users generally focusing on the identification of how faults occur and manufacturers focusing on how faults can be prevented. Furthermore, it is interesting to see the variation in the types of failure described, either very general failure modes such as given by O'Kane and Sander, very specific failure modes such as given by the NPRD or a combination of the two such as described Bonnet.

Types of Stress	Bearings
Thermal	✓
Electrical/Dielectric	✓
Mechanical	✓
Dynamic	✓
Shear	-
Vibration/shock	✓
Residual	-
Electromagnetic	✓
Environmental	✓

Table 10: *Bearing stresses, O'Kane and Sander*

Finally, the information from SKF provides a basic description of the frequency of failure causes which is very useful in the prevention of failures.

The point that appears to be apparent from this review is that most literature deals only with one small aspect of motor or bearing failure such as the identification of trends, failure prevention techniques or failure prediction. It is clear therefore that some work is required to provide a structure or framework to allow a full picture of how, why and how often failures occur.

DEVELOPMENT

A decision was taken to produce two separate models so that the full functionality of the Relex software could be assessed. The first model was that of the complete strapping machine. The other was a model focused specifically on the induction motor.

The intention of the models was to demonstrate how Relex could simulate the reliability and potential failure modes of various components and assemblies included in a model.

Model organisation

When creating a model that consists of many different entities attention must be given to how these entities are organised. There are many ways that entities can be grouped and it is up to the modeller to select the most important relationships to focus on.

For example, objects might be grouped by their function such as all the screws together or all the bearings together. This has the advantages of simplifying the modelling process because it is easy to reuse parts of the model for each variation in the group. This form of grouping, while convenient for creating models for each individual part is not very practical when it comes to assessing the effects that parts have on one another.

For this reason entities are often placed in 'functional groups' such as the motor assembly or the gearbox assembly. This sets up a convenient hierarchical structure where detail can be hidden or exposed as becomes necessary.

Another way of grouping entities is in a linear structure where it is explicitly stated which entities can affect other entities. For example, a motor is connected to a clutch, which is connected to a gearbox and so on.

Model creators must be aware of all these approaches because a complete model will often make use of several of them. Initially, the entities might be built up in groups of like entities. Then the entities are grouped by function and finally linked by their effects on one another.

Model resolution

Another of the initial considerations is the level of detail of the model. Should the model try to incorporate a high level of detail, including every component, down to the last screw and then try to remove unnecessary components if the model becomes unwieldy? Or should the model contain only the major components, and add to this, as the model is developed to try to obtain a more accurate model?

The initial approach has the advantage of ensuring that the maximum possible level of de-

tail is obtained and that the model is comprehensive. The disadvantages are that it requires a large amount of effort which may be wasted as some detail is disregarded. The alternative approach has the advantage of producing a model that is easy to work with but that may require further work to build it up to the required level of detail.

Strapping machine model

Initially the intention was to create a basic reliability model for the entire strapping machine. The aim was to provide an assessment of the reliability of the overall system as well as the various subassemblies and components.

Model organisation

The organisation of the model was directed both by the nature of the physical system and the desired results of the simulation. The actual system is composed of a number of assemblies and subassemblies such as the control unit and the cam group as described in figure 12. This figure shows the major entities, groups and assemblies that make up the strapping machine however the individual components are not listed. A full list of the components and their groupings can be found in the Digital Appendix. The desired result of the simulation was to identify the components and assemblies that were at the highest risk of failure. For these reasons the model was subdivided into a number of assemblies that matched those of the actual system.

The mechanical nature of the parts meant that no standard part numbers existed for each component. It was necessary therefore to go through the model and assign model types and failure data to each individual part by hand. While this was a chore, in future, time-savings will be realised through the utilisation of user part lists to automate this process for common mechanical components.

Model resolution

The decision as to the level of detail for this stage was governed by the objectives of assessing the full capabilities of the Relex software. The focus was on mechanical component reliability rather than electrical component reliability, as mechanical failures are seen to be the most common causes of equipment failure in industry.

Therefore, all the mechanical parts were included in the model down to the screws and washers. Disregarded however, were electrical components such as the IC board. Also ignored were circuit breaker, fuses, transformers and a triac. The nature of the Relex software will however allow electrical components to be included with ease if the need arises.

Component reliability data

Two main sources of failure data were used for the reliability information. These were the Bellcore mechanical models and the NPRD database. While some information can be found below a full description of data sources is given in Appendix 4: Models and Databases, as well as information regarding other sources of component reliability information that were considered.

Bellcore, mechanical models

This reliability prediction standard for equipment is published by AT&T Bell Labs. The standard uses a series of models for various categories of electronic, electrical and electro-mechanical components to predict steady-state failure rates, which are affected by environmental conditions, quality levels, electrical stress conditions and various other parameters.
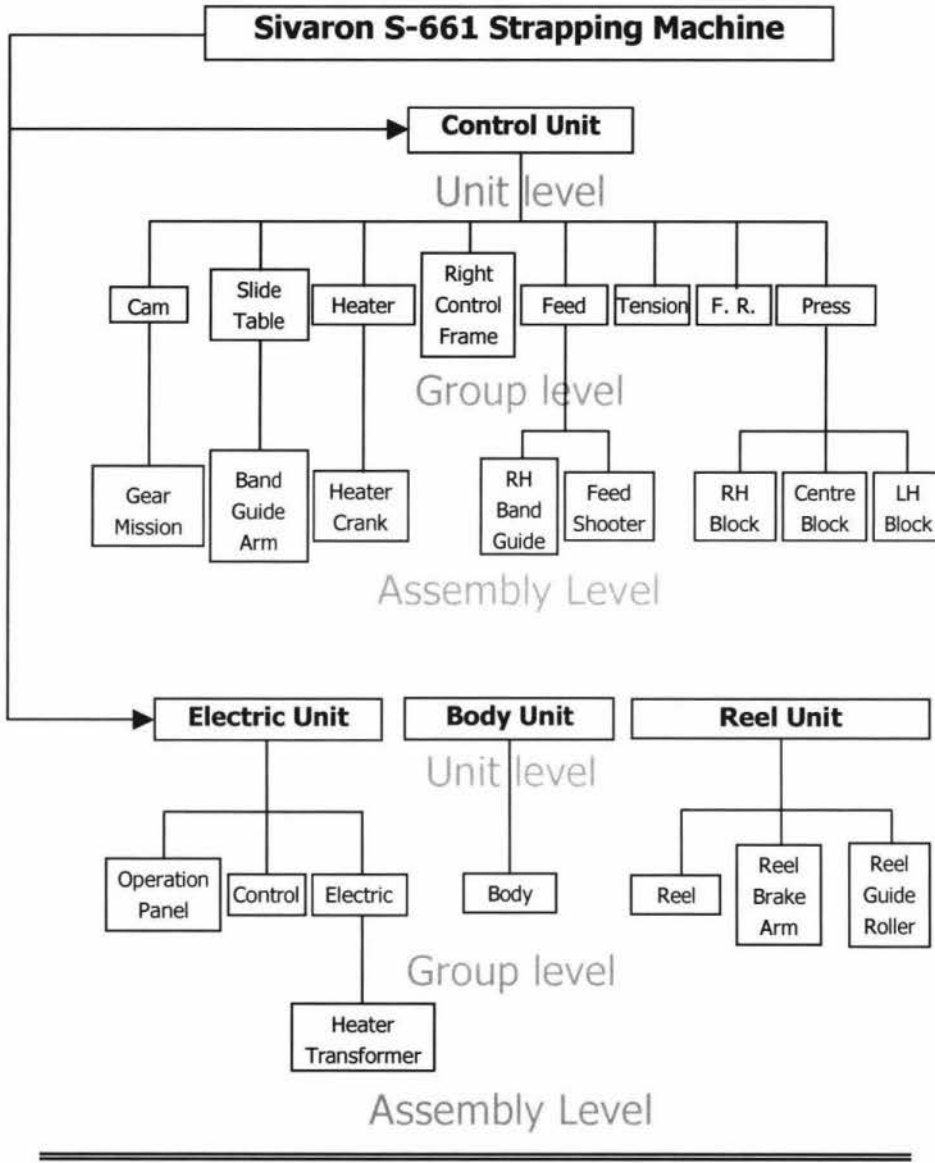
NPRD database

The EPRD and the NPRD are Reliability Analysis Centre (RAC) publications containing failure data on a wide variety of electrical, electromagnetic and mechanical parts and assemblies. It contains information such as failure rate data, total failures and operating hours by part description, quality level, application environment and data source.

Model creation

Building the structure of the model consisted first of listing the components of the strapping machine. The component listing was then converted into Excel and information such as part numbers, descriptions of the parts, quantities of the parts and reference codes was included. This data was then imported into the Relex software and a series of assemblies and sub assemblies were created.

Sivaron S-661 Strapping Machine

- Control Unit — Unit level
  - Group level: Cam | Slide Table | Heater | Right Control Frame | Feed | Tension | F. R. | Press
  - Assembly Level: Gear Mission | Band Guide Arm | Heater Crank | RH Band Guide | Feed Shooter | RH Block | Centre Block | LH Block
- Electric Unit | Body Unit | Reel Unit — Unit level
  - Group level: Operation Panel | Control | Electric | Body | Reel | Reel Brake Arm | Reel Guide Roller
  - Assembly Level: Heater Transformer

Figure 12: *Entity description of strapping machine*

Using the Bellcore model requires a high level of specific component and operating condition information such as the size of the load applied to various components and the rated load for each component. Other information such as the material and dimensions of each component is also required.

If possible, this information was taken from knowledge of the actual system under study. However, in the cases where the necessary data could not be obtained, either from the manufacturer or from physical assessment, the default values given by the software were used.

When it was not possible to find a suitable Bellcore model for a specific component the NPRD database was used.

Where feasible, summary failure rates were used for components that had a range of quality levels or applications listed in the database. This took advantage of a larger sample number and smoothed out unknown factors such as quality level and environmental conditions.

Simulation

Once the model had been created, the reliability of the proposed system was calculated analytically. Changes to the model were then made such as the removal of unreliable components and the reliability of the system was recalculated. This simulation of design changes allowed comparisons of reliability to be made between various designs.

Reports and graphs

A pair of custom report styles was designed. The first was intended to present the failure rates and MTBF of the overall system as well as of each component and assembly. The information included in this report was:

- A short description of the component

- The failure rate of each individual component

- The MTBF of each individual component

- The quantity of each component

- The overall failure rate for that type of component in each assembly or group

- The overall MTBF for that type of component in each assembly or group

The other report presents descriptive information regarding the individual components to illustrate how they were modelled. The information presented in this report was:

- A short description of the component

- The Relex category that the reliability infomation was sourced from

- The Relex subcategory that the reliability information was sourced from

- Specific part data that was used to predict the components reliability

- The calculated MTBF for the component

Examples of these reports can be found in the Digital Appendix.

Induction motor model

The second model that was developed focused on the induction motor. The intention was to develop a modular description that included basic reliability information as well as information concerning likely failure modes and their chance of occurrence.

Model organisation

The organisation of this model was very simple, having all the components grouped as part of the induction motor assembly.

Model resolution

The level of detail for this model was less than that of the complete strapping machine model. Because failure modes were the aspect of the model that was of interest, components that do not commonly fail were not included. This left just the four main components of the induction motor, these being:

- Bearings

- Stator windings

- Rotor bars

- Shaft or couplings

Other components that were disregarded as having negligible failure rates were the motor casing and threaded fastenings.

Reliability data

Component users

The failure mode data for this model came primarily from the work done by Thorsen and Dalva (1999) on failure identification and analysis for induction motors. This work involved the summary of operating experiences of the petrochemical industry concerning induction motors. While the motor studied in this project differs in size and application from those studied by Thorsen and Dalva they were deemed to be sufficiently similar in function to be useful.

Component manufacturers

Other information that was used to identify specific bearing failure modes was sourced from component manufacturers, specifically SKF, producers of bearings (SKF Maintenance and lubrication products 2001, p.5).

Model creation

Creation of the FMEA model started with the identification of the various components that comprise the induction motor system.

