Design Rules and Guidelines for Generic Condition Based Maintenance Software's Graphic User Interface

by

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ABSTRACT

The task of selecting and developing a method of Human Computer Interaction (HCI) for a Condition Based Maintenance (CBM) system, is investigated in this thesis. Efficiently and accurately communicating machinery health information extracted from Condition Monitoring (CM) equipment, to aid and assist plant and machinery maintenance decisions, is the crux of the problem being researched.

Challenges facing this research include: the multitude of different CM techniques, developed for measuring different component and machinery condition parameters; the multitude of different methods of HCI; and the multitude of different ways of communicating machinery health conditions to CBM practitioners. Each challenge will be considered whilst pursuing the objective of identifying a generic set of design and development principles, applicable to the design and development of a CBM system's Human Machine Interface (HMI).

Maintenance professionals and CBM solution providers have been surveyed, with the objective of understanding the present day industrial application of CBM systems and desirable methods of HCI, for these computerised systems. Findings from the survey along with findings from literature investigations have been used to develop a CBM HMI, designed to Royal Mail Plc's user requirements. The CBM HMI takes the form of a simulation, demonstrating ideas for inclusion in a Browser accessible, networked CBM system. Feedback acquired following usability tests on the simulation, provides material for improving the design ideas contained in the simulation, and helping to clarify generic CBM system HMI design and development principles.

As a consequence of the research investigations, a set of categorised rules and guidelines are proposed for aiding the design and development of future generic CBM software's GUIs. The proposed rules and guidelines are intended for CBM designers and solution providers, in order to reduce the development time and improve the quality of generic CBM software GUIs.

Key Words

Predictive Maintenance, Condition Based Maintenance, Condition Monitoring, Human Computer Interaction, Human Computer Interface, Human Machine Interface, Royal Mail.

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CONTENTS

GLOSSARY

ADC	Automatic Data Capture
ACS	Activity Control Schedule
ADO	Active Data Objects
ADST	Automation Development and Support Team
AE	Acoustic Emission
AGQO	Automated Good Quality Output
AHP	Analytical Hierarchy Process
AMM	Area Maintenance Manager
ARIMA	Auto-Regression Integrated Average Model
ASME	Area Shift Maintenance Engineer
ASM	Area Shift Manager
ASPs	Active Server Pages
BCM	Business Centred Maintenance
CBM	Condition Based Maintenance
CFC	Culling Facing and Cancelling Machine
CM	Condition Monitoring
CMMS	Computer Maintenance Management System
CRT	Cathode Ray Tube
DEMATAL	Decision-making trial evaluation laboratory
FMEA	Failure Mode Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
GM	General Manager
GOMS	Goals, Operators, Methods, and Selection rules
GUI	Graphical User Interface
HCD	Human Centred Design
HCI	Human Computer Interaction
HF	Human Factors
HMI	Human Machine Interface
HRM	Human Resources Management
HTML	Hyper Text Mark-up language
HWDC	Heathrow World Wide Distribution Centre
ICT	Information and Communication Technology
ID	Identification
IMP	Integrated Mail Processing

ISCV	Instrument Surveillance and Calibration Verification system
ISO	International Standards Organisation
IT	Information Technology
LED	Light Emitting Diode
LSM	Letter Sorting Machine
LSS	Large-Scale Screen
MIMOSA	Machinery Information Management Open System Alliance
MRM	Maintenance Resource Management
MSTL	Maintenance Shift Team Leader
MTBM	Mean Time Between Maintenance
MTL	Maintenance Team Leader
MTT	Machine de-Tris a Trasseur
NA	Not Applicable
NDT	Non-destructive Testing
NEIDS	North Eastern Interim Data System
ODBC	Open Database Connectivity
PC	Personal Computer
PdM	Predictive Maintenance
PF	Product of Failure
RAS	Remote Access System
RBM	Risk Based Maintenance
RCM	Reliability Centred Maintenance
RM	Royal Mail
RTS	Routine Tracking System
SAA	System Application Architecture
SDMM	Service Delivery Materials Management
SAP	Systeme, Anwendungen, Produkte in der Datenverarbeitung
SVC	Supervisory Control
SWOT	Strengths, Weaknesses, Opportunities, Threats
TMM	Territorial Maintenance Manager
TPM	Total Productive Maintenance
UE	Usability Evaluation
UI	User Interface
UID	User Interface Design
UIMS	User Interface Management System
VBScript	Visual Basic Script

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Chapter 1

1. INTRODUCTION

Research and development presented in this thesis has been sponsored by Royal Mail Plc. and IENSYS Ltd.; financed by an EPSRC CASE award grant GR/P03537/01. Royal Mail Plc are interested in developing technological solutions for maximising return on investment and minimising operating costs, for high cost automated mail sorting equipment. As Britain's number one mail sorting and distribution provider maintenance costs incurred by its automated mail sorting machinery, located in 73 mail centres across Britain, annually amounts to considerable sums. This is an on-going concern that has led Royal Mail to sponsor several earlier research projects besides this one, which have been undertaken within the Mechatronics Research Group, Loughborough University.

Coy et al. [2001] and Coy[2003] describe how intelligent Condition Monitoring (CM), a tool for predictive maintenance, has been identified as a suitable method for optimising mail sorting machinery performance within Royal Mail. Predictive maintenance discussed and defined by Zeng [1995] and Moya [2003], involves taking maintenance decisions based upon calculated remaining machinery working life, as opposed to statistically calculated average component life expectancy figures, or as a consequence of component failure. CM equipment sensor selected physical parameters associated with an operating machine. Measured parameters are analysed, compared and displayed as data and information, supporting decisions related to the operation and maintenance of machinery.

Preventative maintenance and run to failure maintenance, alternatives to predictive maintenance, have long been established as part of Royal Mail's maintenance practices. Introducing predictive maintenance practices at Royal Mail requires a rethink towards the way maintenance is scheduled and planned. Since predictive maintenance is being considered for Royal Mail's entire operation, its introduction should be approached at a strategic level, i.e., by reviewing Royal Mail's maintenance strategy. Maintenance strategy described by Zeng[1995], is the total activities required to retain the system in or restore, or modify them to the state necessary for fulfilment of the production function. Considering Condition Based Maintenance (CBM) from a strategic perspective is necessary in order to gain as broad an understanding of implementation implications as possible, so plans may be formulated and put into action to cope with change. Change is inevitable because CBM necessitates maintenance decisions based upon a machines measured live operating conditions, and not solely on prescheduled preventative works orders, or following component failure, as is the case for preventative and corrective maintenance.

Earlier research projects supported by Royal Mail have investigated the suitability of different technologies for monitoring components within automated mail sorting machinery. The components in question include, rubberised belts, pulleys and electric motors. Belts, pulleys and electric motors were all identified as components whose failure rates and failure condition, necessitates their suitability for CM, Coy et al. [2001]. Figure 1.1 illustrates the combination of belts, pulleys and electric motor, within an automated mail-sorting machine. Figure 1.2 shows an image of an Integrated Mail Sorting Machine (IMP), the most advanced automated mail-sorting equipment presently in use at Royal Mail.

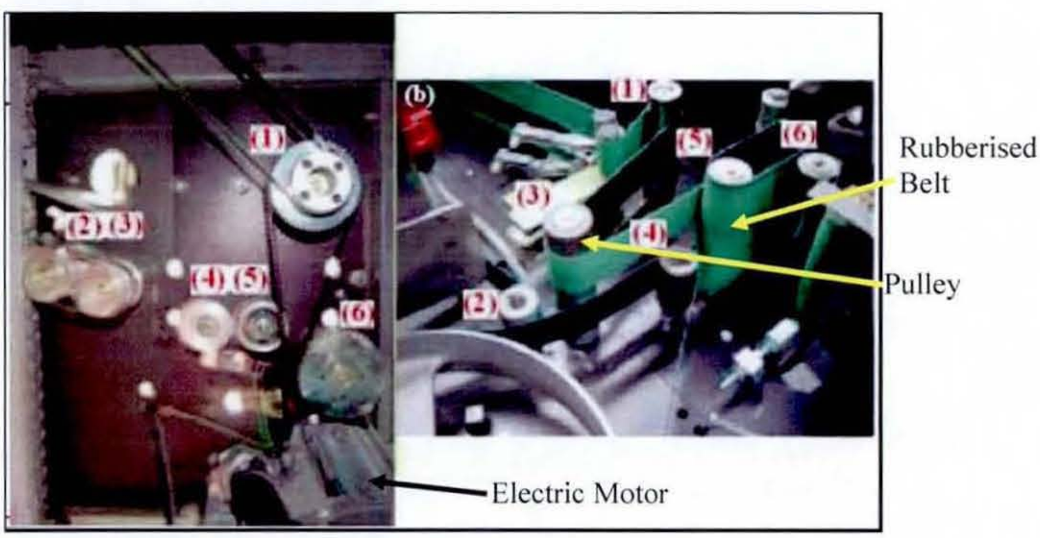


Figure 1.1. Components within an automated mail sorting machine suitable for Condition Monitoring.

Salvan et al. [2004] developed a cost effective method for measuring the condition of multiple pulleys using acoustic emission. Al-Habaibeh et al. [2003] investigated methods of measuring electric motor and pulley temperature, using a budget priced thermal camera. Notini [2005] developed a method for measuring the vibration of belts within automated mail sorting machinery, while the machines are in operation. Research aimed at developing a method of monitoring the surface condition of moving belts, whilst sorting machinery is in operation, is presently on-going. Each CM technique represents a customised approach tailored to Royal Mail's user requirements. Waeyenbergh and Pintelon [2000] discuss the concept of customising maintenance techniques and strategies to meet the needs of customers' requirements.

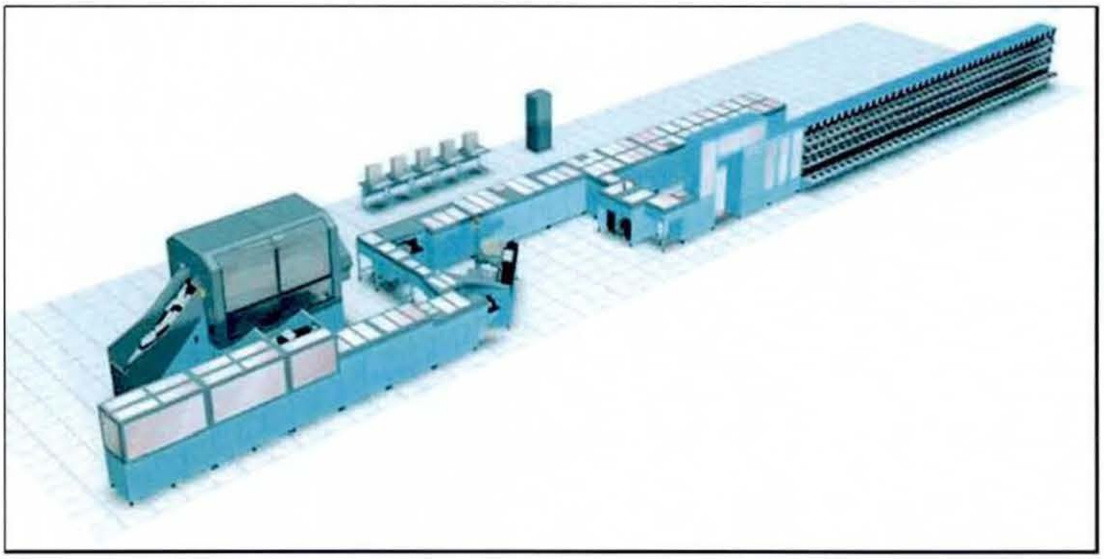


Figure 1.2. An Integrated Mail Sorting Machine, used extensively within Royal Mail.

Each research project conducted by earlier members of the 'Royal Mail University Technology Centre', a sub division within the Mechatronics Research Group, for all research projects sponsored by Royal Mail, developed a Graphic User Interface (GUI) for their purposely designed CM solutions. Graphic User Interfaces provide a method of Human Computer Interaction (HCI) between human operators and computers, or computer controlled devices. Zanino et al. [1994] describes the GUI as a, 'computer screen display that presents information in the form of icons, or images representing objects, actions, and commands, that can be directly manipulated by the user'. HCI discussed by Leune [1995], Lim et al. [1996], and Nielsen [1993] to name just a few, is a multi disciplinary field. It aims to match a method of interacting and communicating interpretable information and commands, between a computerised system and a human operative (user). Researching and developing a method of HCI for CM equipment, monitoring automated mail sorting machinery, located in any one of Royal Mail's 73 mail centres, provides the premise on which this research is based. Research and development presented in this thesis looks beyond the development of individual CM techniques, capable of monitoring individual components within automated mail sorting machinery. A nationwide CBM system operating in all of Royal Mail's mail sorting centres, is anticipated to be most effective in an integrated fully networked state. Networking individual CM equipment into a nationwide computerised CBM system, provides an opportunity for information sharing, remote machinery monitoring, and machinery performance comparison analysis. Having access to information of this type will prove very desirable in a large organisation such as Royal Mail, whose upper management are required to oversee the operations of multiple mail centres, located in different locations. A method of HCI for networked CBM systems will therefore be researched and developed within the contents of this thesis. Due to the nature of this challenge an extensive literature review investigating related scientific disciplines is required.

Literature will be investigated with the objective of understanding what Condition Based Maintenance represents, and how to select and develop methods of Human Computer Interaction. Together both subject areas are intended to provide sufficient material from which a methodology for developing a CBM systems Human Machine Interface (HMI) will emerge. As a result of this process and subsequent research investigations, it is anticipated that a set of rules and guidelines applicable to the design and development of CBM software HMIs, will also emerge. Subsequent research investigations include:

- Understanding the industrial application of CBM systems.
- Identifying values and levels of importance placed upon a CBM systems HMI, by industrial CBM practitioners and CBM solution providers.
- Identifying Royal Mail's user requirements for a CBM system and its method of HCI.