The next step was the definition of the modes file that identifies the failure modes and underlying causes for each component and system. Also included in the modes file is the mode percentage, which is the percentage chance of each failure mode occurring for each failure of the component. A diagram showing the failure modes for various components of induction motors is presented in figure 13.
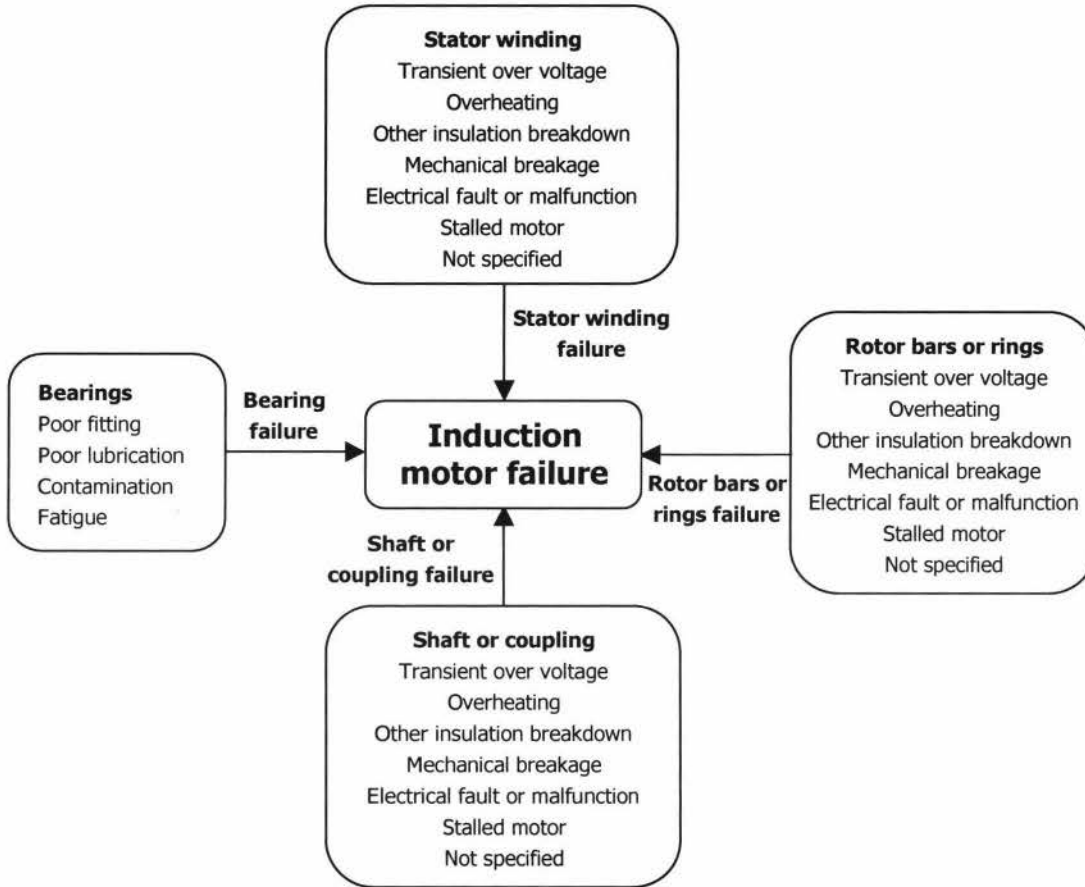
Figure 13: *FMEA model of induction motor*

Also completed was a phrases file, which contains component and mode codes and associated definitions.

The mode and phrase files were then associated with the FMEA model, which compiled the information ready for calculation and simulation.

Simulation

Once the motor model had been produced, the software performed analytical calculations to attribute specific failure rates to the various failure modes.

Reports and graphs

Custom reports styles were designed to automatically display the results of the simulation so that the predominant and critical failure modes can be assessed. The information provided in this report was:

- The name of each component

- A short description of each component

- The failure modes for each component

- The local effect of each component failure mode

- The end effect of each component failure mode
- The component failure rate
- The failure mode ratio
- The failure rate for each component failure mode
- The probability of each failure mode

An example of the report can be found in the Digital Appendix.

Model verification

The verification of both of the models took place at a number of points. Checking for accuracy of the input data was the primary concern and reports were printed as the data was entered to compare the input data with the source of the data.

Other verification techniques used were the checking of calculations by hand and the checking of the hierarchy for consistency.

Model validation

While the models could not be checked against the actual system for validation, intuition was used to identify points at which the model may not be accurate. For example, components that displayed unexpectedly high or low failure rates were double checked for accuracy.

RESULTS

Strapping machine model

This model provided a measure of the reliability of the system. This measure was used to analyse the effects of changes to the system on the overall reliability.

Table 11 shows an abridged version of the simulation results to illustrate this. For a complete listing of the simulation results refer to the Digital Appendix.

Assembly/component	Failure rate (Failures/ million hours)
Strapping machine	51666
Control unit	48727
Cam group	2968
Slide table group	2577
Press group	23574
RH block ass'y	5599
RH block spring	4829
Centre block ass'y	5599
Centre block spring	4829
LH block ass'y	8991
LH block spring	4829
Heater group	5524
Right control frame group	525
Tension group	1141
Feed group	6321
F. R. group	6097
Reel unit	2512
Body unit	277
Electric unit	149

Table 11: *Strapping machine simulation results (abridged)*

Removing the effects of the springs from the simulation by deleting them from the model reduced the failure rate of the overall system to 30411 failures/million hours.

Induction motor model

The FMEA report for the induction motor model shows that the component most likely to fail is the bearing arrangement with a total failure rate of 3.42 failures/million hours and accounts for 51.64 percent of all motor failures. This is illustrated in table 12.

Component	Failure rate (Failures/ million hours)	Percent of total failures
Stator windings	1.65	24.82
Shaft or coupling	.21	3.2
Bearings	3.42	51.64
Rotor bars/rings	.4	6
External device	.9	13.59
Unspecified	.05	.75

Table 12: *Induction motor component failure rates and percentages from simulation*

The most likely failure mode for the bearings is poor lubrication at 36 percent of all bearing failures followed closely by fatigue failures with represents 34 percent of bearing failures.

DISCUSSION

Strapping machine model

Reliability data

Bellcore, mechanical models

The biggest problem with using the Bellcore model was the requirement to identify the various parameters for each component. While in most cases this was possible, in some situations it was not possible to identify what the parameters were. In these cases, the parameters were estimated or the default values supplied by the software were used.

NPRD data base

It was sometimes difficult to find the correct entry for each part. For example a component which is described as a bearing case, or bearing mounting could not be found in the database. The closest alternative was a (bearing) shield, which was substituted instead.

It is also difficult at times to identify exactly which database component best matches the actual component. This is partly due to the lack of part numbers in the database, forcing a reliance on short descriptions which often did not adequately describe the component.

Simulation

The simulation of the strapping machine demonstrated that according to the information that was supplied by the model the overall failure rate of the strapping machine system was 51,666 failures/million hours. The assembly that had the highest failure rate was the control unit at a rate of 48,727 failures/million hours, which accounts for a significant portion of the overall failure rate. The group in the control unit that had the highest failure rate was the press group with a rate of 23,574 failures/million hours. The three assemblies in this group all had very high chance of failure, which is a direct result of the spring components that have failure rates of 4,829 failures/million hours. This is very high for an individual component.

The removal of the springs demonstrates the sorts of gains in reliability that can be achieved through the removal or modification of just one type of failure prone component, in this case seven springs. It is acknowledged that the springs cannot just be removed from the actual system, however they should be replaced with a more reliable type of component or the number of springs should be minimised. Furthermore, design modifications like making the springs easy to replace or repair or including parallel redundancy will have little effect on the operation of the strapping machine but will result in greater uptime for the machine due to less time spent repairing the most common cause of failure.

	Component	Failure mode	Failure rate (failures/ million hours)
1	Bearings	Poor lubrication	1.23
2	Bearings	Fatigue	1.16
3	Stator windings	Insulation breakdown	.61
4	Bearings	Poor fitting	.55
5	Bearings	Contamination	.48
6	Stator windings	Mechanical breakage	.45
7	External component	Mechanical breakage	.40
8	External component	Electrical fault or malfunction	.37
9	Stator windings	Electrical fault or malfunction	.34
10	Rotor bars/rings	Mechanical breakage	.24

Table 13: *Motor component failure profiles from simulation*

At the design stage the differences between reliabilities of various components or applications of components can be assessed. For example, a cam that is expected to transmit power has a much greater failure rate than just a general one, which might operate a micro switch. This allows design decisions to be made that provide a much higher level of reliability.

It is suggested that rather than trying to include every component in a reliability model, only those component types that are known to fail often or that are mission critical are included.

It is expected that there will come a time when all mechanical components will have failure information and/or models as part of the value added process.

Induction motor FMEA model

The FMEA information calculated for the induction motor provides information about the most common failure modes that have been found to occur in the components of induction motors. This information will prove vital for the assessment of which faults to try and predict and prevent.

Furthermore, calculated mode failure rates are used to give a ranking of the most likely component failure modes for the induction motor system. For example, see table 13. The complete FMEA report is provided in the Digital Appendix.

Other activities such as the assessment of the criticality of certain failures, while not dealt with specifically by this simulation, can also be included with ease to provide a further indication of where the greatest needs lie.

FINAL CONCLUSIONS

This chapter presents a summary of the conclusions reached in each chapter and the final conclusions reached through the research presented in this thesis.

FAULT DATA COLLECTION AND ANALYSIS

The fault data collection and analysis provided the basic information required to identify how systems fail. Experience was gained in dealing with failure situations and a number of trends were identified.

These trends included:

- A number of faults arose due to normal wear which could be predicted

- Several faults occurred due to poor repair practices

- Faults due to use beyond normal life expectancy were common

The identification of these trends demonstrated both the value of the classification system utilised and the necessity to develop advanced ways of predicting failures due to normal wear such as that proposed in the research presented here.

PROCESS AND SYSTEM IDENTIFICATION/ ASSESSMENT

The strapping machine system and the induction motor component identified for examination provided a sound demonstration of the capabilities of the software and the value of the techniques used. Furthermore, the results of the simulation, particularly of the motor component, will be of use in future models.

A large body of information was collected regarding induction motors and what their typical failure behaviours are. In addition, a number of prediction techniques have been described so that once the most common or critical failure modes have been identified they can be matched with specific techniques to predict and prevent such failures. This demonstrates how focusing resources on the specific areas that have the greatest need can increase the efficiency and reliability of a system.

PROCESS DESIGN TESTING METHOD

The development of two complementary schemes for the 'Process Design Testing Using Simulation' project has allowed the critical parts of the scheme to be identified. It also demonstrates how the project fits into the overall research programme.

The research described here focuses on the framework of the scheme and the identification of various sources of information that are required for the scheme.

This knowledge provided a starting point for the evaluation of software. This included points such as:

- How the software could be expected to exchange information with other parts of the system
- What types of component reliability information are included with the software
- What facilities for component and system reliability assessment are supported

The identification of how the software addresses these points demonstrates whether or not it is suitable for the process design testing system and what other tools may be required to complete the system.

SOFTWARE EVALUATION

The software evaluation identified Relex and 20Sim software as two tools that could form a significant part of the process design testing scheme. The Relex software provides component reliability information taken from actual components and provides tools for the simulation of system reliability. The 20Sim software simulates system parameters and loading information regarding both the system and individual components.

The Relex software was chosen for the modelling phase of the research as it was deemed to provide the greatest immediate financial benefit and because it represents a major part of the process design testing scheme.

MODEL CASE STUDIES

The models developed for the strapping machine and the induction motor demonstrate the value of the Relex software and the sorts of conclusions that can be drawn from the reliability analysis such as:

- Measure of system and component reliability
- Identification of system and component failure modes

In addition, the development of the models also demonstrated how the Relex software fits into the proposed process design testing scheme. The simulation showed how component reliability information taken from databases, users, manufacturers or reliability models can be used to produce measures of system reliability in a useful format.

Furthermore specific conclusions can be drawn regarding the case studies, these were:

- The springs contained in the control unit of the strapping machine are highly unreliable and are likely to cause a failure
- Removing the effects of the springs in the strapping machine causes an increase in system reliability
- The bearings in an induction motor are the component most likely to cause a failure
- The most likely cause of bearing failure is poor lubrication

The tools and techniques used to create the models for this research will be widely applicable to future testing of process designs.

CONTRIBUTION TO LITERATURE

The contribution to literature that was made as part of this research included a short correspondence, a paper presentation and a pair of posters.

- A short correspondence: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2003), Modelling for Predictive Maintenance and the Role of the Tele-expert. J Chin. Inst. Chem. Engrs. 34(6), 661-666.

- A paper presentation: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2002), Maintenance through the Tele-expert. In A Symposium on Maintenance Engineering, (pp. 15-24), New Plymouth, New Zealand: The Maintenance Engineering Society of New Zealand.

- A poster paper: Bakker, H. H. C., Schneider, W., Martin, N. K. L., (2002), Modelling for Predictive Maintenance and the Role of the Tele-expert. In 9th APPChE Congress and Chemeca 2002 (#572). Christchurch, New Zealand: The University of Canterbury

- An entry to the Foundation for Research Science & Technology (FRST) 2002 poster competition: Martin, N. K. L.: Design Testing Through Simulation.