The next step will be to construct a simulation emulating design ideas incorporated in a networked CBM system's HMI, designed to Royal Mail's user requirements. Ideas included in the simulation will be derived from earlier research findings. Each design idea will be assessed through a series of usability tests. Individuals participating in the usability tests include, maintenance personnel from Royal Mail and maintenance professionals from the general community. Resulting feedback gathered as a result of the usability tests, will be used to generate further design ideas for improving the simulation, in order to bring the design closer to satisfying Royal Mail's expectations. Each area of investigation is documented in the chapters comprising this thesis.

1.1. Research Objective

The objective of this research is to contribute towards Royal Mail's pursuit, of developing technological methods capable of maximising return on investment and minimising operating costs, for high cost automated mail-sorting equipment. This will be accomplished by researching and developing a method of human computer interaction, for a Condition Based Maintenance system, networked across Royal Mail's mail centres. A method of human computer interaction, which meets Royal Mail's user requirements, blends in with Royal Mail's existing maintenance systems, will be accepted, and prove beneficial as a maintenance decision aid. As a consequence of this research, identify and propose a set of rules and guidelines, for designing and developing generic Condition Based Maintenance software Graphic User Interfaces. The proposed set of rules and guidelines, should take into consideration accepted Graphic User Interface design rules, and Condition Based Maintenance system functional design expectations, for different Condition Monitoring techniques.

1.2. Research Novelty

Advancements in Condition Based Maintenance (CBM) technologies and techniques are increasing the variety of possibilities, for representing and displaying machinery health monitoring information. Research conducted and presented in this thesis examines Human Computer Interaction (HCI) techniques available for representing and displaying machinery health information, gathered from CBM systems. Research findings aim to identify a novel generic list of Graphic User Interface (GUI) design rules and guidelines, for consideration and application in all future CBM software. The list of CBM GUI design rules and guidelines should be reputable to both CBM system designers and CBM practitioners. Evidence supporting the reputability of the novelty will include: Findings from surveys conducted amongst the CBM solution provider and practitioner community, and justification that existing design rules and guidelines do not already exist. A CBM GUI incorporating some of the identified design rules, designed to Royal Mail's requirements, will be presented in support of the investigations leading towards the intended novelty.

CBM HMI designers should welcome the intended novelty, as its application is envisaged to speed up CBM software GUI design and development. Design and development time savings will be provided through the identification of generically accepted rules and guidelines for inclusion in a CBM software's GUI.

1.3. Thesis Methodology

The thesis contains nine chapters, references, and an appendix, consisting of nine sections. Chapters two through to seven have the same structure, incorporating an introduction to the chapter, subsequent subsections and a summary of the chapter's contents. A map of the thesis structure, in flow diagram format, is shown in Figure 1.3.

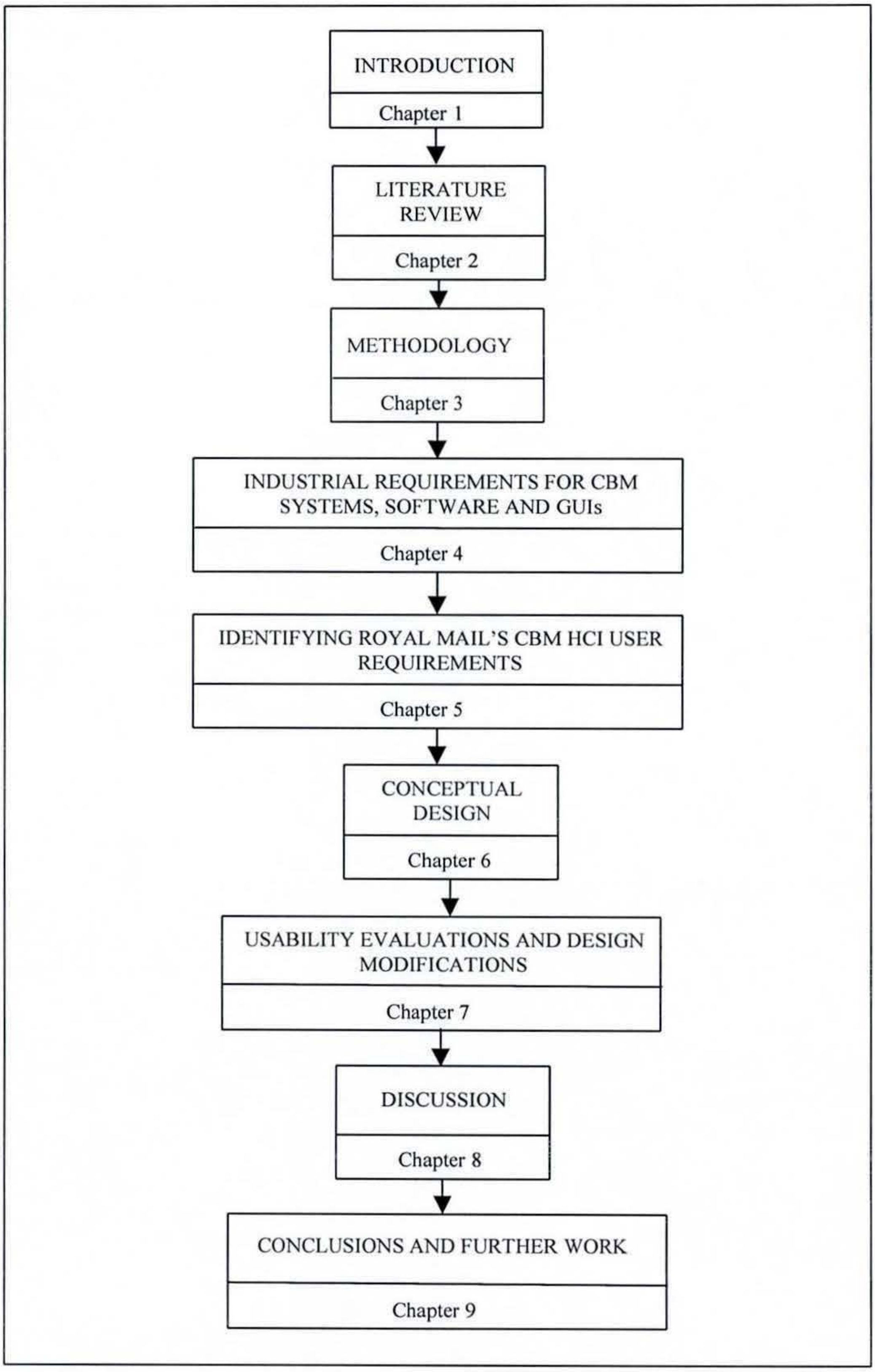


Figure 1.3. Map of Thesis structure

Chapter 1: INTRODUCTION

Introduces the thesis by describing the contexts from which the research project originates. Provides the reader with back ground knowledge, introducing key subject areas to be researched. Describes the research objectives, the research novelty and the research methodology.

Chapter 2: LITERATURE REVIEW

Relevant literature in meeting the research objectives is reviewed and discussed. Reviewed literature originates from recent and up to date journal papers, conference papers, books, magazines articles and Internet sources. Topics discussed in the literature review include:

- Maintenance Strategy and maintenance practices.
- Condition Based Maintenance and Condition Monitoring Technologies.
- Human-Centred Design, Human Factors Principles and User Profiling.
- Human Computer Interaction and User Interface Design.

Chapter 3: METHODOLOGY

A design specification for a CBM HMI is presented. Information contained in the methodology is derived from the literature review, from discussions with members of the Mechatronics Research Group, discussions with maintenance personnel at Royal Mail, and from the researchers own knowledge.

Chapter 4: INDUSTRIAL REQUIREMENTS FOR CBM SYSTEMS, SOFTWARE AND GUIs

Findings from three surveys conducted amongst maintenance professionals and CBM solution providers are presented and discussed. Surveys two and three build upon findings obtained from the previous survey's findings. Survey one investigates the current day application of CBM systems within industry. Survey two identifies desirable methods of communicating information, gathered from CM equipment to CBM practitioners. Survey three assesses values and levels of importance associated with methods of communicating CM information through GUIs.

Chapter 5: IDENTIFYING ROYAL MAIL'S CBM HCI USER REQUIREMENTS

Findings gathered following a series of interviews and visits to various Royal Mail centres and offices, is presented. Information presented includes: details of Royal Mail's maintenance system, maintenance personnel and their responsibilities, and user requirements for a CBM system and its method of HCI. GUIs developed by earlier research projects sponsored or associated with Royal Mail are reviewed and compared.

Chapter 6: CONCEPTUAL DESIGN

Design ideas for a CBM GUI designed to meet Royal Mail's user requirements are presented and discussed. Explanations are provided for the choice of design architecture, the chosen method of HCI, selection of a GUI prototyping tool, and the chosen structure for the web site comprising the CBM GUIs. Functional design explanations are provided for each individual web page, comprising the larger web site, which makes up the CBM HMI.

Chapter 7: USABILITY EVALUATIONS AND DESIGN MODIFICATIONS

Feedback gathered following usability evaluation tests on a simulation, containing design ideas described in chapter 6, are presented and discussed. Usability testing was conducted on maintenance personnel from Royal Mail, and random maintenance professionals. Suggestions for improving upon the existing simulation, in reply to identified areas of concern, are described.

Chapter 8: DISCUSSION

The contents of the entire thesis are reviewed and summarised on a chapter-by-chapter basis. Information and understanding acquired from each chapter for the projects duration, is extracted and described. Research contributions resulting from this thesis are identified.

Chapter 9: CONCLUSIONS AND FURTHER WORK

Final conclusions to the research undertaken and presented in this thesis are discussed, and recommendations for future research suggested. Future research recommendations are suggested for areas insufficiently attended to in the thesis, in meeting the research objectives, and relevant areas outside the remit of the research objectives.

Chapter 2

2. LITERATURE REVIEW

2.1. Introduction

Literature from numerous journal papers, conference papers, articles and advertisements, are discussed and summarised. The literature review will develop an understanding of topics relevant to the research objectives. Direction for further research investigations will be drawn from the literature reviewed. Further research investigations should focus on identifying CBM GUI design rules and guidelines, and suggesting design ideas for a CBM system's GUI, intended for Royal Mail Plc.

Three main topics have been investigated; Maintenance, Human Computer Interaction and Design Methodologies. Each of the three topics forms a category header, located at the top of the literature map, shown in Figure 2.1. The literature map charts subsequent literature topics investigated during the literature review. Colour coding differentiates between the primary literature topics, secondary literature topics and peripheral topics. Primary literature topics were identified early in the literature investigations, as having the greatest level of relevance with respect to the research objectives. Secondary literature topics were identified as a consequence of investigating the primary literary topics. Peripheral topics are considered the least important in satisfying the research objectives.

Each literary topic included in Figure 2.1 is discussed and summarised in the subsections to follow. Reference to authors names and dates of publication, are provided where appropriate throughout this and subsequent chapters.

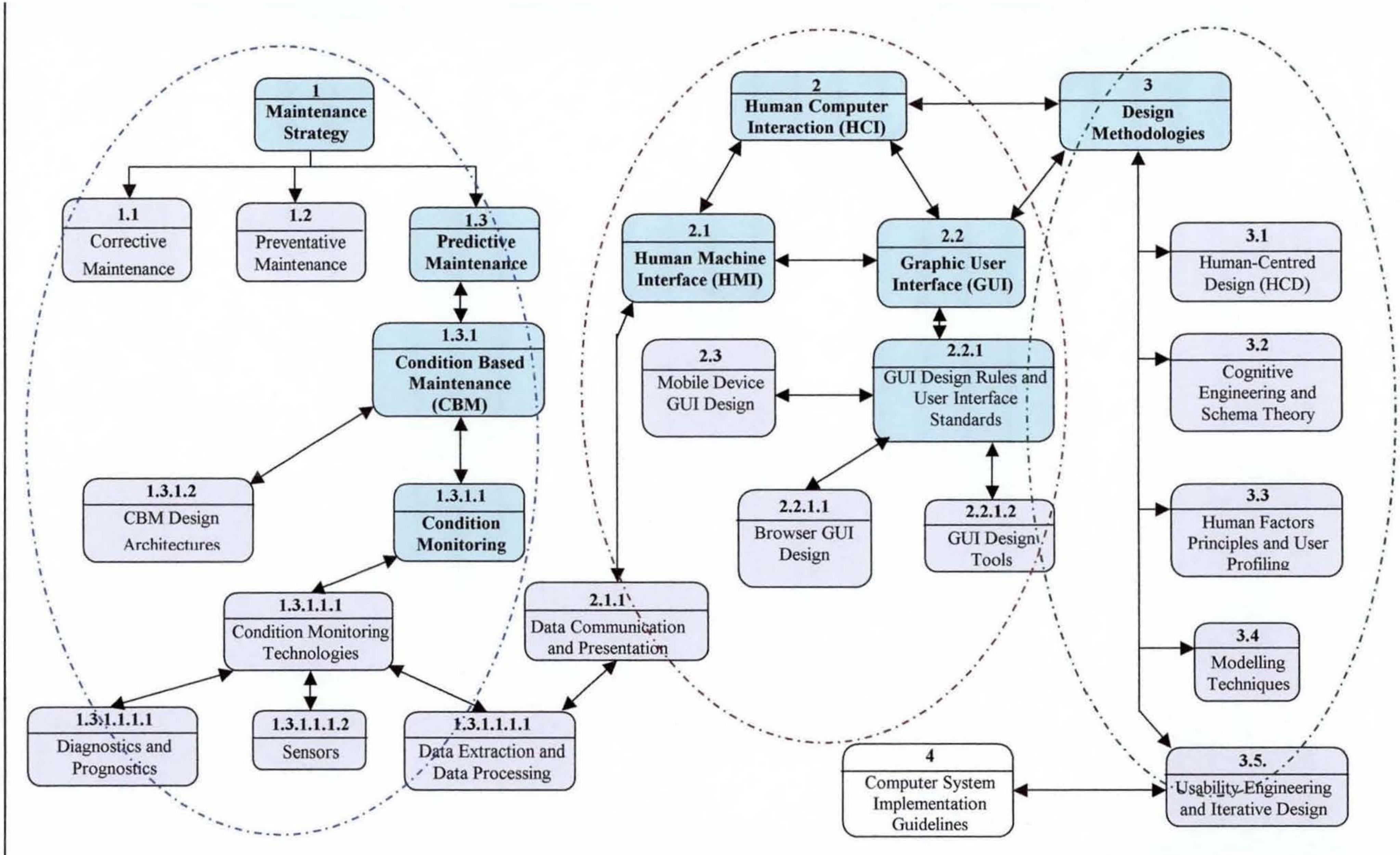


Figure 2.1. Literature Map for researching and developing methods of HCI for a CBM system

Key:
- **Primary Research Focus**
- **Secondary Research Focus**
- Peripheral Research Areas

2.2. Maintenance Strategy

Introducing CBM practices into Royal Mail's mail centres will cause much disruption to their existing working practices, requiring a complete rethink to the way maintenance is regarded and performed and integrates with other business practices. Maintenance Engineers, Operators and Managers will feel the impact of its introduction alike. Considering CBM from a strategic perspective is necessary in order to gain as broad an understanding of implementation implications as possible, so plans may be formulated and put into action to cope with change. Change is inevitable if an organisation is moving from corrective or preventative maintenance to predictive practices. One of the first tasks will be to educate employees, so they can distinguish between preventative and predictive maintenance.

Maintenance Strategy is defined by Zeng [1995] as the total activities required to retain the system in, or restore, or modify them to the state necessary for fulfilment of the production function. Restoring a maintenance system to its previous state can be accomplished using an error recovery strategy, an example of which is discussed by Kontogiannis [1999]. Few businesses have like for like systems or identical production functions, which is why maintenance strategies should be customised. This agrees with Waeyenbergh and Pintelon [2000] and [2003], that maintenance concepts should be tailored to the needs of the company in question. Tailoring can be expected to include a review of different theoretical maintenance concepts, resulting in possibly a solution that integrates various ideas. Periodic reviews should be performed in order to take into account possible changing maintenance demands according to the changing systems and the changing environment.

In the first CBM questionnaire, refer to section 4.2. or Higgs et al. [2004], the question was asked, 'Why did your organisation implement CBM?' Results identify several specific strategic reasons, each very much individual, e.g., to avoid an annual maintenance shut down, improve maintenance planning and scheduling, to act as a maintenance training catalyst, monitor the reliability of equipment, follow the example set by other businesses, and move from a reactive to a proactive maintenance culture. A result that agrees with the earlier understanding, few businesses have like for like systems or identical production functions, indicative of the need for tailored maintenance strategies.

Organisations with well-established deep-rooted maintenance practices are advised to perform an internal assessment of existing maintenance practices before considering alternative maintenance concepts for their organisation. This should help to understand where an organisation is starting from, identifying expected or possible problem areas during implementation. Waeyenbergh and Pintelon [2000] and [2003] puts this in the context that, 'all knowledge is important and valuable because it is already placed in a certain context, namely experience.' Interviewing a wide cross section of the work force should aim to identify maintenance issues concerning workings practices, technologies and staff attitudes.

Waeyenbergh and Pintelon [2000] present three important factors they consider to be critical in the process of selecting a maintenance strategy.

- Thorough knowledge of maintenance technology: the direct production personnel as well as the maintenance workers need knowledge and competence to prevent disruption at an early stage of the production process.
- Management skills regarding planning and control of maintenance tasks as well as Human Resources Management (HRM): Studies have shown that long-term maintenance plans, company-wide maintenance knowledge and participation of manufacturing personnel in the planning of maintenance are of major importance.
- Flexibility to exploit opportunities and trends, such as the expanding maintenance services market and the opportunities offered by Information and Communication Technology (ICT).

Three popular maintenance strategies include:

- Reliability Centred Maintenance (RCM).
- Business Centred Maintenance (BCM).
- Total Productive Maintenance (TPM).

Waeyenbergh and Pintelon [2000] classify each of the three strategies as follows: RCM follows a structured approach, TPM encourages operator involvement, and BCM focuses on economic considerations, aiming to maximise the contribution of maintenance on profitability.

Zeng [1995] presents further evidence for encouraging operator involvement under a TPM strategy with the statement: "According to TPM, maintenance requirements should be identified by the maintenance personnel but (ultimately) carried out by the operator. Action aimed at enhancing the responsibility and motivation of operators and providing maintenance staff with more time to concentrate on developing further maintenance initiatives."

Two further maintenance concepts include Risk Based Maintenance (RBM) and Maintenance Resource Management (MRM).

RBM is described by Khan and Haddara [2003] as a quantitative approach for maintenance/inspection scheduling and planning. RBM systematically breaks a system under investigation down, investigating the probability and consequence of failure, looking for answers to the following questions:

- What can go wrong that could lead to a system failure?
- How can it cause the system to fail?
- What would be the consequences if it fails?
- How likely is its occurrence?
- How frequent an inspection/maintenance of what components would avert such failure?

Answers to these five questions should identify specific high-risk components, sub assemblies and machinery whose failure would result in unacceptable safety, economic or environmental consequences. This will enable users of risk-based maintenance to organise their maintenance activities in such a manner as to achieve better asset and capital utilisation.

Figure 2.2 illustrates the top-level architecture proposed by Khan and Haddara [2003] for a risk-based maintenance methodology. The architecture consists of three key modules: risk estimation, risk evaluation and maintenance planning.

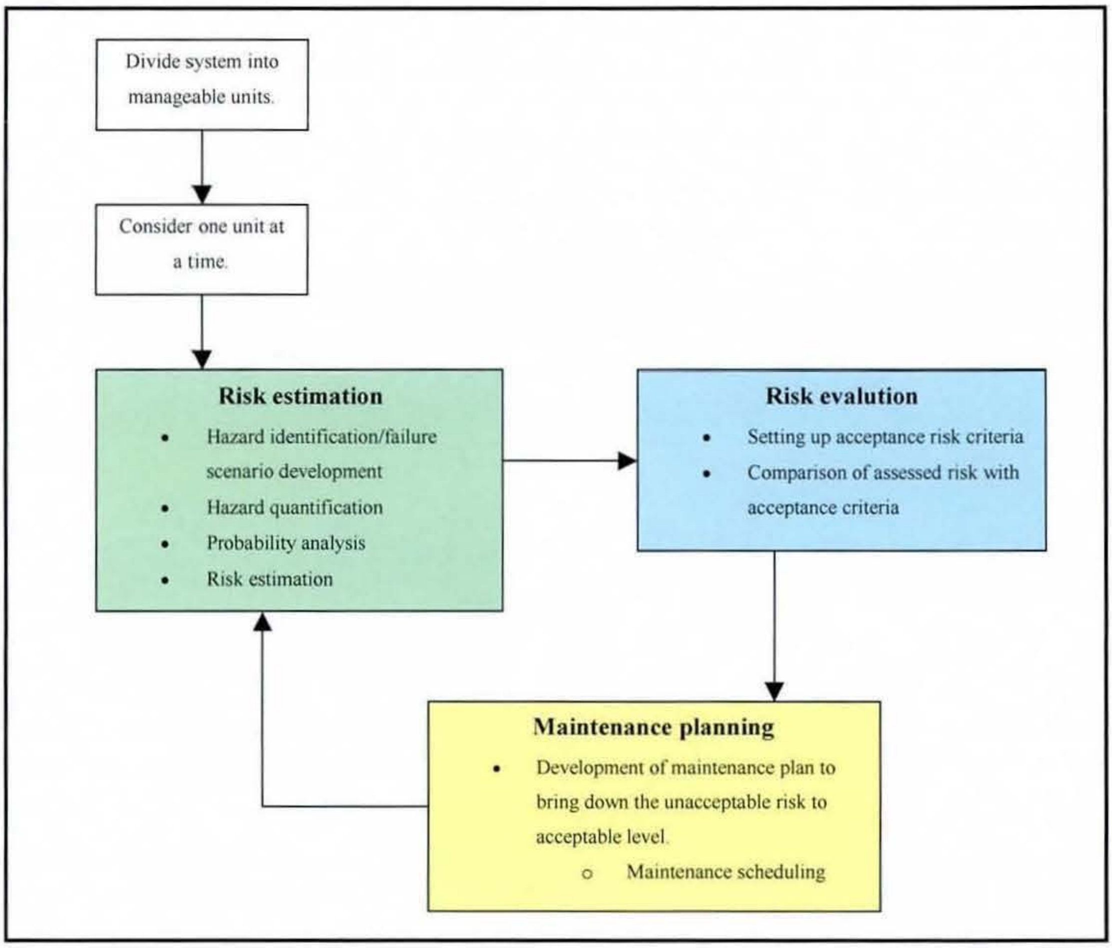


Figure 2.2. Top level architecture of RBM methodology, Khan and Haddara [2003].

Maintenance Resource Management (MRM) represents a Human Factors concept, aimed at improving communication and collaboration between all levels of management concerned with maintenance decision-making. Studies involving MRM conducted by Taylor [1997], confirmed that effective communication is paramount for ensuring co-ordination and good work performance. Where communication was found not to be a high priority, there were more jobs late from maintenance and personnel turnover was higher than average, and there was lower morale among maintenance, inspection, planning, stores, and shop personnel. Communication and training lead to increased enthusiasm. Understanding of the change and the business function itself increase employee enthusiasm. Maintenance Engineers, Operation Managers and operators must fully understand and co-operate with any new system alteration for its likely success.

2.2.1. Maintenance Approaches

Three popular maintenance approaches include:

- Corrective maintenance
- Preventative maintenance
- Predictive maintenance

2.2.1.1. Corrective Maintenance

No maintenance is carried out until the machine breaks down, Zeng [1995].

Corrective maintenance is a suitable maintenance approach in situations where one or a combination of the following factors is true:

- Component failure results in a minimum of damage to other components, machinery, product/service quality, and doesn't cause a safety risk.
- Replacement parts can be obtained and fitted quickly and easily.
- Skilled maintenance engineers or operators are always available to replace the failed component/s.
- Replacement parts are always kept in stock or can be provided at very short notice from suppliers.
- Sudden production stoppages cause minimal disruption, and no or little extra additional expense.
- Purposely designed safety components/sub assemblies, designed specifically to fail before larger more expensive or safety critical components/assemblies; are incorporated into machinery.

Corrective maintenance is not a suitable maintenance approach in situations where one or a combination of the following factors is true:

- Component failures lead to long production stoppages resulting in expensive lost production down times, e.g., repair work takes a long time, replacement parts are not kept in stock or readily available, external labour or machinery needs to be brought in to perform the required maintenance.
- Component failure results in subsequent collateral damage to other components, machines or plant.
- Failure creates a serious safety risk.

- Product quality falls below critical standards, despite best set up, before component failure.
- Maintenance scheduling at pre-determined time slots is critical, i.e., sudden component failures requiring immediate maintenance are unacceptable, for whatever reason.
- It is more desirable to use preventative or predictive maintenance approaches.

2.2.1.2. Preventative Maintenance

Maintenance is carried out on a schedule derived from running time, or according to a calculated average number of cycles before components reach a point where failure mechanisms rapidly increase likelihood of component failure, Zeng [1995]. In other words, preventative (periodic) maintenance is effective in overcoming the problems associated with the wearing of components, Bevilacqua and Braglia [2000]. If insufficient wear has taken place between periodic checks, maintenance may not be required.

Preventative maintenance is a suitable maintenance approach in situations where one or a combination of the following factors is true:

- Sufficient statistical data exists to reliably calculate useful component life expectancy; an average number of cycles before a point of imminent and expected failure arises.
- The occasional random catastrophic failure is acceptable.
- It is preferable and acceptable to schedule maintenance work to occur during factory/operation shut downs and stoppages.
- Maintenance work can be performed within the allotted time period; machinery is available/stopped or shut down.
- Regular routine maintenance, i.e., hourly, daily, weekly or monthly, are essential in order to keep quality levels at an acceptable standard. Maintenance such as: lubrication, tightening and cleaning.

Preventative maintenance is not a suitable maintenance approach in situations where one or a combination of the following factors is true:

- It is unacceptable to rely upon previous statistical component performance data to calculate maintenance routine intervals.

- A business wishes to maximise the useful life of its machinery and still achieve high quality levels.
- It is more desirable to use a corrective or predictive maintenance approach.

2.2.1.3. Predictive Maintenance

Maintenance is carried out when a quantifiable machine condition shows the need for repair or replacement (Condition Monitoring). It allows a machine to run as long as it is healthy, Zeng [1995].

Moya [2003] offers another definition for predictive maintenance: A policy in which selected physical parameters associated with an operating machine are sensored, measured and recorded intermittently or continuously for the purpose of reducing, analysing, comparing and displaying the data and information so obtained for support decisions related to the operation and maintenance of machines. Incorporating predictive maintenance into existing maintenance concepts, e.g., TPM or RCM, is suggested as a method of optimising benefits.

A four-phase predictive maintenance implementation guide presented by Moya [2003] is described below:

- **Design and planning phase.** This refers to the interval of time from the first suggestion of modifying maintenance policies by introducing a Predictive Maintenance Program (PMP) until the human and technical resources are available to begin the set-up.
- **Adaptation phase.** This is associated with obtaining reliable measurements of the state of the machinery under control. This period begins 8 months from the start of set-up and is estimated to last 14 months.
- **Extension or globalisation phase.** Once the time needed to get a return on the investment is reached, the number of machines under control is increased or else new objectives are set. This phase is usually reached after a period of three years from the start of set-up.
- **Integration phase.** With other Computer Maintenance Management Systems (CMMS), corrective, preventative, etc.) and production systems. This aspect is essential, due to the necessary inter-dependence of all the functions of the plant.

Predictive maintenance is a suitable maintenance approach in situations where one or a combination of the following factors is true:

- It is desirable to maximise equipment availability, i.e., perform maintenance only when a quantifiable condition is reached.
- It is desirable to shut a machine down before component catastrophic failure because knock on component wear/failure and safety risks are undesirable.
- It is desirable to schedule maintenance activities around changing production requirements, rather than have maintenance dictate production.
- It is desirable to plan labour requirements around maintenance schedules.
- It is desirable to avoid keeping large stocks of spare parts readily available.