In the case of the posters these publications demonstrated the research to a general audience while the paper and correspondence described the technical applications and implications of the research.

FINAL CONCLUSIONS

The conclusion of this research is that software, specifically the Relex software suite can be used to assess the reliability of mechanical systems before production. Furthermore, a scheme has been identified that includes the Relex software and other tools to provide a full measure of system reliability through simulation, which will ultimately lead to a complete predictive maintenance scheme.

The other tools and resources that have been identified and successfully used in the design testing scheme include:

- NPRD for mechanical component reliability information

- The Belcore standard for component reliability modelling

- User and manufacturer data for component reliability and failure modes

The completion of this project demonstrates the value of the overall programme and represents significant progress towards the overall programme goal of improved process design auditing.

FUTURE DIRECTION

The research described here while having some important results in its own right also provides a structure for future research. As such, there are a number of areas in which more work can be done, these are detailed below.

- **System parameter simulation.** The 20Sim software has been identified as a candidate for system parameter simulation. However, work remains to be done to implement actual simulation of a system using this tool.

- **Direct system parameter measurement.** The investigation of a tool that provides direct measurements of system parameters. This includes such things as sensing and trending of information from actual systems. This will provide validation for the simulation of system parameters.

- **System reliability simulation.** The integration of system loading information, taken from parameter simulation and actual measurements with the system reliability simulation will provide a more complete measure of system reliability than the one presented in this work.

- **Actual system failure rate measurement.** The investigation of a tool for the collection and analysis of actual system failure rates will provide validation for the system reliability simulation.

- **General system information compilation.** A tool for the collection of general system information will provide the final

element required for complete predictive maintenance scheduling.

- **Predictive maintenance scheduling.** Integration of the features described here into a comprehensive predictive maintenance scheme.

- **Fault data collection and analysis.** Further work can also be done to improve the documentation and classification techniques. It is suggested that the cause, stress, symptom technique can be expanded to be more open ended. For example, symptoms could result in further loads and symptoms. Specifically, a bearing may be mounted too tightly resulting in excessive loading and appearing as cage damage. This damage can result in vibration and noise. The vibration of the bearing could result in shaft oscillation and further damaging loads and symptoms. It is obvious therefore that the initial attempt at a classification is over simplified and could be further refined.

- **Process and system identification/ assessment.** The model of the strapping machine provides a demonstration of the types of analysis that can be performed and the range of techniques that can be utilised. However, the model does not necessarily demonstrate the accuracy of

the analysis. It would be valuable therefore if future work compared the various reliability models with actual system failures. To be comprehensive this would require a large sample of how often and in what ways the strapping machine fails. This can then be compared with the reliability simulation for validation and assessment of which techniques and sources of component reliability information are the most accurate.

- **Software evaluation.** A critical part of this research is the use of software tools, therefore any further research would do well to include an assessment of if the advancement of the state of software technology has provided any tools that are more appropriate than those described here. Furthermore, software tools for modelling specific classes of problem such as FEA or fluid flow should be investigated to ensure that the tools used are appropriate for the type of problems encountered and to ensure that the range of problems that can be addressed is as wide a possible. The critical factor in the assessment of the new tools is ensuring that they fit into the overall scheme in a seamless fashion so that they provide a true increase in the functionality of the overall scheme.

APPENDICES

APPENDIX 1: FAULT DATA COLLECTION

This appendix deals with the collection of fault data that took place during the period of work at Graphpak Services Ltd. The document template that was used for the data collection is presented as is the actual documentation that was created for each specific fault.

FAULT PROFILE TEMPLATE

This is the template that was used for the collection of fault information.

Objectives of profile

- Identify common types of faults
- Identify causes of faults
- Identify costs of faults
- Identify prediction and prevention methods for faults

Problem definition

Description of <u>what the fault is</u> and <u>what is at fault</u>. What were the <u>effects</u> of the fault and <u>why is this a problem</u>? <u>Where is the object</u> at fault and <u>where on the object</u> is the fault? When the fault <u>first</u> occurred and <u>when else</u> it occurred? What is the <u>time pattern</u> of occurrence and when in the <u>life cycle</u> of the object did the fault occur?

Service information

When was servicing performed? What is the serial and model numbers of the machine? What is the model number and description of parts at fault? What is the <u>name</u> and <u>address</u> of the company where the problem is occurring?

Type of fault

Is it a <u>stress rupture</u> fault or a <u>wear out</u> fault? Is it an <u>additive</u> process fault or a <u>multiplicative</u> process fault? Is it a <u>sensor</u> fault, an <u>actuator</u> fault or an <u>ergonomic</u> fault?

Cause-stress-symptom

What is the root cause of the fault? What types of stress did this cause? What symptoms were apparent due to this fault?

Costing the fault

How much <u>downtime</u> can be attributed to the fault? What <u>resources</u> are required to remedy the fault? Was there complete failure, some level of deterioration of performance or no actual failure but preventative maintenance was needed?

Prediction

How could the fault be <u>predicted?</u>

Prevention

How could the fault be prevented?

SPECIFIC FAULT CASES

During the time spent with Graphpak a number of fault incidences were attended and information about the causes and the actions taken to repair the faults were recorded. Most of this information is given here, however some data regarding the identity of the companies concerned has been left out due to commercial sensitivity.

Case 1

Problem definition

Three sprockets on the chain drive of a Fuji wrapping machine were very worn and needed replacing. No actual fault had occurred, however failure of the chain drive was imminent. This would have caused the feed conveyer to fail and the operation of the wrapping machine to be seriously impaired.

The sprockets that had worn were all on the feed conveyer chain drive. Graphpak first noticed the fault during routine maintenance in August 2001.

Type of fault

Wear out, multiplicative, actuator fault.

Causes-stress-symptom

Overuse (possible lubrication deficiency), friction resulting in erosion/wear.

Costing the fault

Two hours downtime was required to repair the fault. This was scheduled downtime because the fault had not yet resulted in a failure.

Prediction

The fault was predicted through routine maintenance.

Prevention

It is suggested that this fault could have been delayed through better lubrication.

Case 2

Problem definition

A bearing on a belt-driven shaft on Station II T1 of a 1995 GUK automatic folding machine had collapsed. This caused noisy running and excessive vibration. Left alone the problems would have worsened and the bearing may have seized, possibly causing further damage. The fault first occurred 18 months previous to the date of service and has occurred twice more since then. The failure was regular after the initial episode, which occurred approximately four years after the machine was first used.

Type of fault

Wear out, multiplicative, actuator fault.

Causes-stress-symptom

It is thought that the fault was caused by an excessively tight tolerance between the bearing housing and the mounting shaft. This put extreme pressure on the bearing causing it to fail prematurely.

This is a repair process fault specifically, misalignment of the bearing, resulting in mechanical stresses causing noise, premature fatigue, and bearing cage failure.

Costing the fault

No time was lost because other machines could be utilised until the repairs were made. Two new 6004-2RS1 bearings were required as well as honing the bearing housing and machining the shaft to a smaller diameter so that the new bearings would fit properly. About 2.5 hours work. There little actual degradation of performance but complete failure was imminent.

Prediction

The first identification of the fault was through sound. Advanced listening techniques, vibration analysis, current/voltage drawn analysis, or thermal imaging could have predicted the fault.

Prevention

Having bearings that fitted the housing and shaft better could have prevented the fault.

Case 3

Problem definition

Worn clutch plates and incorrect break setting on a 1959 Perfecta Pivano Johne 626 guillotine. The wear prevented the motor from properly driving the blade, meaning that the blade was going down but not up again, this caused procedures to take longer than usual, slowing down operation. The position of the clutch is on the flywheel of the guillotine. It could not be established exactly when the fault first occurred because it was manifested as a gradual degradation in performance. The problem was intermittent particularly after 20+ cuts and when performing trimming operations. The situation was deteriorating over time.

Type of fault

Wear out, additive, actuator fault.

Causes-stress-symptom

Overuse, friction resulting in clutch wear.

Costing the fault

The direct result of this fault was 2 hours of downtime for maintenance plus several weeks of substandard performance.

Prediction

Measure gaps in clutch or prediction of the amount of wear from the number of operations.

Prevention

Tightening the clutch as soon as it became a problem.

Case 4

Problem definition

The stripped drive sprocket on the conveyer rollers on a F111 feeder for a 1972 Herzog Heymann automatic folding machine. This caused the stripped sprocket to fail to engage with its mate causing the feeder rollers to fail. This meant that the folding machine would not feed. The sprocket was on a shaft between a driven chain sprocket and an optical encoder disk, the teeth of the sprocket were stripped off.

The fault was first noticed when some noise started to appear from the drive train some two or more weeks before the date of service, the rollers completely stopped turning the day before the date of service. The noise was intermittent until a sudden complete failure. Machine has been trouble free since its last change of ownership at about three years of age.

Type of fault

Wear out, additive, actuator fault.

Causes of the fault

Overuse (possible lubrication deficiency), friction and force resulting in gear tooth breakage and erosion/wear.

Costing the fault

Due to the fault one and a half hours of hand folding was required before the date of service. One-hour repair work and one new sprocket were needed. The machine was down for 12 days while parts were being sourced. This was a complete failure.

Prediction

The fault could have been predicted by the odd noises coming from the machine or by the metal filings on the floor. Thermal imaging and noise analysis and voltage/current analysis may also have given some warning of the failure.

Prevention

Replacement of the sprocket before it failed. Better care of the gears, lubrication etc.

Case 5

Problem definition

The 200KW 240V single phase motor on an automatic strapping machine from Strap pack corp (model S-661) was burning out and drawing too much current (18-19amps) through the circuit board. The strap is pulling to tight and is crushing boxes. The motor is inside the strapping machine and some of its windings are discoloured/burnt out. The problem occurs when the machine has been running for a long time and then occurs constantly.

Type of fault

Additive, actuator fault.

Causes of the fault

This is a possible operational fault causing overheating resulting in the breakdown of motor winding insulation and short circuit.

Costing the fault

8 hours to detect problem plus a full service and modification. It was a serious degradation of performance.

Prediction

To predict this fault variables that could be monitored are motor temperature, motor variables, current/voltage drawn, output speed and torque.

Prevention

Better protection of the electronics and motor would prevent this type of failure.

Case 6

Problem definition

A clicking press (die cutting machine) was the item at fault. When the handle was pulled the press would not operate. This prevented the machine from cutting, and many jobs had to be done by hand. The first occurrence of the fault was that when the handle was pulled the press would cycle repeatedly without stopping, this then deteriorated into total non-operation. The failure occurred every time the press was used. It was found that the clutch was slipping and the motor was wired up in reverse.

Type of fault

Wear out, additive actuator fault.

Causes of the fault

Repair process fault (misalignment of wiring), causing shock loading resulting in clutch wear.

Costing the fault

One hour of maintenance was required to tighten the clutch and rewire the motor. This was a complete failure.

Prevention

Correctly wiring the motor.

Case 7

Problem definition

A Johne Perfecta guillotine has broken clips on the false clamp and several bolts that hold the knife are broken or missing, it was noted that one of the broken bolts had a high level of porosity in the metal. The broken false clamp causes damage to the paper being cut unless measures are taken to protect the paper. The broken and missing bolts mean that the knife is not being held securely. The first bolt broke two months before servicing, another bolt broke during servicing and the missing bolts have been gone since the machine was purchased. The false clamp has been problematic for a while. The bolts seem to break when they are being tightened. The machine is approximately 70 years old.

Type of fault

Both faults are stress rupture faults occurring after an extended period of wear out. The faults are also additive, actuator faults.

Causes of the fault

The failure of the knife bolts appears to be due to a production (forging) fault causing residual loads (stress concentration) resulting in breakage.

The false clamp suffers either from poor design (incorrect engagement) or operation (improper loading or overuse), causing shock and force loading that resulted in broken clips.

Costing the fault

The guillotine was still being used so there was zero down time. However, it was only at 80% efficiency and not very safe. About 1 hour of service time was required, the false plate had to be repaired and 12 new bolts and washers were needed. General grease and oil service was also performed.

Prediction

Testing ultra sonic etc. of the bolts, taking note of the level of wear of the false plate.

Prevention

Replacing the bolts earlier, repairing the false plate before it became critical.

Case 8

Problem definition

Bostitch Textron stapler model EHFS, serial number 10450, had a broken coil spring. This stopped the staples from feeding making the process very slow. The object at fault was the core of the coil spring which had come loose from its seating.

Type of fault

This was a stress rupture, additive, actuator fault.

Causes of the fault

A design or operational fault causes force or shock loading resulting in the displacement of unstable construction.

Costing the fault

About one hour servicing and a new spring was needed. Complete failure had occurred.

APPENDIX 2: FAILURE MODES FOR INDUCTION MOTORS

This appendix presents a complete description of the information that was collected regarding the failure modes of induction motors. Specifically covered are the bearing components.

- **Bearing** faults can be caused by improper or insufficient lubrication, heavy radial and axial stresses due to shaft deflection, improper mounting, alignment or foundation. Such stresses may lead to vibrations and thereby increased wear and tear. Bearing faults are best detected by vibration, shock pulse and acoustic emission monitoring.

- **Stator winding faults** may be interturn winding faults caused by insulation breakdown. Such breakdowns lead to imbalance in the stator, as well as changes in harmonic air-gap flux and current time harmonics. Because the relative changes in supply current may be small, it may be difficult to detect a fault on this basis. One alternative is to detect the axially transmitted fluxes that give a reliable indication of small imbalances in magnetic and electric circuits, as well as eccentricity and phase imbalance.

- **Rotor faults** are mainly caused by breaks in the joints between bars and end rings, usually the result of a pulsating load or direct on-line start-ups. The result is increases in the current in remaining bars, leading to increased risk of extensive fractures. Rotor faults are commonly causing torque pulsations, speed fluctuations, vi-

brations and changes of the frequency components in the supply current and the axial fields. Often, these ate combined by acoustic noise, overheating and arcing in the rotor and damaged rotor laminations.

Adapted from Thorsen and Dalva (1999)

BEARING FAILURE MODE PERCENTAGES

- **16% Poor fitting**

"Around 16% of all premature bearing failures are caused by poor fitting (usually brute force...) and being unaware of the correct fitting tools."

- **36% Poor lubrication**

"Although 'sealed–for-life' bearings can be fitted and forgotten, some 36% of premature bearing failures are caused by incorrect specification and inadequate application of the lubricant."

- **14% Contamination**

"A bearing is a precision component that will not operate efficiently unless both the bearing and its lubricants are isolated from contami-

nation." ..."At least 14% of all premature bearing failures are attributed to contamination problems."

• **34% Fatigue**

"Whenever machines are overloaded, incorrectly serviced or neglected, bearings suffer

from the consequences, resulting in 34% of all premature bearing failures."

Adapted from SKF Maintenance and lubrication products (2001, p.5)

Rotor Assembly Stresses		Stator Stresses	
Thermal	**Environmental**	**Thermal Stresses**	**Environmental stresses**
Thermal overload	Contamination	Thermal aging	Moisture
Thermal unbalance	Abrasion	Voltage variation	Chemical
Excessive rotor losses	Foreign Particles	Cycling	Abrasion
Hot spots	Restricted ventilation	Loading	Damaged parts
Sparking	Excessive ambient temperature	Ventilation	Excessive ambient
Magnetic	**Mechanical**	Ambient	Restricted Ventilation
Rotor pullover	Casting variations	**Electrical Stresses**	**Mechanical Stresses**
Noise	Loose laminations	Dielectric aging	Coil movement
Vibration	Incorrect shaft/core fit	Tracking	Rotor strikes
Off magnetic centre	Fatigue or part breakage	Corona	Defective rotor
Saturation of lamination	Poor rotor to stator geometry	Transients	Flying objects
Circulating currents	Material deviations		Lugging of leads
Residual	**Other**	Bearing Stresses	
Stress concentrations	Misapplications	**Dynamic and static loading**	**Electrical currents**
Uneven bar stress	Poor design practices	Radial	Rotor dissymmetry
Dynamic	Manufacturing variation	Axial	Electrostatic coupling
Vibration	Loose bars, core	Pre-load	Static charges
Rotor Rub	Transient torques	**Thermal**	AFD's
Overspeeding	Wrong direction of rotation	Friction	**Environmental**
Cyclic Stresses		Lubricant	Condensation
Centrifugal force		Ambient	Foreign materials
Shaft Stresses		**Vibration and shock**	Excessive ambient
Mechanical	**Thermal**	Rotor	
Overhung load and bending	Temperature gradients	Driven equipment	
Torsional load	Rotor bowing	System	
Axial load	Environmental		
Dynamic	Corrosion		
Cyclic	Moisture		
Shock	**Erosion**		
Residual	Wear		
Manufacturing processes	Cavitation		
Repair processes	Electromagnetic		
	Side loading		
	Out of phase reclosing		

Table 14: *Induction motor assembly stresses, Bonnett*

Types of Stress	Stator Winding	Rotor Assembly	Bearings	Shaft
Thermal	x	x	x	x
Electrical/dielectric	x	x	x	-
Mechanical	x	x	x	x
Dynamic	-	x	x	x
Shear	-	-	-	x
Vibration/shock	x	x	x	x
Residual	-	x	-	x
Electromagnetic	x	x	x	x
Environmental	x	x	x	x

Table 15: *Stress occurrences for induction motors, O'Kane and Sander*

GENERAL BEARING DAMAGE

Cause	Symptom	Examples
Faulty mounting, radial preloading	Flaking of the outer ring raceway	Driven to hard on an adapter sleeve or on a tapered seating.
Faulty mounting, axial preloading		Insufficient space for the bearing in the housing; the bearing could not follow axial displacement of the shaft which occurred because of thermal loading
Faulty mounting, blows to the bearing or shaft	Indentation on raceways and rolling elements	If a bearing is mounted with an interference fit and is driven up by blows to the outer ring
Faulty lubrication	Highly polished raceway, surface micro cracks, cage failure, seizure, hot running	Insufficient lubrication
Foreign matter in the bearing	Indentations in raceways and rolling elements, eventual flaking	Solid particles entering the bearing during mounting or sealing
Water in the bearing arrangement	Corrosion	Sudden drop in temperature causing condensation
Inaccuracies of the form of the shaft or housing seating	Damage in two diametrically opposite points on the bearing ring	Ovality of the housing or shaft seating, a fragment of metal between the outer ring of the bearing and the housing
Vibration	Washboard effect in raceway caused by rubbing	Machines vibrating while the bearings are stationary
Passage of electric current	Burn craters or washboard effect caused by arcing	Faulty earthing when welding, static electricity.
Metal Fatigue		Bearing has reached the end of its endurance life

Table 16: *Causes, symptoms and examples of bearing damage, SKF*

BEARING DAMAGE DUE TO IMPERFECT LUBRICATION

Symptom	Cause	Notes
Noise	Staved lubrication	Local metal-to-metal contact; interrupted lubricating film without load transmitting and damping effect.
	Unsuitable lubricant	Lubricating film too thin, due to too low a viscosity of the oil or base oil of the grease. The structure of the grease thickener can be unsuitable. Particles can produce noise.
	Contaminants	Dirt particles disrupt the lubricating film and produce a noise.
Cage wear	Staved lubrication	Local metal-to-metal contact; interrupted lubricating film without load transmitting and damping effect.
	Unsuitable lubrication	Too low a viscosity of oil or base oil, lubricants without anti-wear additives.
Wear on rolling elements, raceways, lip surfaces	Staved lubrication	Local meal-to-metal contact; interrupted lubricating film without load transmitting and damping effect. Tribocorrosion due to oscillating relative motions, slip marks.
	Unsuitable lubricant	Too low a viscosity of oil or base oil. Lubricants without anti-wear or EP additives (high loads).
	Contaminants	Solid hard particles or liquid, corrosive media.
Fatigue	Starved lubrication	Local metal-to-metal contact, and high tangential stresses at the surface. Wear.
	Unsuitable lubricant	Too low a viscosity of oil or base oil. Lubricant contains substances whose viscosity increases only slightly under pressure.
	Contaminants	Hard particles are rolled in resulting in high local contact pressure. Corrosive media produce corrosion spots which are particularly fatigue promoting.
High bearing temperature, discoloured bearing parts, seizure marks (over heating)	Starved lubrication	Local metal-to-metal contact; interrupted lubricating film without load transmitting and damping effect.
	Unsuitable lubricant	High friction and temperature due to local metal-to-metal contact.
	Over lubrication	At medium or high rotational speed high lubricant friction especially in the case of sudden over lubrication.
Damaged lubricant (discolouration, solidification, loss of lubricity)	Unsuitable lubricant	Operating temperature higher than the temperature permissible for the lubricant (formation of residues).
	Excessive operating time	Excessively long relubrication or renewal intervals.
	Contaminants, alterations of the lubricant	Foreign or wear particles in the bearing. Reactions between lubricant and bearing material.

Table 17: *Cause and symptoms of bearing damage due to imperfect lubrication, SKF*

APPENDIX 3: DIAGNOSIS TECHNIQUES FOR INDUCTION MOTORS

Listed here are a number of techniques that can be used to diagnose the state of induction motors. It is included here to provide a guide for some of the techniques that can be used to identify faults once the most common failure modes have been identified.

Performance monitoring

This is the online measurement of parameters such as supply voltage and current, input and output power and mechanical stress in couplings.

Vibration monitoring

The use of vibration transducers can identify imbalances in magnetic, mechanical and aerodynamic forces that cause vibration. Faults that can be identified include mechanical faults in bearings, uneven air gaps, stator winding and rotor faults, asymmetrical power supply and imbalances in motor load.

Shock pulse monitoring

Piezoelectric transducers applied to the bearings can identify the various shock waves that can indicate damage to specific parts of the rolling element.

Acoustic emission monitoring

The utilisation of ultrasonic and audible frequencies to identify shockwaves that are indicative of cracks and other damage in rolling elements.

Speed fluctuations monitoring

This method detects defects through the measurement of fluctuations in the rotational period of the motor. It can detect problems such as rotor faults, vibrations, air-gap eccentricity, rotor asymmetry, damaged bearings/couplings and misalignment.

Current monitoring

The analysis of a motors supply current can be largely indicative of the motors condition. Current analysis can revel damaged rotor bars and other mechanical problems.

Air-gap torque monitoring

Faults can be detected using this method both in run up as well as in service. This method can detect cracked rotor bars and unbalances due to faulty stator windings.

Instantaneous stator power monitoring

This gives information about the motor condition and is affected by current, voltage and phase shift.

Magnetic field power monitoring

Monitoring of the magnetic field in the air gap can identify faults such as broken rotor bar, a stator winding inter-turn short circuit, the loss of a phase and an eccentricity amongst others.

Temperature monitoring

Thermocouples and thermistors have a long tradition of use and the rise in temperature of the coolant can often indicate imminent friction problems.

Visual monitoring

Real-time inspection by eye or using closed-circuit television, or delayed monitoring in order to determine deviate trends.

Surge tests

These tests can be used to diagnoses winding faults, such as insulation failures between windings, coils and groups of coils.

Measuring of partial discharges

This may provide a measure of the condition of the motors insulation properties.

Oil particle analysis

This technique is not widely used for motors however in certain cases it can detect particles of metal, fibres or dust in the oil.

Gas analysis

This is the analysis of the exhaust cooling air for possible carbon monoxide gas, typically indicative of windings overheating.

APPENDIX 4: MODELS AND DATABASES

The reliability databases and reliability modelling standards that are listed here provides and reviews a number of sources that can be used to provide reliability data for the process design testing scheme.

COMPONENT RELIABILITY DATABASES

A number of databases exist for industrial purposes containing failure information concerning a wide range of mechanical and electrical components. The reliability information can come in a number of forms, the most common have been described previously and include MTBF, Weibull plots and failure rates.

An important consideration when evaluating these types of databases is how well the parameters recorded in the database for previous components describe the situation that the current components are experiencing. For example, measuring failure rate over time is common but for variable speed applications, failure rate versus the number of cycles might be a better measure. These factors must be considered when using data from any source.

Electronic Parts Reliability Data (EPRD) and Non-electric Parts Reliability Data (NPRD)

The Electronic Parts Reliability Data (EPRD) and the Non-electronic Parts Reliability Data (NPRD) are Reliability Analysis Centre (RAC) publications containing failure data on a wide variety of electrical, electromagnetic and mechanical parts and assemblies. It contains failure rate data, total failures and operating hours by part description, quality level, application environment and data source.

Offshore REliability DAtabase (OREDA)

The Offshore Reliability Database (OREDA) is a project organisation sponsored by eight oil companies with worldwide operations. OREDA's main purpose is to collect and exchange reliability data among the participating companies and act as the forum for coordination and management of reliability data collection within the oil and gas industry. OREDA has established a comprehensive databank with reliability and maintenance data for exploration and production equipment from a wide variety of geographic areas, installations, equipment types and operating conditions. Offshore subsea and topside equipment are primarily covered, but onshore equipment is also included. The data are stored in a database, and specialised software has been developed to collect, retrieve and analyse the information.