Predictive maintenance is not a suitable maintenance approach in situations where one or a combination of the following factors is true:

- Companies have a limited maintenance budget.
- Companies do not have the resources or expertise to gain the benefits from predictive maintenance.
- It is not possible to incorporate sensors, and therefore monitor the condition of a component, machine or process, due to hostile environmental conditions.
- It is more desirable to use a corrective or predictive maintenance approach.

2.2.2. Maintenance approach selection

Various reasons for and against the use of each maintenance approach have already been identified. Specific influential factors include:

- A company's maintenance budget.
- How frequently failures occur.
- The cost of replacing the failed item.
- The impact upon other parts of a system resulting from an item breakdown.
- Safety and environmental risks resulting from an item failure.
- The importance a machine has in the larger system.
- Whether performance reliability data exists for the machine/s.
- The length of time a machine/process has to be stopped in order for maintenance work to be performed.
- How easy is it for maintenance work to be performed, i.e., what constraints exist.

- Whether spare parts are readily available and easy to get hold of.

It is not easy to prioritise between each of these factors because of their intangible and complex nature. Bevilacqua and Braglia [2000] suggest the application of Analytic Hierarchy Process (AHP) for selecting the best maintenance approach. AHP is a multi-criteria decision-making tool for complex problems where both qualitative and quantative aspects need to be considered. AHP helps analysts organise critical aspects of a problem into a hierarchical structure similar to a family tree. Complex decisions are reduced into a series of simple comparisons and rankings and the results synthesised, helping analysts arrive at a best decision, and providing a clear rationale for the choices made. AHP does not make decisions for the analyst, but rather acts as a guide. AHP is well supported by commercial software programs.

Alternative methodologies for selecting the best maintenance approach include Reliability Centred Maintenance (RCM) and failure mode effect and criticality analysis (FMECA).

2.2.3. Summary

Maintenance strategy is the total activities required to retain a businesses system in, or modify them to the state necessary for fulfilment of the production function. Academics and industrialists have created numerous maintenance strategies alike, including the as mentioned RCM, BCM, TPM, MRM and RBM. Despite efforts by consultants to promote specific maintenance strategies, possibly for their own financial gain, no one maintenance strategy provides the answer to every situation. Businesses should aim to select ideas from possibly more than one maintenance strategy and tailor a select group of maintenance approaches to suite their own requirements. The three most recognised maintenance approaches are corrective maintenance, preventative maintenance and predictive maintenance. Techniques designed to assist in the selection of the most appropriate form of maintenance include, failure mode effect and criticality analysis (FMECA), Reliability Centred Maintenance (RCM), and Analytic Hierarchy Process (AHP).

Condition Based Maintenance is a predictive maintenance practice, to be incorporated within any one of the mentioned or additional maintenance strategies. Implementing Condition Based Maintenance into an organisations maintenance strategy should be approached in a well-planned and structured manner, being tailor selected or designed, to suite an organisations machinery, resources and existing maintenance practices. Training and familiarising employees to distinguish between predictive maintenance and other maintenance practices is critical in order to create an initial understanding of the purpose and intended benefits of Condition Based Maintenance. A four phase predictive maintenance implementation guide has been proposed, consisting of: an initial design and planning phase, followed by an adaptation phase, further adaptation and extension of predictive maintenance throughout an organisation, and finally integration of accepted predictive maintenance procedures with other business maintenance systems and procedures.

In the next section Condition Based Maintenance and Condition Based Monitoring are discussed in greater detail.

2.3. Condition Based Maintenance

Condition Based Maintenance is a predictive maintenance method. Predictive maintenance differs from preventative maintenance in that decisions are made based on calculated remaining component life expectancy as apposed to recommended experience based intervals. Predictive maintenance is not a substitute for preventative maintenance, as there is always a need for routine interval controlled maintenance. In time predictive maintenance may come to influence or even control the time intervals periodic maintenance is undertaken.

The constituent components for Condition Based Maintenance include:

- **Condition Monitoring (CM) technique selection**: Selecting a CM method suitable for the machinery and environment it is operated in.
- **Diagnosis level 1**: Analysing sensory data gathered from the CBM system in order to identify trends and signals indicative of component condition.
- **Diagnosis level 2**: Identifying trends and signals representative of condition failure modes.
- **Prognosis:** Identifying and selecting forecasting techniques capable of predicting expected remaining component life before failure.
- **Human Computer Interaction**: Communicating the CM sensory data and subsequent data analysis results to interested human parties.
- **Human intervention:** Taking decisions based upon information interpreted from the Condition Based Maintenance system, e.g., schedule maintenance, alter production schedule, reassess inventory levels.

The first constituent component listed above, 'CM technique selection', involves monitoring the condition of machinery by applying one of a variety of monitoring processes, such as: visual inspection, performance monitoring, trend monitoring, vibration monitoring, acoustic monitoring, thermography and tribological analysis to name a few.

Four different CM Methods are being investigated for consideration at Royal Mail: Bearing Acoustic Emission, Belt Vibration and Slippage, Infrared Thermography, and Belt Surface

Degradation. Each method is being trialed as a viable option to reduce maintenance expenditure on mail sorting machinery. Coy et al. [2001] explains that costs incurred by commonly used maintenance strategies such as the periodic replacements of components, which can be wasteful and does not eliminate the random occurrence of catastrophic component failures, include the expenditure involved in keeping large numbers of components on site. An ability to determine the condition of components can reduce the cost of system maintenance. Such ability facilitates the detection of faults before the occurrence of catastrophic failures, it also allows prediction of incipient faults or catastrophic failures to be made based on the previous and current condition of a component. This information allows maintenance plans to be optimised accordingly and machine downtime minimised.

Coy et al. [2001] anticipates successful CBM trials at Royal Mail, will lead to further initiatives aimed at integrating multiple monitoring technologies into a machine mounted system, that uses artificial intelligence techniques, to continuously learn about the machine condition and to highlight the need for specified corrective action, in advance of significant functional deterioration; resulting in an autonomous CBM system.

Communicating pertinent, timely information/knowledge, from Royal Mail's anticipated autonomous CBM system, to operational staff and combining it with operational considerations, for the purpose of scheduling and plant management, is critical if financially rewarding asset management improvements, through predictive maintenance, are to be realised. Pertinent, timely information/knowledge transfer, depends upon the machine-man interface communicating this information to decision makers at the right time, Coy [2003].

Looking to the future Coy [2003], suggests further benefits can be envisaged from these intelligent monitoring systems if they are combined with actuators, in effect a machine that can monitor itself and adjust its settings, so that minimum energy is consumed or wear minimised. Also, the benefits of automation are circumscribed by the ability of people to manage and work with it; user centred design practices have to become an essential element of future generations of process plant.

Examples of successful industrial case studies, identified from literature, where Condition Based Maintenance has been successfully implemented include: the implementation of vibration, speed, process and other CM techniques to monitor machinery within a paper Mill, in New Zealand, described by Weinstein and Werner [2002]; a CBM system designed to receive and process data via Ethernet, from machinery located on oil plants and offshore production platforms, described by, Lopes et al. [2002]; a CBM system referred to by the author as, 'a web-based health monitoring system', designed to monitor parameters within the high pressure section of a supercritical 700MW steam turbine, described by Orsagh et al. [2000], and a CBM system designed to monitor the condition of reciprocating compressors, described by Lenz [1999].

2.3.1. Summary

Condition Based Maintenance is a predictive maintenance technique employed for monitoring the live condition of machinery components. Information gathered from sensors located within machinery, monitoring component conditions, is transferred to database for analysis. Results from sensory data analysis provide information for monitoring the live and historical changing health conditions for machinery components. Analysis of historical data provides users with an opportunity for identifying component failure mechanisms, and predicting remaining useful component life, before absolute component failure. Three methods of CM have been trialed at RM: acoustic emission, vibration and belt slip, and thermography. Condition Based Maintenance should be considered as an opportunity to reduce maintenance expenditure and improve the efficiency of asset management. In the next section technologies utilised within a CBM system are examined.

2.4. Condition Monitoring Technologies

Technologies incorporated within CBM systems and recent technological advances are discussed in this section. Explanations are provided for intelligent CBM, a fairly new terminology describing CBM systems with built in diagnostic and prognostic capabilities, and ends with a discussion concerning sensory data extraction and data processing.

Advances in CBM systems are being driven by commercial demands for improvements in: productivity, quality, inventory control, and expenditure on plant and machinery. Technological advances take place gradually as new scientific discoveries are made, accepted and applied to CBM systems. Recent technological advances include:

- Improved knowledge of material failure mechanisms.
- Advancements in failure forecasting techniques.
- Advancements in monitoring and sensor devices.
- Advancements in diagnostic and prognostic software.
- Acceptance of communication protocols.
- Developments in maintenance software applications and computer networking technologies.

In 1994 Jacob [1994] made a prediction that future CBM systems would include electronics incorporating parallel processing and distributed architectures; fieldbus digital transmission; intelligent on-line sensors; re-programmable sensors; algorithms, fuzzy logic and neural networks designed to detect trends in sensory data representative of component condition. These technological predictions were made on the assumption that improvements will be seen in: process control and monitoring technologies, a move towards distributed computing architectures, and the use of standardised communication networks and protocols. Ten years on, many of these technologies have become or are rapidly becoming standard design features within modern CBM systems.

Technologies designed for the purpose of providing diagnostic capabilities within a CBM system include, fuzzy logic, neural networks and the application of Dempster Shafer theory. Integrated together each of these technologies, as explained by Vachtsevanos and Wang

[2001], will determine a CBM systems performance to accurately diagnose failure conditions and then predict (prognosis) remaining component working life. Dempster Shafer Theory is explained by Sentz and Ferson [2002] and Wu et al. [2002], to combine Bayesian notions of probability with the classical idea of set, where a numerical value signifying confidence can be assigned to sets of simple events, rather than to just mutually exclusive simple events. For example, 'this is A' or 'this is likely to be either A or B'. In Dempster-Shafer's reasoning system, all possible mutually exclusive context facts (or event) of the same kind are enumerated in the frame of a discernment equation. Dempster-Shafer Theory is a potentially valuable tool for the evaluation of risk and reliability in engineering applications, when it is not possible to obtain a precise measurement from experiments, or when knowledge is obtained from expert elicitations.

Jennings et al. [2002] describes technologies developed to determine the integrity of data feed back from sensory monitoring devices within a CBM system. Smart sensors, sensors incorporating intelligent decision-making capabilities, have been developed capable of analysing and filtering source sensory data. Intelligence is provided using trained neural networks, and fuzzy logic analysis built into each sensor. Filtering helps remove detectable unwanted sensory signals, before the remaining signal is passed onto a database for storage and post processing.

Orsagh et al. [2000] describes another method for determining CM sensory data integrity. They describe the application of trained neural networks, and fuzzy logic analysis within a sensory diagnostic system, designed to isolate and detect specific sensor failure modes. In the event of a sensor failure, sensor recovery is possible through the use of artificial intelligence algorithms that can provide proxy data until the malfunctioning sensor can be repaired. Hines and Shannon [2000] describe a further CBM system capable of producing proxy values, named an Instrument Surveillance and Calibration Verification system (ISCV). Hines and Shannon [2000] explain that the ISCV system was developed in the MATLAB environment, transferred to C++ code, and embedded in a graphical user interface using National Instrument's Labview software

Monitoring machinery conditions on a continuous basis will produce a substantial quantity of sensory data, increasing data processing and data manipulation requirements. This creates the need for additional system requirements, notably: larger server storage capacity;

improved database management efficiency; faster processing capabilities; and clever database mining programs. Coping with excessive sensory data is potentially a huge concern in the development of an enterprise CBM system at Royal Mail, because sensory data gathered from 1000s of bearings and belts incorporated within mail sorting machines will rapidly add up.

Zorriassatine et al. [2003], explains the advantages of wireless sensors, a technology suitable for taking sensory measurements in environmentally challenging situations. For example, components in difficult-to-reach locations, electrically noisy environments and mobile applications where wire cannot be installed. They explain that implementation requirements will ultimately influence the decision to adopt wireless sensors instead of fixed cable connected sensors within CBM systems. Lee [2001] identifies some of these wireless communication concerns as being: reasonable data transmission speeds, reliability, security, ability to initiate a communication link at any time, duplex data transmission, a low bit error rate, short synchronisation times, mobility, length of data transmission and inexpensive infrastructure. Spread spectrum signal techniques are suggested as promising signal transmission technologies suitable for wireless sensors.

Infrared cameras adapted for making CBM decisions based on thermography information are discussed by Al-Habaibeh et al. [2003]. The paper describes the effectiveness and possibilities of using low budget infrared cameras to monitor the performance of machinery. Present day costs push thermography CM using high-resolution infrared cameras beyond the allocated maintenance budget of many businesses.

Fieldbus digital data transmission techniques for CBM is investigated by Pietruszkiewicz et al. [2001]. He suggests combining machinery control signals with CM data along a fieldbus transmission offers advantages in the form of, hardware reduction, systems compatibility, no data redundancy and no data transformation. He states that, digital signals are more robust in the presence of noise. In addition, cabling costs are substantially reduced (hardware reduction) by using fieldbus technology, because all devices are linked to the same cable so that wasteful point-to-point communication links are no longer required.

Looking to the future Dunn [2002a] suggests six trends where Condition Monitoring is going in the 21st. century:

- The development of smart sensors, and other low-cost on-line monitoring systems that will permit the cost-effective continuous monitoring of key equipment items.
- The increasing provision of built-in vibration sensors as standard features in large motors, pumps, turbines and other large equipment items.
- Increasingly sophisticated Condition Monitoring software, with rapidly developing 'expert' diagnosis capabilities.
- The acceptance of CM for the day to day maintenance of production operations, with operators increasingly utilising CM technologies as part of their day-to-day duties.
- An increasing focus on the business implications and applications of CM technologies, leading to the utilisation of CM technologies to improve equipment reliability and performance, rather than merely predict component failure.
- A reduction in the cost-per-point of applying CM technologies-possibly leading to more widespread use of these technologies.