European Industry REliability DAtabase (EIREDA)

The European Industry Reliability Database (EIREDA) is a reliability database providing reference information to engineers preparing safety studies for power plants and other industrial installations.

The database comprises estimates of reliability parameters, failure rates and probabilities of failure, for equipment such as pumps, tanks, valves, motors, and sensors. Estimates were based on operation and failure data collected from nuclear power plants operated by Electricite de France.

COMPONENT RELIABILITY MODELLING STANDARDS

For the simulation of component reliability to be useful industrially and to be widely applicable, it is necessary for recognised industry modelling standards to be utilised.

A number of these standards exist and some are described below.

MIL-HDBK-217

This is a reliability prediction standard for electronic equipment published by the US Department of Defence. It uses a series of models for various categories of electronic, electrical and electro-mechanical components to predict failure rates, which are affected by environmental conditions, quality levels, stress conditions and various other parameters.

Bellcore

This reliability prediction standard for electronic equipment is published by AT&T Bell Labs. The standard uses a series of models for various categories of electronic, electrical and electro-mechanical components to predict steady-state failure rates, which are affected by environmental conditions, quality levels, electrical stress conditions and various other parameters. These models allow reliability prediction to be performed using three methods:

- Method I Parts Count procedure

- Method II Combines Method I predictions with laboratory data

- Method III Combines Method I predictions with Field Tracking Data

Telcordia is the latest version of this standard.

NSWC 94/L07

This industrial standard is published by the US Navy and it predicts the failure rates of various mechanical components using a series of models for various categories which are affected by temperature, stresses, flow rates and other parameters. Some of the categories covered by this standard include: Seals and gaskets, springs, solenoids, valve assemblies, bearings, gears and splines, actuators, pump, filters, brakes and clutches, compressors, electric motors, threaded fasteners, mechanical couplings, and slider-crank mechanisms.

Prism

PRISM is a standard for Mean Time Till Failure prediction and reliability analysis developed by the Reliability Analysis Centre (RAC). It is compatible with RAC's Electrical Parts Reliability Data (EPRD) sets and their Non-electrical Parts Reliability Data (NPRD) sets.

GJB/z299b

This is a Chinese standard that calculates failure rates for parts and assemblies based on environmental use characteristics, piece part counts, thermal and electrical stresses, subsystem repair rates, and system configuration.

CNET

CNET is a reliability standard developed by France Telecom that provides reliability models for a wide range of components. CNET 93 is a comprehensive model similar to MIL-HDBK-217, which provides a detailed stress analysis.

HRD5

A reliability standard developed by British Telecommunications that also provides models for a wide range of components. In general, HRD5 is similar to CNET, but provides simpler models and requires fewer data parameters for analysis.

APPENDIX 5: SOFTWARE EVALUATION

Presented here are the complete reviews of all the software that was tested as part of the research. Also included is a listing of the main features of other software packages that were considered.

REVIEWED SOFTWARE

Item ToolKit from Item Software

Main features

Website:

http://www.itemsoft.com/

Contact details:

Item Software
2190 Towne Centre Place
Suite 314
Anaheim
California
92806
USA

Phone 714 935 2900
Fax 714 935 2911
Email itemusa@itemsoft.com

Pricing (US dollars unless stated):

Evaluation copy available

Platforms/operating systems supported:

Windows

Features:

- A range of component libraries available
- Customisable reports
- Hierarchy diagrams
- Maintenance cost modelling
- Spares cost modelling
- Availability simulation

Area of expertise:

Reliability and maintainability analysis.

Techniques supported:

- Failure rate calculations
- Redundancy calculations
- Failure Mode Effects and Criticality Analysis
- Reliability block diagrams
- Fault Tree Analysis

Compatibility:

Exports/imports to Access, Excel, text and comma delimited formats.

Support services available:

Software customisation, consulting services, training and education. Software support via email, fax and phone.

Review

The Item Toolkit Software is a reliability-modelling tool specifically designed for use with mechanical and electrical systems.

The software includes powerful, easy to use tools for FTA, FMECA, and RBD analysis. Also provided are extensive libraries containing failure information for electro and mechanical parts.

Import and export facilities exist for use with many different formats.

The only problem that discovered was that the tutorial in the manual was a little hard to follow.

Relex from Relex Software Corporation

Major features

Website:

www.faulttree.com

Contact details:

540 Pellis Road
Greensburg, PA 15601
United States of America

Phone: 724-836-8800
Fax: 724-836-8844
Email: info@relexsoftware.com

Pricing (US dollars unless stated):

Evaluation copy available

Platforms/operating systems supported:

Windows

Features:

- Extensive set of parts libraries provide reliability data for over 100,000 parts

- Provides part data for thousands of integrated circuits, diodes, transistors, resistors, capacitors and nonelectronic parts

- Download monthly and quarterly updates with data on thousands of new parts. Create customized report formats for your Relex analyses

- Relex-supplied report formats include output items such as pi factors, overstressed parts, system tree summary, fail-

ure mode and effects analysis, maintainability data and more

- Automatically transfers your design information from a CAD system, or a parts listing in a database, spreadsheet, or word processor into Relex format

- Various styles of 2D and 3D graphs

- Graph your entire system, individual components, or parts of your system

- Support for Visual Basic for Applications (VBA) macros

Area of expertise:

Reliability and maintainability analysis

Techniques supported:

- Reliability block diagrams

- Failure Data Analysis

- Failure Modes and Effects [Criticality] Analysis

- Monte Carlo simulation

Compatibility:

Excel, Access, dBase, Lotus 1-2-3, FoxPro, Paradox, Mentor Graphics and ASCII comma and tab delimited files.

Support services available:

Web based demonstration

Review

Relex is a reliability analysis tool with a range of supported techniques such as reliability prediction, block diagrams, FMEA/FMECA, fault tree, failure data analysis, maintainability prediction and life cycle cost.

Relex appears to be very easy to use and very powerful allowing import and export to Microsoft Access, Microsoft Excel, Microsoft FoxPro, dBASE, Lotus and Paradox. It can also give outputs in the form of automated reports and charting.

The parts library appears to be comprehensive but is focused mainly on electronic components although it does support some mechanical components. The components include default failure and reliability data and can be set to specified values by the user, the user can also define the minimum and maximum stress values for each component.

Relex is Both ISO 9001:2000 and TickIT 2000 accredited.

@Risk from Palisade Corporation

Main features

Website:

http://www.palisade.com

Contact details:

Palisade Corporation
31 Decker Road
Newfield, NY 14867

Phone 607 277 8000

Fax 607-277-8001

Email: sales@palisade.com

Pricing (US dollars unless stated):

$1495 @RISK 4.5 Industrial version, gold maintenance plan $299 per annum. Free 10-day trial.

Platforms/operating systems supported:

Windows

Features:

- Runs as an add-on to Excel
- Large range of distribution functions
- Graphical visualisation of results
- Distribution fitting
- Sensitivity and scenario analysis

Area of expertise:

Risk analysis

Techniques supported:

- Monte Carlo
- Latin hypercube

Compatibility:

Works with Excel and a version is available for Project

Support services available:

Free technical support with maintenance plan

Review

This program is an Excel add in and is designed to evaluate the risk inherent in certain activities based on the risks of subtasks. Primarily designed to evaluate business risks it has been suggested that it may be applied to a mechanical situation to deal with failure rates and failure distributions.

@Risk is very good at dealing with a variety of different distributions and is very flexible in this regard. However, @Risk does not specifically have ways of dealing with time series data such as changing loads although it may be possible to build this in through Excel.

Furthermore, @Risk does not incorporate some of the tools that are common with other failure analysis packages such as FTA and FMEA amongst others. This work could be done by hand however this approach may be unwieldy for large problems.

It was suggested during an @Risk seminar conducted by HRS that Precision Tree another software product from Palisade Corporation may be able to add extra functionality to @Risk.

20Sim from Control Lab Products

Major features

Website:

www.20sim.com

Contact details:

Controllab Products B.V.
Drienerlolaan 5 EL-RT
7522 NB Enschede
The Netherlands

Phone +31 53 489 3096

Fax +31 53 489 2223

Email: info@20sim.com

Pricing (US dollars unless stated):

$4000 for an industrial licence or $800 for an academic licence. There is also the option to lease for $1.30/day for academic purposes. Demo and shareware version are also available.

Platforms/operating systems supported:

Windows, Imac

Features:

- Iconic, block diagrams, bond graphs and equations
- Fully observable, unlimited hierarchical model structure
- Multiple libraries with a large set of domain-oriented sub models

- Full support of vectors and matrices, as well as multi-dimensional bonds and signals
- Built-in runtime compiler to speed up simulations
- ANSI-C Code Generation toolbox
- Linearisation toolbox
- Graph Animation toolbox
- 3D Animation toolbox

Area of expertise:

- Automotive
- Control system design/analysis
- Electronics
- Manufacturing
- Mechanics/compression systems
- Motion control/robotics
- Process control/monitoring
- Real-time systems
- Simulation

Techniques supported:

- Linear
- Non-linear
- Discrete-time
- Continuous-time
- Hybrid systems

Compatibility:

MatLab interface, generation of Simulink S-functions and M-files

Support services available:

Consulting, e-mail, fax, on-site assistance, telephone, training

Review

The major selling point of the 20Sim software is its support of a number of different techniques for entering relationships between entities, for example models can be entered using equations, block diagrams, bond graphs or ionic diagrams. This allows great flexibility when combining systems that work in several domains, such as mechanical and electrical.

3D graphical animations can be easily linked to the models, with a good range of tools available for this. The animation however did tend to be a little jerky.

Tight integration with MatLab means that functionality can be easily expanded through the transfer of variables between the two systems.

Editing models was relatively easy with smart block connections that move around the block to make shortest line. Hierarchy navigation is simple with up and down buttons and a visual representation of the model tree. Icon graphics can be defined by the user giving clear model representations.

A wide range of simple components is available in the demo version such as electrical, mechanical (rotation & translation), signals (linear and non-linear blocks, continuous and discrete controllers, discrete and logical signals and signal sources), and system blocks. More complex components can be found in the professional version, specifically in the mechatronics libraries.

Some of the problems found with the demo version were a lack of support for some of the standard windows editing features such as Ctrl-Z for undo and no use of SHIFT for multiple selections. It was also not possible to delete items from the model tree. Other small issues were that some of the tutorials contained errors and some menus disappeared off screen.

WinGEMS 5.0 from Pacific Simulation

Major features

Website: www.pacsim.com

Contact details:

Main Office
Pacific Simulation
Invensys Performance Solutions
1187 Alturas Drive
Moscow, ID 83843

Phone 208.882.0322 (8 AM - 5 PM PST)
Fax 208.882.8143

Pricing (US dollars unless stated):

$15500 industrial licence, $7750 academic licence. Demo version also available

Platforms/operating systems supported:

Windows

Features:

- Physical properties database
- Block library

Area of expertise:

Pulp and paper processing

Techniques supported:

Steady state and dynamic simulation

Compatibility:

Excel

Support services available:

Free training courses, HTML based help

Review

Primarily designed to be used by the pulp and paper industry the WinGems block set of components is quite specific to the industry but are fairly detailed and flexible within their parameters.

The simulation method uses blocks and streams to represent processes with both steady state and dynamic situations able to be simulated. The debugging of the simulation process is also very flexible, supporting both block by block and iterative stepping. Furthermore, the order in which calculations are performed is easily modified.

WinGems can run Visual Basic macro during execution and can export results straight to Excel while running.

The user has a lot of control as to how the model appears with user defined icon graphics and user defined compound blocks for model simplification.

WinGems gives visual indicators of variables while the simulation is running, such as levels of tanks and flow rates.

The lack of an obvious hierarchy for the model was one problem as well as the lack of flexibility in the types of blocks that could be used.

TaylorEd 2000 from Enterprise Dynamics

Major features

Website:

www.taylorii.com

Contact details:

Enterprise Dynamics Corporation
1366 South 740 East
Orem, Utah 84097

Phone: 801-224-6914
Fax: 801-224-6984
E-mail: info@taylorii.com

Pricing (US dollars unless stated):

$34000 AUS for an industrial licence and dongle. An academic licence is available, as is a demo version.

Platforms/operating systems supported:

Windows

Features:

- Library of ready to use atoms
- Consulting available
- Model and atom development
- 3D modelling
- Visualisation
- Control

Area of expertise:

- Manufacturing
- Logistics
- Service systems

Techniques supported:

Object oriented

Compatibility:

DDE for Windows apps. ODBC for database access, Oracle, Access etc. Also through IP addresses.

Support services available:

FAQ, Q&A (email), tricks and tips, online meeting, consultancy, training

Review

My initial impression of the Taylor Ed package is that it is primarily a manufacturing and materials handling simulator, with the ability to quickly represent three-dimensional versions of the models. It deals well with queuing problems and statistical event distributions.

The package is event oriented with entry and exit event triggers and a 4Dscripting language for more complex events. The system is de-

signed to cope with statistical input and output and can explicitly handle distributions such as 'Mean Time Before Failure'

It was fairly simple to get TalorEd up and running. Libraries available include idealised representations of products, queues, servers, sinks and sources, as well as a variety of other blocks such as storage, transport and operators. TaylorEd uses the term 'atoms' for entities, these atoms can be to modify so sub models are easily created from other atoms, or a new atom can be built up from scratch. Unfortunately it was a little difficult on occasion to get each atom to update to reflect changes, forcing them to be deleted and reloaded to refresh.

Model navigation was aided by the hierarchy tree display and a variety of ways of viewing sub models was supported. I could not get the zoom function to work however which was a little frustrating.

Setting up visual representations of simulations was very easy with 3d animation supported and simple to set up and use, although a few more tools would have been nice.

Simprocess and Simscript II.5 from CASI Products Company

Major features

Website:

www.caciasl.com

Contact details:

CACI Products Company
1011 Camino Del Rio South, Suite 230
San Diego, CA 92108

Phone: 877-663-3746
E-mail: simprocess@caci.com

Pricing (US dollars unless stated):

Demo available.

Platforms/operating systems supported:

PC

Features:

- Activity-based costing
- Animation
- MS-Access based output reports
- Interfaces to workflow management tools

Area of expertise:

- Business Process Modelling
- Supply Chain Simulation
- Defence Modelling
- Transportation Modelling
- General Purpose Solutions

Techniques supported:

- Hierarchical process mapping
- Object oriented modelling
- Event scheduling
- Process interaction

Compatibility:

Compatible with Microsoft Access and outputs HTML

Support services available:

On line demonstrations, tutorials, demo models, email assistance

Review

This group of products is primarily a business process-modelling tool. It supports both object oriented and event oriented modelling and has a range of basic entities included in the standard libraries such as activities, processes and resources, as well as provision for user-defined entities and reusable templates.

Output of results is well managed with animation supported visualisation and report generation capability. Easy to move up and down hierarchy however there is no way to view the overall model.

One of the major strengths of this software is its support many statistical distributions such as random number generation etc.

Simulink from MathWorks

Major features

Website:

www.mathworks.com/products/simulink

Contact details:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098
UNITED STATES

Phone: 508-647-7000
Fax: 508-647-7001
Email: info@mathworks.com

Pricing (US dollars unless stated):

30 day trial available

Platforms/operating systems supported:

PC, Mac, Unix. Requires Matlab

Features:

- Extensive library of predefined blocks
- Simulink graphical debugger
- Model Browser for navigating model hierarchies
- Finder for searching models and libraries
- Models can be grouped into hierarchies to create a simplified view of components or subsystems
- Simulink data objects enable you to create application-specific MATLAB data types for your Simulink models
- Intellectual property protection using S-functions

Area of expertise:

Design and simulation of continuous- and discrete-time systems

Techniques supported:

- Linear
- Non-linear
- Continuous time
- Discrete-time
- Multirate
- Conditionally-executed
- Hybrid systems

Compatibility:

C, Ada, Matlab, and Fortran code

Support services available:

Online support, knowledge database, training and consulting

Review

Navigation in Simulink is very easy with block diagrams and hierarchy trees showing system layout.

A wide range of continuous and discrete mathematical and control functions, including fuzzy logic, neural network functions are included with the package. Both continuous and discrete functions are supported.

Uses the standard Matlab scripting language.

New blocks are easily defined.

Dymola from Dynasim

Major features

Website:

www.dynasim.se

Contact details:

Dynasim AB
Research Park Ideon
SE-223 70 Lund
Sweden

Phone: +46 46 2862500
Fax: +46 46 2862501

Email: info@Dynasim.se

Pricing (US dollars unless stated):

$18900 Industrial licence. $3685 University licence. Demo version available.

Platforms/operating systems supported:

PC/Win Unix/Motif Sparc/SolarisHP/UX PC/Linux. Requires simulink and MATLAB.

Features:

- Modelica language promotes reuse of library models
- Graphical model composition
- Efficient continuous/discrete simulation

Area of expertise:

Handles large, complex multi-domain models

Techniques supported:

- Acausal modelling
- Object oriented

Compatibility:

M-files can be used in Dymola simulations and Dymola blocks can be used in Matlab simulations

Support services available:

Conferences, literature, 12 months free upgrades, several books are also available such as Introduction to Physical Modeling With Modelica (The Kluwer International Series in Engineering and Computer Science, Secs 615) by Michael Tiller.

Review

Dymola provides a large number of well documented libraries including: Mathematical and physical constants, mathematical functions, SI-unit type definitions, input/output blocks, electric and electronic components, 1D-rotational and 1D-translational mechanical components, 3D-mechanical systems, components to model state machines and Petri nets, linear interpolation in one and two dimensions.

'Acausal modelling' is supported with two-way interactions between blocks. Also hybrid modelling of both discrete and continuous systems is possible. The scripting language used is based on Modelica.

The main problem with this program is the difficulty in navigating the model hierarchy, There does not appear to be any kind of map or tree. Opening entity after entity is both tedious and results in a large number of windows being opened, cluttering the workspace.

Other problems were that some demos do not work in the evaluation version and the animation speed could not be adjusted.

VisSim from Adept Scientist

Main features

Website:

http://www.adeptscience.co.uk/products/mathsim/vissim/

Contact details:

Adept Scientific Inc,
7909 Charleston Ct
Bethesda
MD 20817
USA

Tel: 301 365-0720

Fax: 301 767-1675

Email: info@adeptscience.com

Pricing (US dollars unless stated):

$2,495.00 for purchase, free 14-day trial, free academic version

Platforms/operating systems supported:

Windows

Features:

- 3D Visualisation
- User blocks menu
- Triggered or conditional compound blocks

Area of expertise:

- Modelling, simulation and control system design
- Signal processing and communication system design
- DSP and embedded system design

Techniques supported:

- Linear
- Non-linear
- Continuous time
- Discrete time
- Time varying and hybrid system designs

Compatibility:

Seamless communication with Matlab and Mathcad, OLE and ActiveX support, compatible with Visual C/C++

Support services available:

Free seminars, technical support, training and magazines

Review

The basis of VisSim modelling format is the block diagram. Hierarchy navigation makes use of a navigation tree, and movement between layers requires just a simple mouse click. Blocks available are simple including animation, annotation, arithmetic, Boolean, DDE, integration, linear systems, MatLab interface, matrix operations, non-linear, optimisation, random generator, signal consumer, signal producer, time delay, transcendental. Algebraic expression and user defined function blocks are also available.

Scripting can be done using the C programming language. A variety of plots and graphs can be used to view the results of a simulation.

Animations are also available to aid visualisation but are limited to bitmap manipulation.

MAIN FEATURES OF OTHER SOFTWARE CONSIDERED

AutoMod from ProModel Corporation

Main features

Website:

www.promodel.com

Contact details:

PROMODEL Corporation
1875 S. State Street
Suite 3400
Orem, UT 84097

Fax: (801) 226-6046

Phone: (801) 223-4600

Email: support@promodel.com

Pricing (US dollars unless stated):

$31,100 AUD for the commercial version, several other licensing configurations, including stand-alone, student, network etc. also exist

Platforms/operating systems supported:

Windows

Features:

- Build custom models with graphics for manufacturing, warehousing and transportation

- Accurate modelling of your entire system, including machines, operators, forklifts, AGV's, conveyors, tanks and storage areas

- Capture system randomness and variability by utilising over 20 statistical-distribution types, or directly import data

Area of expertise:

- Manufacturing

- Healthcare

- Supply chain

- Product development

- Customer service operations

Techniques supported:

Compatibility:

Will interface with Excel, Word or any other program with OLE capability

Support services available:

24 hour technical support, "Solutions Café", PROMODEL Annual Solutions Conference, upgrades etc. for one year

DynaWiz from Concurrent Dynamics

Main features

Website:

www.concurrent-dynamics.com

Contact details:

Email:

support@concurrent-dynamics.com

Pricing (US dollars unless stated):

Works on a lease arrangement $22,000 for the first year of the full version and $6,600 for every subsequent year. 30% educational discount and the less comprehensive versions are cheaper. Demo version also available.

Platforms/operating systems supported:

PC. Requires DOS, MatLab and Simulink

Features:

- Loads calculation

Area of expertise:

- Aerospace

- Automotive

- Biomechanics

- Robotics

Techniques supported:

Multibody Dynamics (Lagrangian)

Compatibility:

Generates M scripts for MatLab and Simulink

Support services available:

Simulation rehosting and custom simulation

ACSL from Aegis Technologies Group

Main Features

Website:

http://www.aegistg.com/ACSLCUT/ACSLCUT.html

Contact details:

Email: acsl-admin@aegistg.com

Phone: 256-922-0802

Fax: 256-883-5516

Pricing (US dollars unless stated):

Free viewer available

Platforms/operating systems supported:

Windows, Unix

Features:

- Choice of integration routines
- Root locus, Bode, Nyquist and Nichols plots
- A discrete section for modelling on-line digital controllers
- Gears integration algorithm for stiff systems
- Array capabilities complemented by vector and matrix integration operators
- Automatic steady state determination for plant
- Eigenvalue/eigenvector calculation for linearised model
- Signal processing
- Parametric studies
- Set the error model parameters or have ACSL Optimise find the most likely one

Area of expertise:

- Guidance and flight control
- Land vehicle dynamics
- Power plants
- Chemical processes
- Robots
- Aircraft and missiles

- Automotive power train and driveline dynamics
- Wastewater treatment
- Power electronics circuits
- Shuttle-based solar optical telescope
- Chemical reaction kinetics
- Stepper motors with mechanical stoppers
- Antenna track error and torque disturbance
- Space-based laser pointing and retargeting

Techniques supported:

Object oriented

Compatibility:

Fortran, C/C++, ADA

Support services available:

FAQ, Technical Support, training programmes

Piping Systems FluidFlow from Flite Software Ltd

Main features

Website:

www.fluidflowinfo.com

Contact details:

Flite Software Ltd.
Block E,
Balliniska Business Park,
Springtown Road,
Londonderry,
BT47 0LY,
Northern Ireland

Phone: +44 28 71279227

Fax: +44 28 71279806

Email: feedback@fluidflowinfo.com

Pricing (US dollars unless stated):

Platforms/operating systems supported:

Windows 95/98/NT

Features:

- Model, analyse and design almost any type of liquid or gas flow system
- Pre-defined component types such as pipes, valves, pumps, and sprinklers

- Importing capabilities for new components

- Component types can be customised on purchase of the software

- Instantaneous results, solutions provided as soon as problem defined

- Connectivity and data within the Flowsheet is continuously checked as network is constructed

- Engineering hints and build errors of the network, as they occur

Area of expertise:

- Electronic chip manufacturing industry

- Oil and gas industry

- Chemical process industry

- Engineering consultancy firms

- Food and beverage processing

- General industrial

- Heating, ventilation and air conditioning (HVAC) industry

- Mining industry

- Power industry

- Education

- Shipbuilding

Techniques supported:

- Energy and mass balance differential equations are solved by a unique direct solution method

- Head losses through fluid equipment components are based on best practices and standards

- Pipe head losses are based on Darcy-Weisbach (or optionally Hazen-Williams)

Compatibility:

Excel

Support services available:

Six months free technical support and unlimited updates

AutoMod from AutoSimulations Division of Brooks Automation

Main features

Website:

www.autosim.com

Contact details:

5245 Yeager Road
Salt Lake City
UT 84116-2877
Phone: (801) 736-3201

Fax: (801) 736-3443

Email: automod-info@brooks.com

Pricing (US dollars unless stated):

$17500-$30000 for an industrial licence or $800 dollars for and educational licence

Platforms/operating systems supported:

PC

Features:

- Determination of the optimal equipment configuration

- Troubleshoots existing systems

- Identifies bottlenecks in the operation

- Provides training for system operations

- Communicates changes in the design

- Testing of equipment controls prior to installation using emulation

Area of expertise:

- Manufacturing operations

- Material handling systems

- Tanks and pipe networks

- Warehousing/distribution centres

- Transportation and logistics systems

- Baggage handling and airport operations

- Semiconductor manufacturing and material handling

Techniques supported:

Discrete and continuous simulation

Compatibility:

Support services available:

Customer support hotline, monthly bulletin for product use tips

VisualMetrics2000 from Drying Doctor Corporation

Main features

Website:

www.visualmetrix.com

Contact details:

Drying Doctor Corporation
P. O. Box 63134,
Verdun, Quebec,
Canada H3E 1V6

Email: info@visualmetrix.com

Telephone: +1 (514)-767-2897

Fax: +1 (514) 761-6474

Pricing (US dollars unless stated):

£249 for full licence. 30 day demo and educational licences also available

Platforms/operating systems supported:

Windows

Features:

- Equation modelling and graphical layout
- 2D and 3D charting and tabular spreadsheet data
- An interactive database of physical constants, properties, variables and equations
- Physical property tools including units conversion, periodic table, thermodynamic and transport properties of steam and air, psychometric calculator and a pressure drop calculator

Area of expertise:

- Electricity and magnetism
- Fluid mechanics
- Heat and mass transfer
- Heating, ventilation and air conditioning systems
- Engineering mechanics
- Beam mending

- Oil and gas processes
- Pulp and paper processes
- Thermodynamics
- General engineering and mathematics

Techniques supported:

Compatibility:

Support services available:

Email technical support

Active Modeler from KAISHA-Tec Co.