2.4.1. Intelligent CBM

The term intelligent implies a CBM system is capable of understanding and making decisions without human intervention. Technologies making this possible include:

- Sensors with built in intelligence (SMART Sensors), capable of transmitting relatively rich, high grade information, Coy et al. [2001].
- Re-programmable on-line sensors, Jacob [1994], designed to be reconfigured with new rules in the event that detectable recognisable patterns change.
- Algorithms, fuzzy logic and neural networking, designed to analyse trends within recovered sensory data, and produce decisions on the likelihood of failure of monitored plant items, Jacob [1994].
- Artificial intelligence algorithms capable of providing proxy data as a substitute for failing or a failed sensor, whilst the malfunctioning sensor is repaired, Orsagh et al. [2000].
- SQL databases with open database connectivity (ODBC) capable of embodying and extracting domain knowledge related to identified system faults, Gale and Watton [1999].

Further intelligence is possible through integration of a CBM system with other company computerised systems, e.g., purchasing, and production scheduling, thus automating parts ordering, and suggesting convenient times to fit maintenance work in between scheduled production down time.

2.4.2. Diagnosis and prognosis theory

Diagnosis is defined as a thorough analysis of facts or problems in order to gain understanding. An opinion reached through such analysis, Brookes [2003].
Prognosis is defined as any prediction, sign of some future occurrence. Brookes *[2003].*

CBM systems rely upon the accuracy of their diagnostic and prognostic capabilities. Research conducted by Gale and Watton [1999] whilst developing a real-time expert CBM system incorporating diagnostic capabilities, cited system integrity in expert fault prediction as being the most important factor to consider during system specification. Predicting the growth of faults and remaining working life before component failure, will assist maintenance personnel in maximising machinery up time by avoiding unnecessary maintenance stoppages, thereby maximising useful life of a businesses critical assets. Figure 2.3 illustrates the architecture for a CBM system incorporating diagnostic and prognostic capabilities.

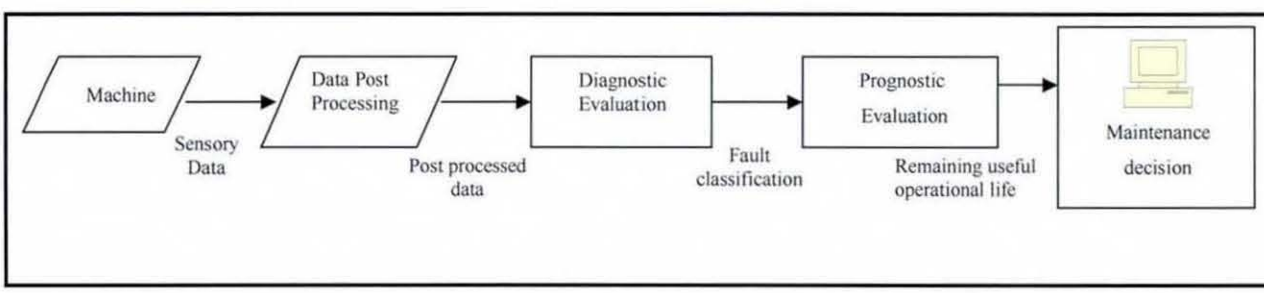


Figure 2.3. Architecture for a diagnostic and prognostic CBM system.

Before selecting suitable diagnosis and prognosis strategies, threshold component parameters must be selected. Orsagh et al. [2000] states, threshold parameters should include a sufficient level of redundancy to support sensor validation algorithms and ensure reliable results without becoming overly complex.

If optimal thresholds cannot be identified, one practical way to handle the situation is that once one piece of equipment in a group fails to work, it can be regarded as an alarm for the rest, Zeng [1995].

Uncertainty is a dominant influence in diagnostic and prognostics, which must be accommodated and managed, Vachtsevanos and Wang [2001]. Various techniques and technologies have been developed to overcome and assist the diagnosis and prognosis problem including, Stochastic Auto-Regression Integrated Average (ARIMA) models, fuzzy pattern recognition principles, knowledge-intensive expert systems, non-linear stochastic models of fatigue crack dynamics, polynomial neural networks and notions from Dempster-Shafer theory. Gale and Watton [1999] state that in the event of multiple conditions impacting upon anticipated failure conditions it is desirable to construct and incorporate cross-correlation algorithms (matrix of cause and effect) into diagnostic systems.

In the industrial and manufacturing arenas, prognosis is interpreted to answer the question: What is the remaining useful lifetime of a machine or a component, once an impending failure condition is detected and identified? Vachtsevanos and Wang [2001].

Any prognosis model presents two challenging issues: How do we 'measure' the growth of faults and how do we 'predict' the remaining useful lifetime of such a failing component or machine? Vachtsevanos and Wang [2001]

Byington et al. [2002] state that prognostic algorithms can be generic in design but specific in terms of application. He identifies groups such as, Machinery Information Management Open System Alliance (MIMOSA), that have brought their feelings and ideas together to develop open-system standards relevant to Condition Based Maintenance and Prognostics and Health Management development, forming the International Standards Organisation (ISO/TC 108/SC 5) committee.

Examples of computerised process/machinery monitoring systems incorporating diagnostic and/or prognostic capabilities include: a system developed for use on a turbine –based cogeneration system, described by Biagetti and Sciubba [2004], and a system developed for use in a smelter, described by Jounela et al. [2003].

2.4.3. Sensory data extraction and data processing

Before condition sensory feedback gathered using CM equipment can be communicated to users, it goes through the following sequence of events:

- Post processing aimed at filtering out unwanted signals identified as interference, otherwise referred to as noise.
- Transferred for storage onto a database or some other digital storage device.
- Extracted from the database on the command of a structured query language (SQL) request.
- Post processed and communicated to users through a method of human computer interaction, e.g., a Graphic User Interface (GUI).

Research published by Kennedy et al. [2000] describes the methods associated with extracting post processed CM sensory data stored within a database, generating web pages and displaying them through an Internet Browser Graphic User Interface (GUI). He identifies post processing techniques and data storage arrangements, as greatly influencing the technique used within CBM system's software, for presenting data to users. His group developed an experimental Internet CBM system represented in Figure 2.4.

The system represented in Figure 2.4 presents component and process information through web pages, using simple Hypertext Mark-up language (HTML). Interaction between users and the Internet CBM system is performed by Active Server Pages (ASPs). ASPs programmed using VBScript and JavaScript, working behind the scenes within the Web server, offer flexibility to system designers. They carry out programmed instructions within the web server, define how the HTML is assembled and presented to users, providing users with the power to interact with the User Interface (UI) and make choice selections. Displaying component or process-monitored information in this manner can be performed automatically by embedding a timer in the web page, a useful function when monitoring in real time.

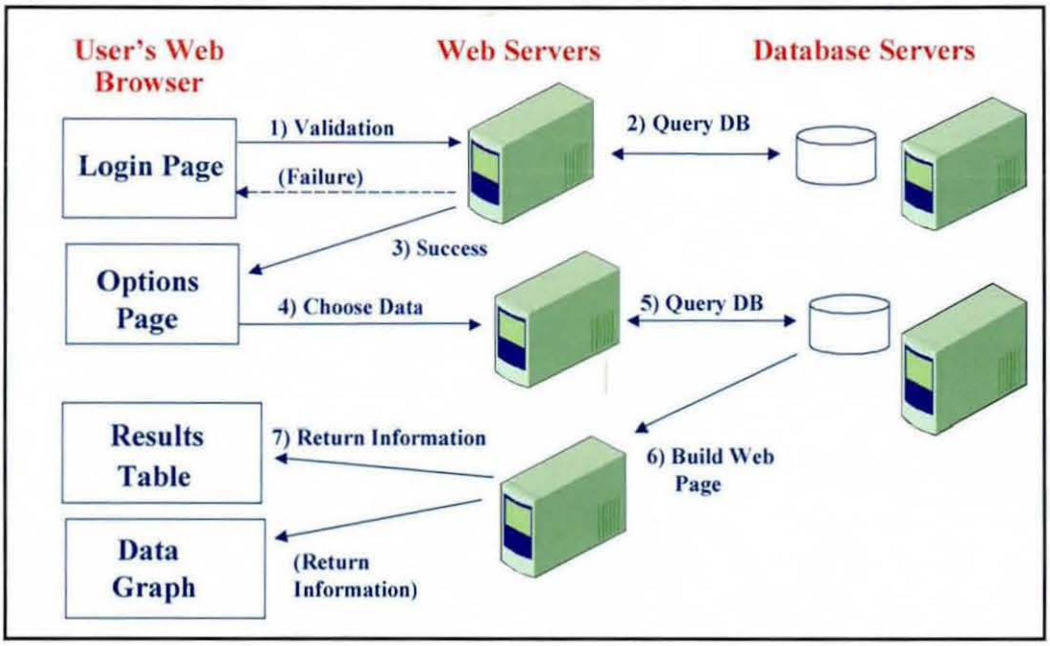


Figure 2.4. Logical representation of how information is extracted from an intelligent process monitoring system, Kennedy et al. [2000].

Handing the task of data processing to web and database servers and presenting information through Browsers, represents a move from Thick Client to Thin Client. A thin client relationship represents minimal specialised software requirements at the client end, thus a plant can be monitored from any computer in the world equipped with a web Browser and an Internet connection. As much as possible, the processing required by the client to view and interact with a service must be undertaken on the server itself. Thus the burden of providing adequate performance lies solely in the hands of, and therefore under the control of, service providers, Kennedy et al. [2000]. Since web Browsers can operate on many different platforms from Windows to Linux, remote access to web server hosted CBM systems, opens up to multiple users working on any type of operating system, equipped with an Internet Browser.

Examples of presentation flexibility include:

- Linking user name login access rights to web specific addresses and navigational rights once inside a web site.
- Building user association intelligence into the web server, providing users with a degree of personal control towards the information automatically loaded onto their Browser, on first entering the web site.

- Displaying process and machine information back to users in a far more graphical manner, using an interactive spreadsheet. This is performed using Java Applets and Servlet programs.

Archer and Tuan [1995] describe how mobile telephone User Interface Designs (UIDs) have been simulated using multi media authoring packages, as well as hardware prototypes. Emphasis is placed on selecting a suitable simulation technique for the task at hand in the first place. Further discussion concerning the application of a mobile CBM system is provided in section 2.10, GUIs for Internet and Mobile Applications.

Simulating and testing a UID during the design process and prior to system roll out, on a group of employees is highly recommendable. For example, systems operated using a User Interface (UI), rely upon a user's ability to interact appropriately through the UI and make correct decisions. Simulating a UI therefore improves the success rate of workable UID. Further discussion concerning simulation and usability testing is provided in section 2.9, User Interface Design and User Interface Standards.

2.4.4. Summary

CM technological advancements are being driven for financial reasons. Businesses consider Condition Based Maintenance as an opportunity to reduce the number of machine breakdowns through a process of diagnosis and prognosis, aimed at improving maintenance scheduling, improving inventory control over machine spare parts, and extending machine life. Key technologies being improved upon within CBM systems are diagnostics, prognostics, sensors, data filtering and post processing, and data presentation. CM architectures are discussed in the next section.

2.5. Condition Based Maintenance Design Architectures

Three CBM architectures: localised, remote and Internet, are discussed. Distinguishing between the different architectures helps the reader recognise and appreciate implementation implications, when deciding which CBM architecture best suites their business's requirements. RM's requirements include implementing a CBM system with local access capabilities for maintenance engineers and possibly machine operators at mail centres around the country, as well as remotely to operational and management staff located at sights other than where machinery being monitored can be found.

2.5.1. Localised CBM

Localised CBM of machinery involves periodically using manual or automated techniques, e.g., taking dial/digital readings from instrumentation, reviewing graphical plots, examining test samples, or by down loading data to a plug in hand held device. Monitoring and subsequent decisions are taken at the site location the machinery being monitored resides. Localised CBM is the most popular architecture, because it requires the least resources, is easier to control and manage, and quickest to set up. Decisions based on localised CM information will be taken immediately by the maintenance engineer collecting the data, or some time later following further scrutiny and analysis by interested parties. Figure 2.5 illustrates the architecture for localised CBM.

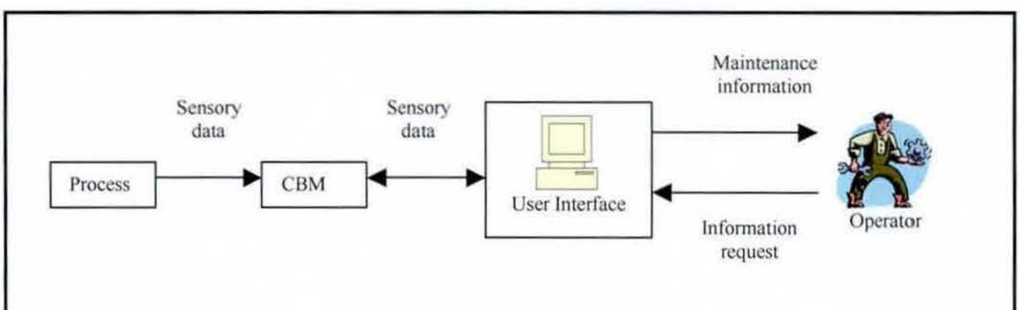


Figure 2.5. Architecture for a localised CBM system.

2.5.1.1. Advantages of localised CBM

- Requires the least amount of resources, e.g., a hand held CM device and a trained and capable operator.
- Low initial costs.
- Quickest form of CBM to adopt and integrate into an organisations existing maintenance working practices.
- It brings an operator into direct contact with the machinery being monitored. Coming into direct contact with machinery, places a person in a position to use their own sensory capabilities to assess and judge a situation. Therefore the heuristic maintenance decision-making process potentially becomes a combination of human sensors and technological CBM instrumentation.

2.5.1.2. Disadvantages of localised CBM

- Not suitable for situations considered too hazardous for human machine close contact.
- In most cases localised CBM requires a human to be in attendance whilst the machinery or process are monitored, tying up a valuable resource and adding to labour costs.
- Condition Monitoring is performed at predetermined intervals, not in real time. Transferring / downloading condition-monitoring data onto other business systems for further analysis is a manual process.