Main features

Website:

www.activemodeler.com

Contact details:

Mitaka Sangyo Plaza Annex 3-32-3
Shimo Renjaku
Mitaka-shi Tokyo
181-0013 JAPAN

Email: sales@kaisha-tec.com

Pricing (US dollars unless stated):

Platforms/operating systems supported:

Windows 95/98/NT or Windows 2000

Features:

- Process and structure modelling and analysis
- Scripting object model
- Comprehensive reporting
- Constraint analysis

Area of expertise:

- For modelling business processes
- Proposed changes
- Activity analysis
- Designing workflows

Techniques supported:

Compatibility:

Java, Visual Basic, C++

Support services available:

Consultants

FEMLAB from Comsol

Website:

www.femlab.com

Contact details:

COMSOL, Inc.
1100 Glendon Avenue
17th Floor
Los Angeles, CA 90024
USA

Phone: +1-310-689-7250

Fax: +1-310-689-7527

Email: info@comsol.com

Pricing (US dollars unless stated):

$3690 AUD for an industrial licence, perpetual teacher licence also exists with an educational discount. No demo version available.

Platforms/operating systems supported:

Femlab is available on PC, Mac and Unix platforms

Features:

- GUI with free-form geometry modeller

- DXF-import/export with geometry repair

- High-order elements available

- Extensible element library

- Able to solve problems with hysteresis and non-linear materials (plasticity)

- Can study the combined effect of thermal and mechanical loads

- Efficient model management with the Model Navigator

- Powerful visualisation capabilities

Area of expertise:

- Plane stress problems

- Plane strain problems

- Axial symmetric problems

- Kirchhoff (thin) plate problems

- Mindlin (thick) plate problems

- The analysis capabilities available are: Linear static, linear dynamic, eigenfrequency, frequency response, non-linear geometry, non-linear material, heat transfer

Techniques supported:

Finite element analysis

Compatibility:

Tightly integrated with MatLab including interface to Simulink and the Control System Toolbox

Support services available:

Email and FAQ

Empower from Tecnomatix

Website:

www.tecnomatix.com

Contact details:

Shireen Brooks
Marketing Manager
IMAG Australia Pty Ltd
P O Box 6798 Wellesley St
Auckland

Phone: 522 8234 or 021 809 172

Email: imagack@ihug.co.nz

Pricing (US dollars unless stated):

Platforms/operating systems supported:

Features:

- Planning and designing of complex assembly facilities, lines and workplaces

- Design, simulation visualisation and optimisation of production systems and processes including human, spot-welding, arc-welding, painting, assembly/disassembly and stamping processes

- Analyses of bottlenecks, and optimisation of throughput and buffer sizes

- Accurate simulations of robot-motion sequences

- Controller-specific information, including motion and process attributes, can be added to the generated robot paths

- Generates the controller program, which is downloaded to the real controller

- Organises process data and simulation work cells in a line structure that corresponds to the plant floor

- Web-enabled presentation and analysis of manufacturing data across the enterprise

- Creation of documentation for management, line builders, shop-floor personnel and suppliers
- Definition, measurement and analysis of features and tolerances in a CAD model
- Creation of off-line inspection programs for CMM and CNC machines within a CAD environment
- Analysis and evaluation of measured data against nominal models
- Consistent mathematical and graphical data to perform best-fit analyses and the verification of possible causes of failure

Area of expertise:

- Automotive industry
- Power train industry
- Aerospace industries
- Electronics industry
- Quality and tolerance management

INITIAL SOFTWARE LISTING

These web sites were all accessed between the dates of 16 July and 14 September 2001

Engineering Technologies LTD.
www.fea.guru.com

FEMLAB (MATLAB Library)
www.femlab.com

Simulink (MATLAB)
www.mathworks.com

Technomatix empower
www.tecnomatix.com

Concurrent Dynamics
www.concurrent-dynamics.com

Hysis
www.hyprotech.ab.ca

WinGEMS 5.0
www.pacsim.com

Modeling & Technology Development
http://www.m-td.com/index.en.htm

Active Modeler
http://www.activemodeler.com/

CACI Products Company
http://www.caciasl.com/products.cfm

Dymola
http://www.dynasim.se/

VisSim
http://www.adeptscience.co.uk/products/mathsim/vissim/

Kismet
http://iregt1.iai.fzk.de/#TOP

20-Sim
www.20sim.com

ACSL
http://www.aegistg.com/ACSLCUT/ACSLCUT.html

APROS
http://www.vtt.fi/aut/tau/ala/apros.htm

AutoMod
http://www.autosim.com/simulation/simindex.asp

FluidFlow
www.fluidflowinfo.com

IsographDirect
www.isograph.com

Relex
www.faulttree.com

GPSS/H
www.wolverinesoftware.com

ProModel
www.promodel.com

Taylor ED 2000 Software
www.taylorii.com

SmartSignal
www.smartsignal.com

WonderWare
www.wonderware.com

Artesis
www.artesis.com

WinR-PdM
http://reliability.sandia.gov/Software/WinR-PdM/winr-pdm.html

APPENDIX 6: TYPES OF MODELS

There are numerous types of models and many of them can be applied to the implementation of process testing. This listing gives a feel for the breadth of the field of modelling and some of the fundamental techniques and forms that are commonly applied.

- **Symbolic models.** Use of symbols to represent that which is being modelled. Such as mathematical formula, logical relations, words, or pictures.

- **Mental models.** These exist only in the mind of individuals.

- **Physical models.** Models that are made of tangible components.

- **Scale models.** Scale models are static models that are at a different scale to the thing that they represent, such as models of aircraft, ships, buildings and people.

- **Imitation models.** These models physically symbolise that which they are supposed to represent, such as mannequins, maps and molecular structures. These are also known as iconic models

- **Analogue models.** Models that rely on an analogy between something with a different physical structure to that which they are supposed to be symbolising, but that have similar behaviours. For example, inductor capacitor resister circuits to model car suspension, water flow to study traffic flow, or animals to test new medical treatments.

- **Prototype models.** Models that have a very similar structure and function to that which they represent are prototypes. For instance, an inductor capacitor resister circuit to study electrical oscillations, mass spring and damper assembly to test car suspension.

- **Linguistic models.** These models are verbal or written representations of systems, events, or processes. Such as stories, news articles or statistics.

- **Graphical models.** These models use a visual representation. Such as paintings, graphs, drawings or computer graphics.

- **Schematic models.** Layout, network diagrams, flowcharts, maps, or circuit diagrams.

- **Mathematical models.** This is the mathematical representation of the entities comprising a system and their attributes. Functions are described that build the relationships between variables.

- **Dynamic models.** These are generally characterised by differential or difference equations. The outputs at anytime can depend on both past and present inputs.

- **Static models.** These are generally characterised by algebraic equations. A system is static if its outputs at any time depend only upon its inputs at that time. A static model can represent a dynamic system at steady state.

- **Analytic models.** Analytic models use only formal mathematical laws. These types of model are particularly useful because of the identification of functional relationships between variables. Often solutions of this kind will solve all problems of the same type.

- **Numeric models.** This type of model provides numeric solutions through the substitution of numbers for input variables and using them to find a specific solution.

- **Stochastic models.** A stochastic model is one in which some of the state variables take on a value according to some statistical distribution. This allows uncertainty to be dealt with in the model, however this uncertainty often permeates the entire model so the results will also be stochastic in nature. This type of model deals with not only systems that are intrinsically random in nature, but also where there is some uncertainty as to what the actual values may be.

- **Deterministic models.** Where the output of an activity can be completely determined from the inputs then that activity is deterministic.

- **Simulation models.** This technique does not attempt to establish specific relationships between variables. Instead, it observes the way in which all variables change with respect to time. Relationships must then be derived from these observations.

- **Linear models.** A linear model is one in which the principle of superposition applies, that is, where the response to several simultaneously applied inputs is the same as the same as the sum of the individual responses.

- **Non-linear models.** A non-linear model has terms in it that are non-linear, such as the products of two or more variables or trigonometric functions.

- **Causal models.** These models represent the effects of changes in some variables on other variables.

- **Predictive or forecasting models.** These models present possible future outcomes based on statistical correlation.

It is important to note that a model can have elements belonging to more than one of these categories. In the case of computer simulation, models of both static and dynamic mathematical elements as well as symbolic, non-mathematical, graphical elements may be contained within the one model.

In addition, the model may not necessarily have the same category as the system being modelled. For example, static modelling (at steady state) of parts of a dynamic system, or discrete (stepwise) modelling of a continuous system.

Figure 14 shows one way of classifying some of these model types into a hierarchy. This ranking method concentrates on the class of model. Other ways of sorting models are by what is being modelled, by the medium that is used to represent the model, or by the purpose of the model.

In the case of this project, two major types of model are considered. Both models have much in common, both being implemented on the same medium, a computer, and are by nature analytical, mathematical, causal, predictive, simulation models that incorporate graphical and schematic representations. However, the two models have different areas of application and therefore some difference in form.

The first is a deterministic, non-linear, dynamic representation that attempts to predict the types and levels of loading exerted upon a system, based on numerical inputs.

The other is a stochastic model that attempts to predict the reliability of a system based on statistical inputs.

The exact description of how these models fit together is provided in the process design testing scheme section.

Adapted from Neelamkavil (1987)
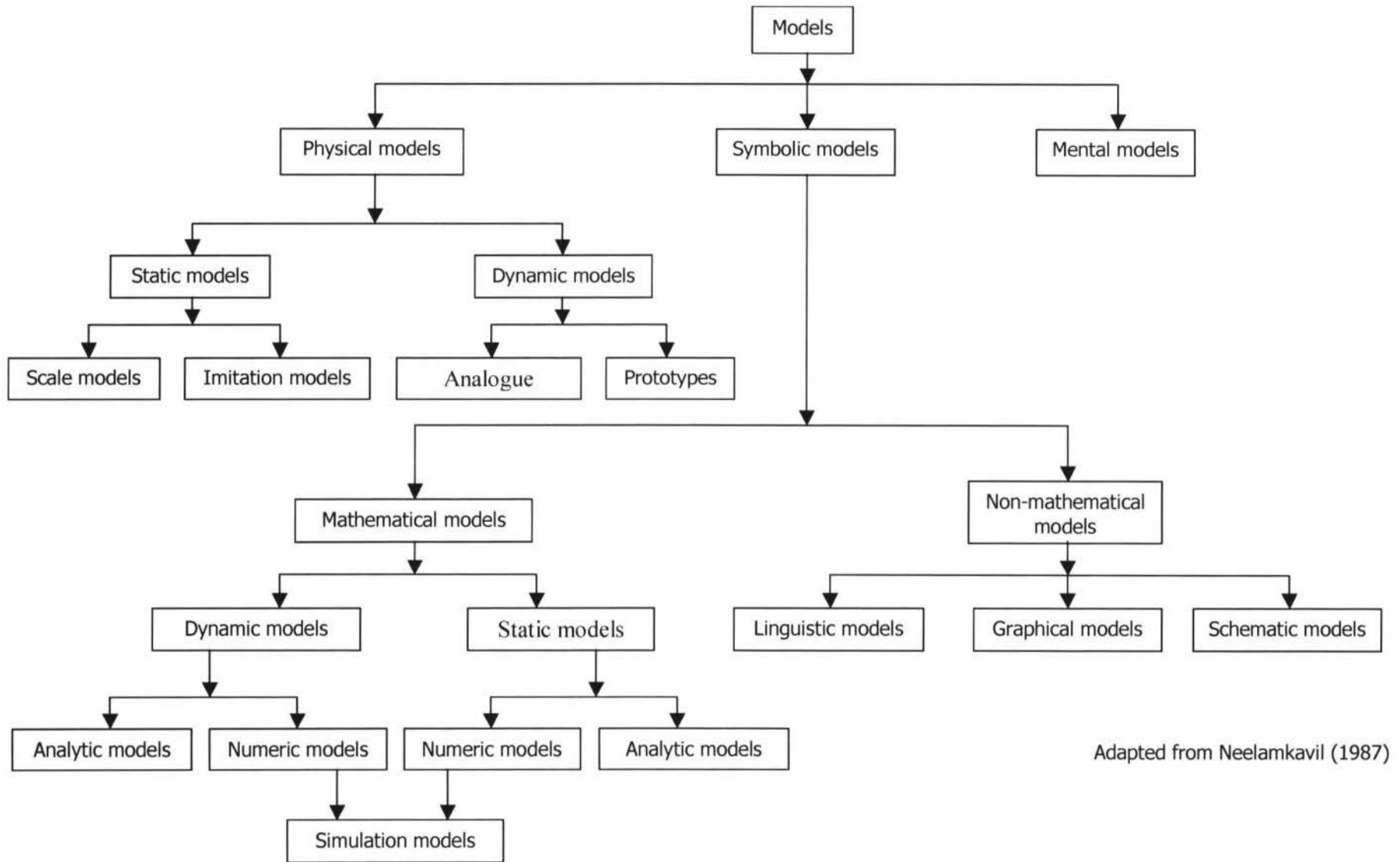
Figure 14: *Model hierarchy*