2.5.2. Remote CBM

Remote CBM systems can be either standalone or networked to another business system/s. Remote CBM involves monitoring the condition of a component at a location away from the immediate vicinity of the component in question. Monitoring will be undertaken automatically or manually depending upon the systems capabilities at intermittent time periods. Diagnosing the condition of the component/s and predicting remaining satisfactory working life may be either automatic or manual, again depending upon the systems capabilities. Figure 2.6 illustrates the architecture for remote CBM.

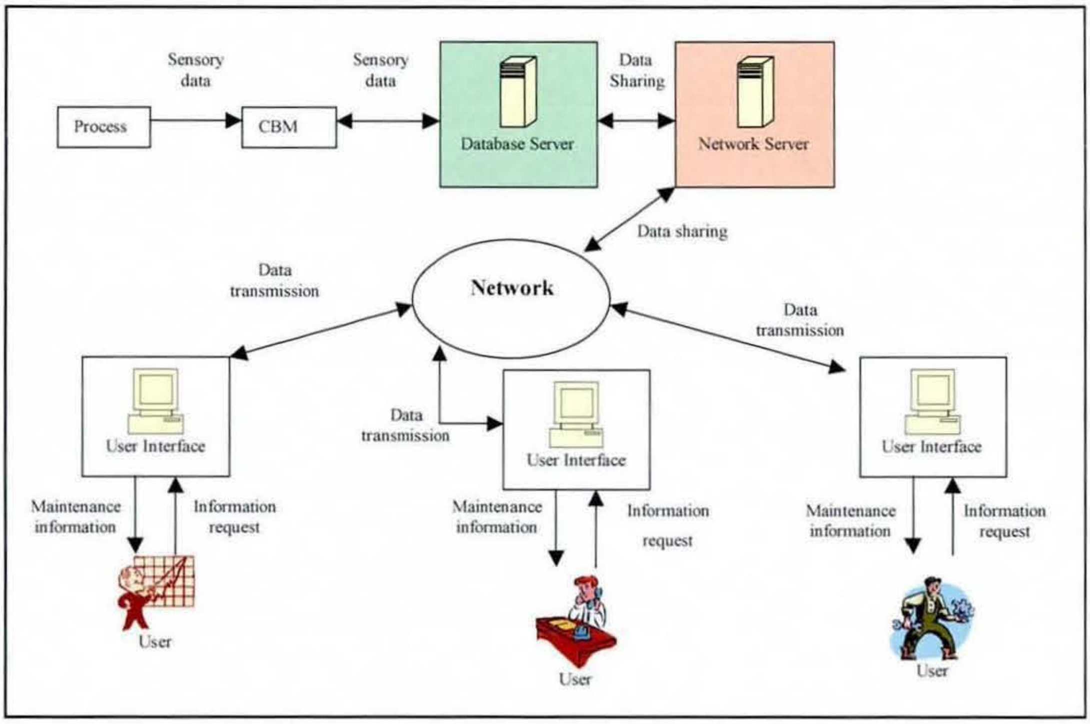


Figure 2.6. Architecture for a remote CBM system.

Marquez et al. [2003] description of a remote CBM system for monitoring the performance of railway junction points is a good understandable example of remote CBM. A localised CBM option is not a practical option because of the widely dispersed distribution of automated rail junctions. What is needed is a remote CBM solution, designed to integrate with rail track's network computerised control centre.

Providing remote CBM solutions is not always possible due to difficulties in placing sensors in hard to reach machinery and plant locations, electrically noisy environments, and mobile applications, where wires cannot be installed. Advancements in wireless sensors discussed by Zorriassatine et al. [2003], present opportunities to overcome these difficulties, opening up further possibilities for remote CBM.

Providing access to CM information through a network provides opportunities for departments other than maintenance to be influenced by machine performance data. Departments such as: Purchasing, Production/Operations, and Inventory Control/Stores. Viewed from a broader perspective networking CM information offers opportunities for smoother departmental integration, assuming the information is understood and correctly applied by all concerned. Devices for communicating remote CM information to users include: Computer system GUIs, mobile phones and other mobile devices. Designing effective GUIs for mobile devices is discussed later in section 2.10, GUIs for Internet and Mobile Applications.

Royal Mail's present maintenance system described briefly in chapter 5, reflects upon the need for remote CBM capabilities as well as localised capabilities. Day to day maintenance monitoring by maintenance engineers and machine operators, necessitates localised CBM. Machinery performance analysis on a nationwide scale and maintenance task identification, based upon accumulated knowledge, necessitates remote CBM.

2.5.2.1. Advantages of remote CBM

- It doesn't require a human to be in attendance at the machine/process whilst CBM readings are recorded, freeing up labour for other duties.
- Makes real time CM a reality. Real time CM reduces the time interval between identifying failure conditions, and taking corrective action.
- Networked remote CBM systems provide access to CM information for multiple authorised users, increasing information sharing.
- Provides a greater likelihood that departments other than maintenance will be influenced by maintenance information, removing machine process performance uncertainty.
- User authentication and password access offers the potential for faster decisions based on maintenance information. User access authentication provides the opportunity for presenting users with information relevant to their own needs and requirements, nothing else.
- Remote CBM systems are able to incorporate user interfaces with a large choice of information analysis options. Providing date data selection, data sorting, data filtering and presentation style options, offers users information analysis choice. Increased data analysis improves operator machine and process performance awareness, which should in turn improve maintenance decision-making accuracy.

2.5.2.2. Disadvantages of remote CBM

- Remote CBM is limited by restrictions applicable to the robustness and reliability of fixed sensors Fixed sensors positioned permanently within machinery, recording component conditions, may be subject to high electrical interference, excessive vibration, wide ranging temperature vibrations and changing atmospheric conditions, caused by the machinery or environment they are located in.

- Making CM information accessible to multiple users could potentially slow down the maintenance decision process. Differences in opinion amongst multiple individuals can lead to long drawn out debates, which may or may not provide added benefit to the final decision.
- Networked information is more susceptible to security breaches.

2.5.3. Internet CBM

Internet CBM is a term used to describe a web site providing access to CM information over the Internet through a compatible Browser. Providing access to CM information over the Internet is a form of remote CBM. Internet CBM enables authorised personnel to monitor the performance of machinery or processes from any where in the world with an Internet connection of satisfactory speed and a compatible Browser. Figure 2.7 illustrates the architecture for an Internet CBM system.

Security measures designed to stop unauthorised access to a companies computer maintenance management system (CMMS) or any Internet accessible business system includes: the inclusion of authentication user name and password, PC and network firewalls, and document encryption. Authentication recognition also offers the possibility to control user access rights once entry to a business web site has been approved, in much the same way as an administrator sets user access rights for users on a network. Jennings et al. [2002] illustrates this by considering a factory environment. Different users of a CMMS require different information from the system in order to perform there given duties. For example, a machine operator will only be interested in data referring to the machine, while a manager may be interested in a manufacturing area. The same situation applies within Royal Mail.

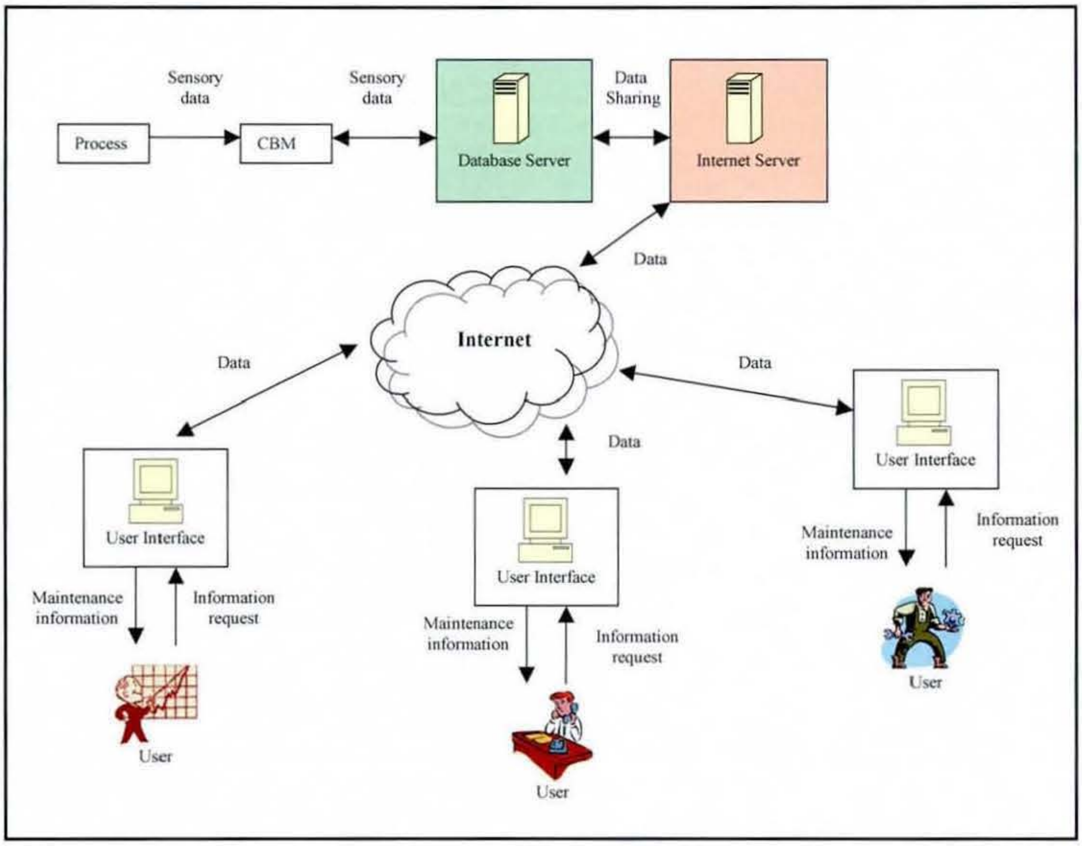


Figure 2.7. Architecture for an Internet CBM system.

Various literatures are available describing design considerations for Internet CBM systems. Jennings et al. [2002] describes the advantages of using dynamic web pages instead of static web pages; web pages designed to actively query CBM database repositories, using active server pages (ASP), providing users with Internet data query on request capabilities. Kennedy et al. [2000] provides further explanation by describing the operation of ASPs. ASPs driven using VBScript and JavaScript working behind the scenes within the web server, offer flexibility to system designers. They carry out programmed instructions within the web server, define how HTML is assembled and presented to users, providing users with the power to interact with the UI and make choice selections. Further ASP generation techniques include the inclusion of active data objects (ADO) as mentioned by Orsagh et al. [2000], and Aglets, as described by Yu et al. [2003]. Friedman [2003] describes the importance of database replication and database synchronisation for Internet CBM systems, where data is stored on more than one database and may be updated at any time by multiple sources. Database changes made include test configurations, alarm criteria or even edited reports. Database synchronisation allows information to be managed from afar.

Examples of Internet CBM systems include descriptions by Lee [2001] and Orsagh et al. [2000]. They explain how vibration or process levels are transmitted over the Web and presented to the end user as gauges, reporting the condition of the remote machine in real time. Additionally graphs and tables showing machinery component performance trends, anomalies, and diagnosed faults, are automatically generated and displayed using ASP. Kunze [2003] takes the concept of presenting machinery component data to users through web pages a step further with an online diagnostic laboratory. His system represents a CBM Internet application designed to extract sensory data from numerous machines, offering users the capability to perform comparative data analysis.

Lopes et al. [2002] discuses a system for intelligent on-line condition supervising, named AD4. The system receives vibration data through an Ethernet network linking CBM systems fitted to machinery located on oil plants and offshore production platforms. The system operates in accordance with the steps below:

- Continuous online monitoring of equipment to determine actual mean time to failure.
- Historical data capture and storage e.g., 4 times daily data is captured and stored to hard drive.
- Transfer of data via an Ethernet Network for remote access over the Internet.
- Data processing using neural networks for verification of data quality.
- Data categorisation, representing the extent of a foreseeable component failure.
- Triggering of alarms for urgent concerns.
- Scheduling machine down time for maintenance according to severity of wear.

Details of the UI developed for the AD4 system described by Lopes et al. [2002], are adapted to form a list of possible system requirements for a remote CBM Human Machine Interface for Royal Mail. The list and associated flow diagram, shown in Figure 2.8, follow below:

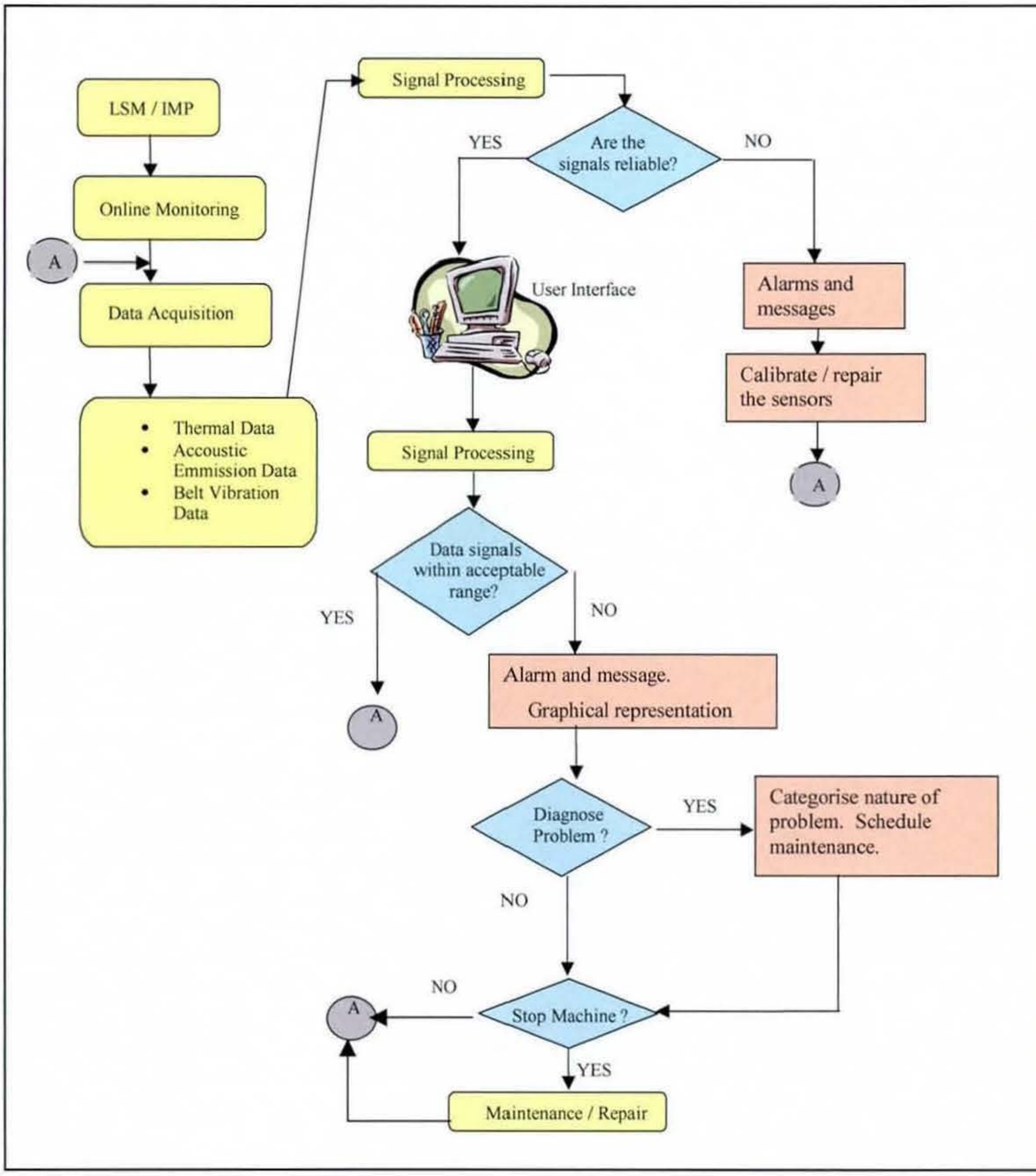


Figure 2.8. Flow diagram depicting system procedures for a remote CBM system for monitoring Letter Sorting Machines and Integrated Mail Processing Machines.

- Visual representations of the Letter Sorting Machines (LSM) and IMP machines present an operator with a familiar image when locating a detected problem area.
- Graphical representation of data, e.g., bearing noise, bearing temperature, belt slip, belt vibration, belt temperature, motor temperature.
- Upper and lower limits incorporated into graphs displaying machinery condition parameters.
- Fault diagnosis through either a trained Neural Network, or a Knowledge Base, and or integration with reference to Royal Mail's Knowledge Hub.

2.5.3.1. Advantages of Internet CBM

- The same advantages identified for remote CBM, listed under section 2.5.2.1.
- Provides access to a companies CM information from any computer in the world with an Internet connection and a suitable Browser.

2.5.3.2. Disadvantages of Internet CBM

- The same disadvantages identified for remote CBM, listed under section 2.5.2.2.
- Performance of Internet CBM systems cannot be guaranteed because the Internet is not a controllable environment.
- There is always a security risk of unauthorised access into a companies computer system if connected to the Internet.
- Complex to set up and manage, requiring experts advice and knowledge in multiple disciplines.

2.5.4. Summary

Three CBM architectures have been discussed, localised CBM, remote CBM and Internet CBM. Deciding which CBM architecture to adopt should be undertaken shortly after the business decision to adopt predictive maintenance. Considerations to take into account when deciding which CBM architecture/s to adopt include: the available (maintenance) budget, the type of machinery being monitored and the environment the sensors will be located in, the number and location of machines to be monitored, the ability and availability of resources, integration factors associated with existing maintenance practices and strategies, and the impact on other business practices. Localised and remote CBM architectures are both likely candidates to meet Royal Mail's requirements. Remote and Internet CBM both require considerably more investment, resources and time than localised CBM.

2.6. Human-Centred Design (HCD), Human Factors (HF) Principles and User Profiling

Involving existing and intended users of a system during the design, development, test, and implementation phases of a product is the main theme when applying HCD, HF principles and User Profiling. Each approach will be introduced and discussed as a method to follow during the design of a software application and a UI, for a CBM system.

Maguire [2001] describes HCD as representing a process of incorporating the user's perspective into the software development process in order to achieve a usable system. Kontogiannis and Embrey [1997] liken this to designing for users with users.

Principles of HCD applicable to software design, development and testing are summarised by Maguire [2001] in the bulleted list below:

- Active involvement of real or substitute users during the design and development phases. Involving end users can enhance acceptance and commitment to new systems. Staff come to feel that the system is being designed in consultation with them rather than being imposed on them. Appreciating what information is required to make decisions in each users own authorised area, forms part of the process. Reference to examples using real or substitute users, during design and development of Human Computer Interaction (HCI) devices, is discussed by Clemmensen [2004].
- An appropriate allocation of function between user and system. If an old system is being modernised, user participation in the design process can help to pass positive aspects of the old system into the new one, and ensure that the new operating practices are compatible with well-established working methods.
- Iteration of design solutions. Iterative software design entails receiving feedback from end-users following their use of early design solutions, e.g., beta software releases.
- Multi-disciplinary design teams. Teams might consist of managers, usability specialists, end-users, software engineers, graphic designers, interaction designers, training and support staff and task experts.

Standard (ISO 13407) identifies 5 essential processes that should be undertaken in order to incorporate usability requirements into the software development process:

- Plan the human-centred design process.
- Understand and specify the context of use.
- Specify the user and organisational requirements.
- Produce designs and prototypes.
- Carry out user-based assessment.

Each process should be performed in an iterative fashion as depicted in Figure 2.9, the cycle being repeated until the final level of usability is attained.

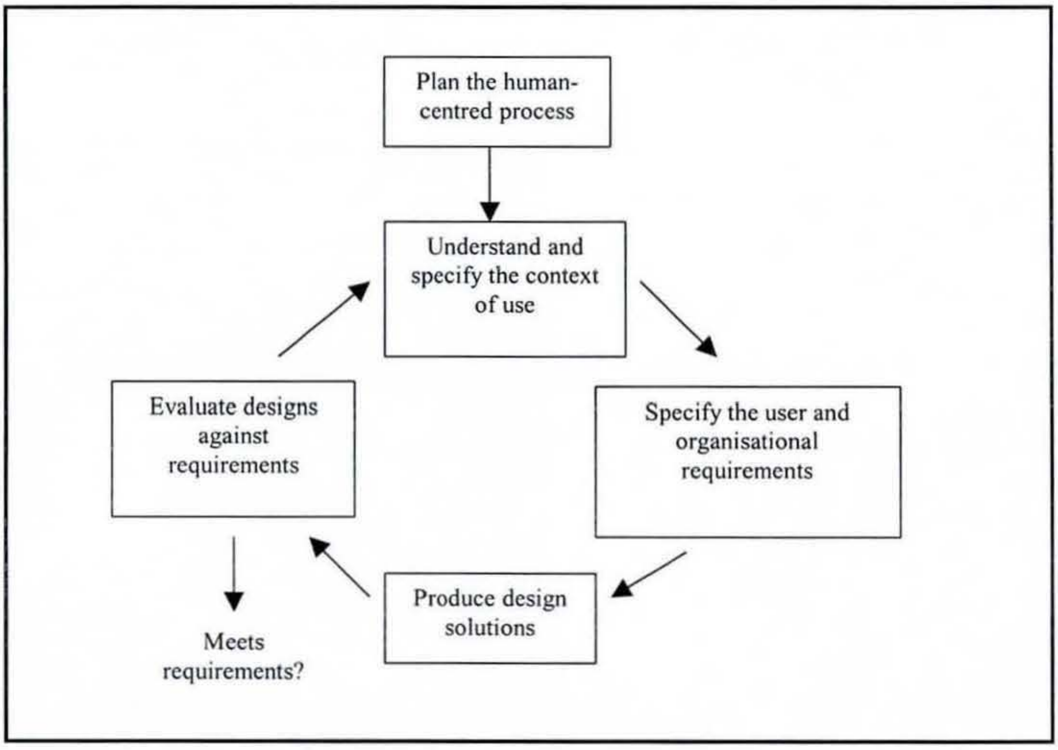


Figure 2.9. The human-centred design cycle, from ISO 13407.

Harnden [2001] says, identifying user requirements prior to designing the UI is critical for setting the usability requirements of a graphical user interface, because different users demand different interaction styles.

A case study presented by Kontogiannis and Embrey [1997] lists a series of steps as part of a HCD project. The steps listed below appear equally applicable to the development of a human system interface for a remote CBM application at Royal Mail.

- Observation of control room operations.
- Interviews with operators from all shifts along with technical specialists.
- Analysis of operating procedures.
- Analysis of incidents described by operators.
- Analysis of incidents documented in plant records and international databases.

2.6.1. Benefits of HCD

- User participation helps evaluate the impact of new technologies, not only on interface design, but also on other job aspects, such as staffing levels, allocation of tasks, and new policies for operational aids and training to ensure acquisition and retention of skills, Kontogiannis and Embrey [1997].
- If an old system is being modernised, user participation in the design process can help to pass positive aspects of the old system into the new one, and ensure that the new operating practices are compatible with well-established working methods. User participation will also generate a feeling among the workforce that the new system is an evolution of their own efforts and expertise, and this may result in greater acceptability and commitment in making the new operational practices work, Kontogiannis and Embrey [1997].
- If people determine that they can use a system to complete their current job assignment, or are given meaningful new work to perform with the system, they will be more motivated to use the system. In as much as usage leads to enhanced ease of use, the availability of meaningful work should contribute to improved ease of user perceptions, Zanino et al. [1994].
- Involving users in the design and development process is more likely to result in a workable solution, capable of exhibiting characteristics that are consistent with a user's real-life experience. For example, an interface design that is consistent with a users real-life experience is more likely to lead to better performance by facilitating automatic processing, Lim et al. [1996].

- Integrating Human Factors advice with user participation early in the design process improves the prospect of matching operator capabilities, and gaining the acceptance and commitment of the workforce, Kontogiannis and Embrey [1997].
- A high level of usability via human-centred design is the key to future commercial success for the myriad of IT systems, consumer and PC software, Internet and on-line services and telecommunications products being developed, Maguire [2001].

2.6.2. Disadvantages of adopting a HCD approach

- Distrust from management towards involving users so openly in the design and development process.
- A discontented workforce if they perceive that their input will have no impact on the decision-making process or their task environment, Kontogiannis and Embrey [1997].

Both disadvantages contradict earlier stated advantages. True because benefits resulting from collaborations between management / system developers and the work force / intended users, depends upon the relationship between the management and the workforce. If the relationship between the management and the workforce in a company (department) is good, management are likely to be trusted and therefore user involvement during HCD is greatly beneficial. Equally so, good relations leads to a work force more likely to perceive their input during the design stage, if called upon, will be incorporated in design decisions and therefore feel it is worth putting forward. However, the opposite is true if the relationship between the management and the workforce is poor. The benefits and disadvantages of user involvement during HCD is therefore proportionally linked to the state of the management workforce relationship. One might assume however that companies with poor management workforce relationships would rapidly go out of business in today's competitive environment.

2.6.3. Developing user interfaces using HCD and HF principles

Kontogiannis and Embrey [1997], suggests that adopting a Human Factors approach to interface design will focus effort on examining how information is structured on a computer screen, the degree of process automation, and the implications for skill retention and transfer, job aids and training.

Still of relevance today, Norman [1983] explains that it is essential to analyse separately the different aspects of human-computer interaction. Detailed analyses of each aspect of the human-computer interface are essential, but because design decisions interact across stages and classes of users, the question must be asked, for what purpose is the system to be used, and determine how best to accomplish that goal. Only after the global decisions have been made should the details of the interface design be determined.

Hori and Shimizu [1999] present a paper describing design methods for the development of human interfaces within a centralised supervisory control room. Human Factors engineering and Cognitive Engineering are both applied in achieving their final recommendations. Their work tackles the task of designing a supervisory control centre following the transition from distributed control to centralised control. Transitions popular in power plants, railway and traffic supervisory control centres, iron and steel plants, drainage pump plants, and chemical plants. Transitions of this nature result in the amalgamation of information sources and labour reductions. Resulting computer systems have to process and display much more information to fewer personnel. Of particular interest is discussion describing the steps involved in human interface design; the design methods for the specification and layout of hardware in a Supervisory control room, and the screen construction for supervisory control software. Hori and Shimizu [1999] apply a methodology known as decision-making trial evaluation laboratory (DEMATAL), to design and evaluate the structure and layout of user interface screens. Steps followed in this methodology include:

- Evaluating the relationship between sets of paired supervisor control user interface screens, in terms of the frequency and direction of mutual operator eye movement.
- Create a matrix exposing the relationship between the operator eye movements and the various user interface screens, during the course of operators' normal day-to-day duties whilst manning a supervisor control centre.
- Define the relationships between the various screens and an operators eye movements, based upon the sum of lines and sum of rows for the matrix.

2.6.4. User Profiling

Harnden [2001] describes User Profiling as a process for discovering the characteristics of your target user population. Ordinarily User Profiling is conducted by formally surveying a statistical representative sample of the user population, or by interviewing a few 'expert informants' who are familiar with the needs and characteristics of a range of users. Characteristics the survey should aim to identify may vary, but should include:

- Job function.
- Demographics such as age, gender, and education.
- Computer (and/or web) related attitudes, motivations, and expertise.
- Business skills and experience (including language skills, typing ability, and knowledge of specific business rules pertinent to the application being designed).
- Physical characteristics (such as visual acuity, colour-blindness, dexterity, or other special needs).

It is advisable to identify a user populations profile prior to designing a UI. User Profiling will improve the prospects of identifying every sensible user requirement that should be incorporated into the UI design. Information gathered through User Profiling will enable designers to identify categories of users, who will be using the system most frequently, or who require specific functions to be incorporated into the UI, thus concentrating the most efficient allocation of your development resources. It is a good idea to reassess your user profile periodically, because demographic or economic shifts may alter the requirements of your user population.