APPENDIX 7: REASONS FOR SIMULATION

Some of the reasons simulation is used is described here to give a feel for how simulation may be used in engineering. There are many reasons for simulation to be used and several of them may apply in a single project, either consecutively or concurrently.

- **Analysis.** This aims to understand how an existing or proposed system works. It allows experiments to be performed through simulation and inferences made about the system.

- **Design.** In system design simulations, the objective is to produce a model that meets certain specifications. The simulation allows different configurations of design to be assessed and performances measured before actual construction or modification of the system takes place.

- **Postulation.** This is the use of simulation to test hypotheses of how systems work. Models are produced based on the hypotheses and the results of simulations compared with reality.

- **Control.** This type of simulation uses models to allow different control strategies to be tested and analysed, before the implementation of the strategies upon a real system.

- **Prediction.** Also known as forecasting, these types of models attempt to predict the future behaviour of a system through simulation from known initial conditions and parameters.

- **Optimisation.** Often the objective of simulation is to find the optimum operating conditions for the system.

This project deals with prediction, design and optimisation, the prediction of when faults will occur in a given system and the design and optimisation of a system based on these predictions.

APPENDIX 8: MODEL DEVELOPMENT TECHNIQUES

As part of the model development stage a lot of research was undertaken into modelling techniques and processes. The algorithms suggested by various authors are presented below.

The modelling process

Initially research done into the various methods and processes for model building. It was found that there were a wide range of techniques such as Frantas (1977) 'modelling process' as shown in figure 15.

Another process, that was considered is one taken from lecture notes presented by Marsh, C. (Mathematical modelling lecture notes Massey University, 1999), figure 16.

An alternative process adapted from Neelamkavil (1987) is presented in figure 17.

While these processes may initially appear to be different they share many of the same features. The first of these is that the all use the verification and validation concepts described previously. This demonstrates the importance of checking that the model works in the way that it is supposed to (verification) and ensuring that the model is a valid representation of the real system (validation).
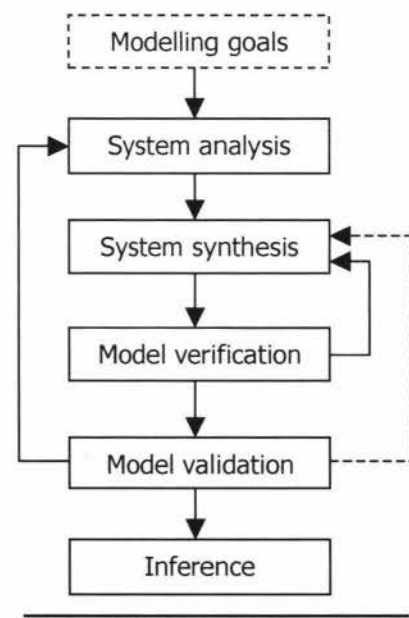
Figure 15: *Frantas modelling process*

Another feature that all these proposed modelling processes share is that of iteration. It is considered very likely that the initial model will not meet the requirements set for it and will have to be reformulated. This can happen at either the verification or the validation

stages if the model does not meet the requirements, or at the results stage if it is found that the model does not solve the problem that it was designed to address.

The results stage is also described as the inference stage or the use stage. This is the point where the model is used for simulation.

Other points of similarity include, analysis and investigation of the real system. The formulation or synthesis of the equations or structure to represent the system and the implementation of these equations or structure into some type of modelling medium, in this case a computer model.
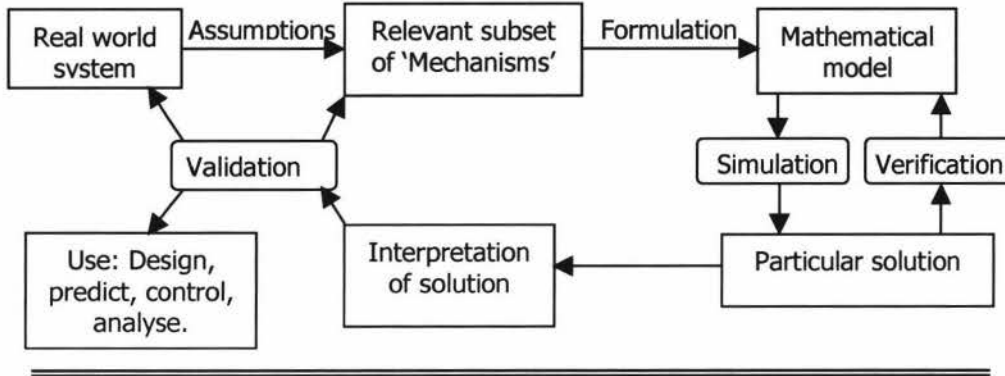
Figure 16: *Marsh's modelling process*
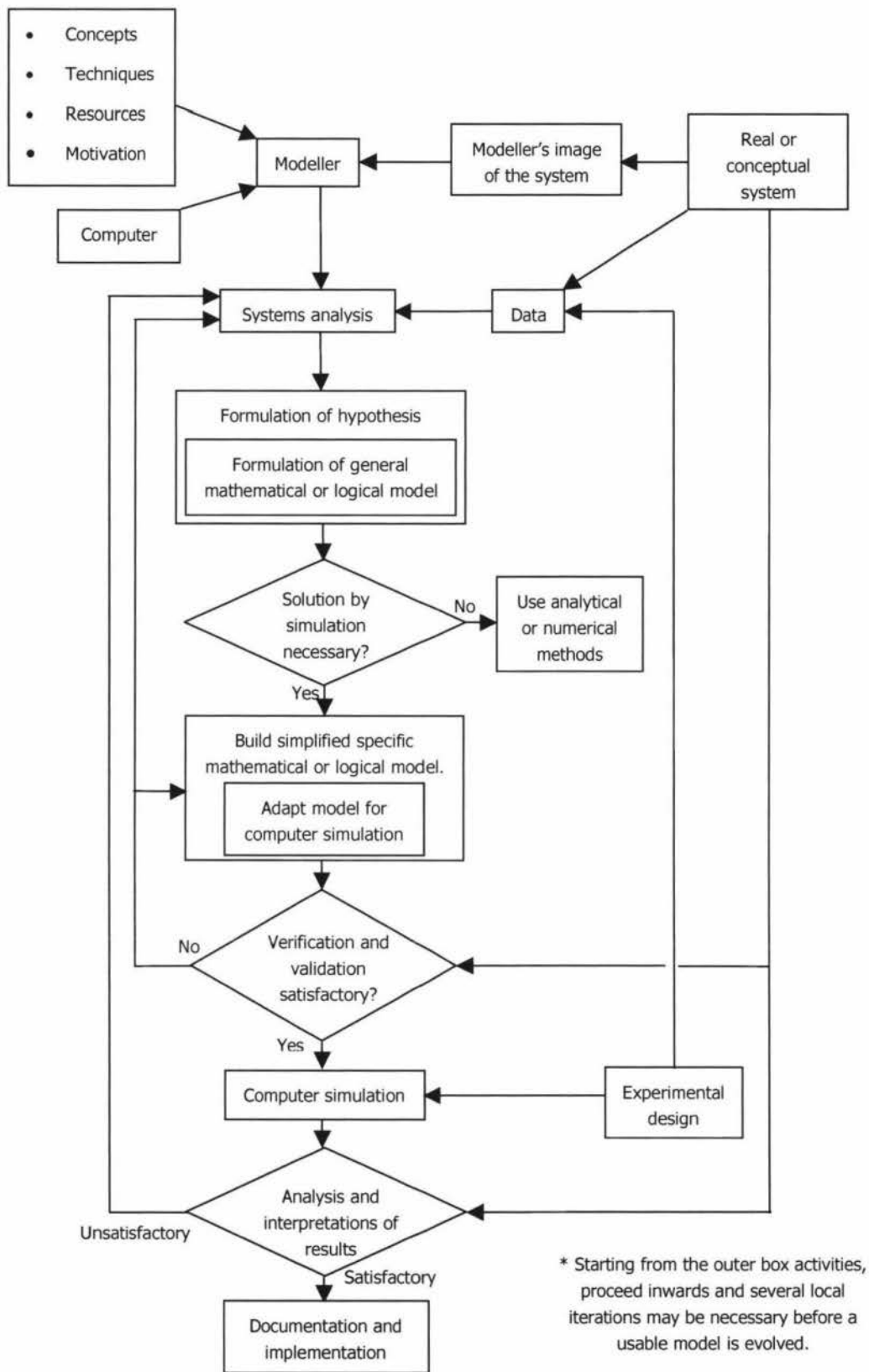
Figure 17: *Neelamkavil's modelling process*

DIGITAL APPENDIX

Due to the electronic nature and the length of the reports generated by the modelling and simulation task it was decided to present the results in the form of a digital appendix which can be found on the CD included with this thesis. Furthermore, several of the references examined as part of the research are only available on the internet. To ensure the preservation of these references the documents have been reproduced in the Digital Appendix. The contents of the Digital Appendix is listed below.

RESULTS

- Component information for the Sivaron S-661 Strapping Machine
- Reliability prediction for the Sivaron S-661 Strapping Machine
- FMEA analysis of the Induction Motor

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* These entries are available in the Digital Appendix.

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Software sites.

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www.fea.guru.com 1 Aug 2001

www.femlab.com 1 Aug 2001

www.smartsignal.com 1 Aug 2001

www.wonderware.com 1 Aug 2001

www.artesis.com 1 Aug 2001

www.tecnomatix.com 1 Aug 2001

http://paper.about.com/gi/dynamic/offsite.htm?site=http%3A%2F%2Fwww.microtec.net%2Fwinmet%2Fdds.htm 9 Aug 2001

www.pacsim.com 9 Aug 2001

http://www.activemodeler.com/ 9 Aug 2001

http://www.m-td.com/index.en.htm 9 Aug 2001

http://www.adeptscience.co.uk/products/mathsim/vissim/ 9 Aug 2001

Other sites

Susan M. Heathfield
Change, Change, Change: Lessons From the Field
www.humanresources.about.com 7 Aug 2001

Reason Root Cause analysis system
www.rootcause.com 8 Aug 2001

Process model
www.airtime.co.uk/users/wysywig/bpm_1.htm 8 Aug 2001

Transactions on Modeling and Computer Simulation (TOMACS)
http://www.acm.org/pubs/tomacs/ 8 Aug 2001

The Society for Modeling and Simulation International European Council
http://hobbes.rug.ac.be/~scs/ 8 Aug 2001

A collection of modeling and simulation resources on the internet
www.idsia.ch/~andrea/sim.html 8 Aug 2001

The society for computer simulation international
http://www.scs.org/ 8 Aug 2001

Systems Simulation: The Shortest Path from Learning to Applications
http://ubmail.ubalt.edu/~harsham/simulation/sim.htm 10 Aug 2001

Simulation System Database
http://www.nmsr.labmed.umn.edu/~michael/dbase/outgoing/FAQ.html 10 Aug 2001

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http://www.lmphotonics.com/index.htm 1 Feb 2002