2.6.5. Summary

Understanding user requirements and building them into the design process prior to product release increases the probability of user acceptance. Knowing user requirements provides designers with targets and design specifications to work with. Various methods have been discussed aimed at identifying user requirements including: surveying a cross sectional representation of intended users in order to establish user profiles, including intended users in the design process, examining documented literature (if it exists) related to the design in question, and testing design ideas and prototypes on users prior to release.

Incorporating HCD, HF principles and User Profiling ideas into the design and development of a CBM UI improves the prospects of creating a useable and therefore accepted product.

2.7. Cognitive Engineering and Schema Theory

Cognition is defined as acquiring knowledge and schema defined as a process of formulating a plan. Combining cognition and schema together can be considered to be an act of constructing order out of knowledge. Cognitive Engineering applies to the process of breaking a product into its individual constituent parts, for detailed analysis and understanding. Schema Theory, introduced by Bartlett [1995], considers how easily the human mind can construct understanding from knowledge acquired through human sensors.

Chalmers [2003] and [2000], explains that schemas are generally thought of as ways of viewing the world and in a more specific sense, ways of incorporating instruction into our cognition. Reason [1990] describes schemas as the creation of high-level knowledge structures that support any aspect of knowledge and human skills. Understanding and applying Schema Theory can prove useful in order to improve a users ability to construct a schema and speed up a users' ability in orientating through a UI. Once the human mind has established a set of schemas for a known situation, they gradually become fixed and ingrained. Unfortunately fallibility exists with this behaviour, referred to as negative transfer. Negative transfer occurs when existing schema patterns already memorised from previous tasks, are associated with a new task incorporating unfamiliar problems. In this situation, operators run the risk of applying previous knowledge incorrectly to try and solve new problems. Besnarda and Cacitti [2005] linked negative transfer as attributing towards an industrial accident resulting in an operator's death, caused by the incorrect use of a modified Human Machine Interface. Authors of further work concerning schemas include: Bernstein et al. [2003], Satzinger et al. [2002], Piaget and Smith [2000].

Cognitive load is another cognitive learning theory. Cognitive load is a term used to describe the amount of information processing expected of the learner. Intuitively, it makes sense that the less cognitive load a learner has to carry, the easier learning should be. Chalmers [2003] goes further to explain how learners construct knowledge based on previous knowledge and that learners transform information, construct hypotheses, and make decisions based on their previous cognitive structures.

Lim et al. [1996] describes the cognitive activities when working with a UI as: "Remembering and mapping instructions and icons, formulating goals, and developing action plans". He further emphasises that a task (UI interaction) can be decomposed into perceptual activities, cognitive activities, and motor activities. Perceptual activities include reading instructions and the icons. Motor activities include moving the mouse and dragging (or clicking on) icons.

Three cognitive abilities, namely: Working Memory, Visual Memory, and Flexibility of Closer, were considered by Gwizdka and Chignell [2004] whilst testing users abilities to manage and extract information from two email handling software packages. Their results indicate higher levels of each cognitive ability have a beneficial effect on performance times. Their results also highlight the importance of considering alternative GUI designs, for different population groups and for different tasks, which accommodate individual differences in ability.

Numerous articles have been written supporting the application of Cognitive Engineering methods for the design of complex human-machine systems, including: work by Woods and Roth [1988], Kontogiannis and Embrey [1997], Hoffman et al. [1998], and Roth et al. [2002]. Each described approach typically includes in-depth data collection through interviews of domain experts and observation of practitioner systems, operator, and task modelling. Knowledge acquired through data collection helps identify system and task demands operators encounter during human machine interaction. Resulting outputs include: function allocation, design of interfaces for the control of information systems, task definitions, and training requirements. Resulting outputs help identify design solutions for human-machine systems, Bisantz et al. [2002].

Kontogiannis and Embrey [1997] describe a Cognitive Engineering framework for matching system demands and cognitive processes, for examining GUI design in the context of system demands, cognitive processes and problem representations. They explain how user participation can contribute to both the analysis of machine interactions and the acceptance of design decisions. Their discussions suggestion new systems should not be introduced simply to catch up with technological advancements, but support operators in their tasks. This assumes that the task and business objectives remain on a similar track. To this extent, system demands, operator tasks and psychological processes must be studied in depth using a Cognitive Engineering approach. The Cognitive Engineering approach known as, "The Think Aloud Method", is discussed by Jaspersa et al. [2004]. They used this approach whilst developing a GUI for a paediatric oncologist's software application.

2.7.1. Summary

Cognitive Engineering and Schema Theory combine the mental process of gathering and making sense of information, through human senses. Techniques of Human Computer Interaction (HCI) designed with due consideration for Cognitive Engineering and Schema Theory, will exhibit intuitive design characteristics. For example, braking down a method of HCI into its individual elements and activities exposes the detail behind the process of HCI. Arranging the individual elements and activities comprising the method of HCI into an ordinary easily interpretable and usable form, increases the HCI's intuitiveness. Avoiding communicating large quantities of information before decisions can be made, will reduce user cognitive load, making for faster interpretability and subsequent decision-making.

Due consideration must be given to existing design and operational procedures whilst developing new methods of HCI, in order to avoid negative transfer. Negative transfer in its most disastrous cases has resulted in tragic industrial accidents.

2.8. Human-Computer Interaction (HCI)

Questions to be answered in this section include:

- What is HCI?
- What factors influence successful HCI?
- What tools have been developed to assist HCI?
- And what does the future hold for HCI?

Leune [1995] describes HCI as a multi-disciplinary field. The main scientific contributions for HCI, come from computer science, cognitive science, work and organisational psychology, and Human Factors. However, other areas of interest include artificial intelligence, graphic design, engineering and human psychology, sociology, and anthropology. Figure 2.10 illustrates this inter-relationship.

Lim et al. [1996] makes reference to Norman and Draper [1986] findings that the interaction process between a person and a computer represents both a mental and physical activity. Physical activities relate to the motor actions performed by the user, such as using the keyboard or mouse, to provide inputs. Mental activity refers to the cognitive process associated with using the computer.

Jennings et al. [2002] pin points HCI success factors as: data storage, extraction and presentation, e.g., as the size of database tables increase, so does the time to run a query, extract data, build it into HTML web pages and present it to users through a GUI.

Leune [1995] makes reference to Nielsen's [1993] recommendations that effective HCI should exhibit five usability attributes:

1. Learnability: The system should be easy to learn so that the user can rapidly start getting some work done with it.
2. Efficiency: The system should be efficient to use, so that once the user has learned the system, a high level of productivity is possible.

3. Memorability: The system should be easy to remember, so that the casual user is able to return to the system after some period of not having used it, without having to learn everything all over again.
4. Errors: The system should have a low error rate, so that users make few errors during the use of the system, and so that if they do make errors they can easily recover from them. Further, catastrophic errors must not occur.
5. Satisfaction: The system should be pleasant to use, so that users are subjectively satisfied when using it, this means that they like it.

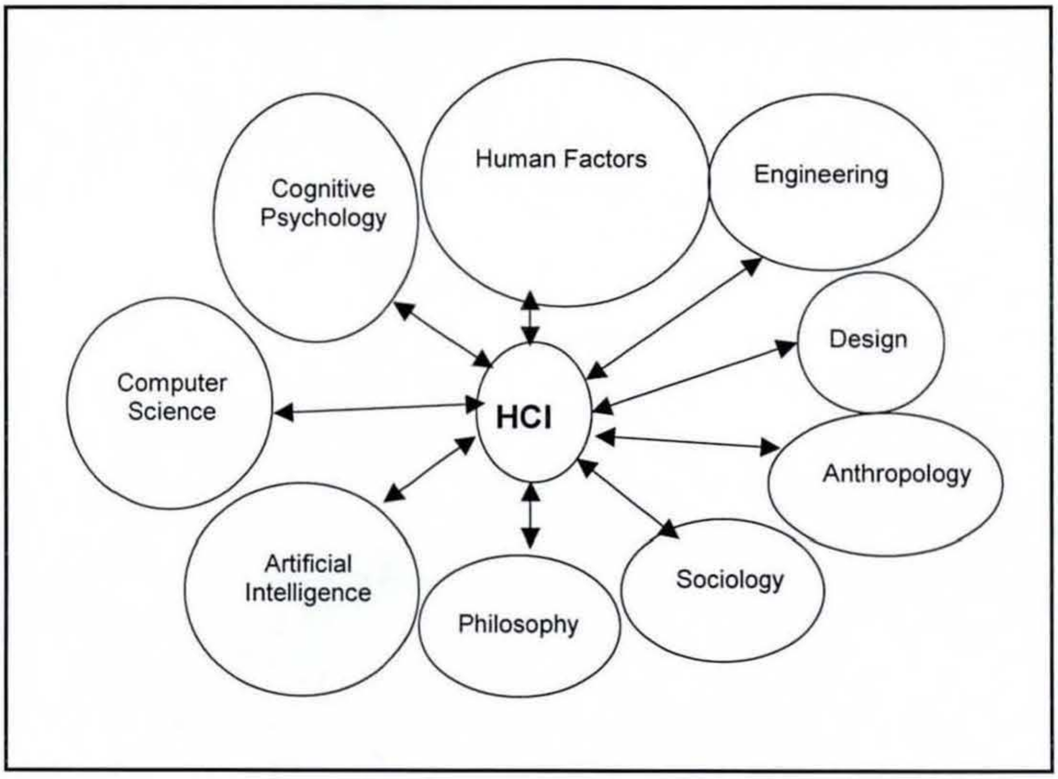


Figure 2.10. Disciplines contributing to HCI, Leune [1995].

Leune [1995] makes further reference to the fourth usability attribute, errors. Handling errors is an essential responsibility of the human-computer interface. Error messages should be informative and give the user insight into what caused the error so that he can learn from his mistakes and repetitions can be avoided.

Designing Human Computer Interfaces for large corporations adopting centralised control requires changes in the type of information and manner information is displayed through a UI. Hori and Shimizu [1999] present a list of typical design considerations for plants located over a wide area, or a large-scale plant that has much equipment or many instruments, very much the same is true at Royal Mail.

- Wider human interface display areas, capable of presenting more information than traditional ones.
- Adopting a centralised cathode ray tube (CRT) display operation results in a Human Computer Interface requiring less space than the traditional one.
- Large-scale screens (LSS) such as a video wall system, helps operators to monitor information from all plants under control, and to share information between operators.
- Introducing various styles of supervisory control (SVC) systems by applying multimedia technology or using various types of display.

As well as deciding upon display types and sizes, Human Computer Interface designers and users alike should be made aware of the effect on memory sustainability and ease of reading different screen luminance contrasts have. Research by Shieh et al. [2005] found that visual performance from digital display screens increased as contrast ratios increased up to 1:8 and then degraded once the contrast ratio was greater than 1:8. They also concluded that higher luminance contrasts (1:15) might interfere with higher cognitive activities.

Numerous techniques and tools have been developed to assist HCI, including:

- Hypertext, a computer-based medium to support thinking and communication. Hypertext allows and encourages a writer to make reference, and allows a reader to make his own decisions about what links to follow and in what order, Leune [1995].
- Direct Manipulation using objects and icons.
- Interface Agents. Computer programs that have the ability to learn user preferences and working habits, and to provide proactive and reactive assistance in order to increase the users productivity, Schiaffino and Amandi [2004].
- Animated characters. Designed to offer similar capabilities to computer agents, but in a more anthropomorphic manner, exhibiting greater interactivity than through question and answer capabilities, Rickenberg and Reeves [2000].

- Process visualisation using three dimensional (3D) process virtual representation, Wittenberg [2004].
- Fold up qwerty keyboards capable of plugging into mobile phones and PDAs, described by Curran et al. [2005] as essential for improving speed and accuracy of data entry.

Myers et al. [2000] suggests in the future Human Computer Interfaces will become more cinematic, with smooth transitions, animation, sound effects, and many other visual and audio effects. Bernard [1998] continues with a prediction for greater use of voice recognition and hypertext format language.

2.8.1. Human Machine Interaction

Zanino et al. [1994], describes the Human-Machine Interface, a method of HCI, as representing the most crucial element of a computer system as its design determines eventual user acceptance and utilisation.

Functional capabilities Human Machine Interfaces should include, presented by Lint [1995] include:

- Facilitating satisfactory monitoring of machines by humans.
- Support human intervention in machine operations.
- Aid human decision-making through system diagnosis and intervention possibilities.
- Establish error-free or error-tolerating operation of the full system.
- Guarantee efficient and reliable system performance.

Further design rules for HMI concerning human response time with respect to the location of controls and the use of auditory alarms, are offered by Chan and Chan [2005]:

- The relative positions of signals should be compatible with both the response key positions and the hand positions of the operators. Control–display configurations with compatibility designed in both the longitudinal and transverse orientations lead to the best performance. If compatibility can only be built in one orientation, the transverse orientation should be selected.
- Configurations requiring users to cross their hands to respond should not be used.

- For faster responses and higher accuracy, a warning before period of 2 seconds or longer should be given, to alert operators prior to the presentation of the operation signal asking for action.
- For faster responses, a visual signal is preferable to an auditory signal for requesting operator response on a control console.
- For faster reactions, auditory signals should be positioned on the right hand side of right-handed operators.

Experimental results presented by Wittenberg [2004], proved highly pictorial interfaces using 3D virtual process visualisation, are more effective than other interface designs, at representing process and machine knowledge. Since operators cannot easily visualise what is happening in a process, any design improvements such as 3D virtual process representation capable of improving intuitive understanding are welcomed. Nishitani [1996] agrees but adds, it is also important that operators use a logical approach to understanding process state at any moment in time.

A considerable amount of research concerning HMI and the design and development of Human Machine Interfaces has been completed by Johnnsen including: Johnnsen [1995], Johnnsen [1997a], and Johnnsen [1997b].

2.8.2. Summary

HCI describes the integration of a computer-controlled system with a human user. HCI represents the most crucial element of a computer system as its design determines eventual user acceptance and utilisation. Successful HCI can be attributed to, learnability, operational efficiency, operational memorability, ability to deal with errors, and operational satisfaction. Several tools designed to assist HCI have been identified including: hypertext, direct manipulation, interface agents and animated characters. In the future Human Computer Interfaces can be expected to incorporate multiple human action recognition systems, as well as smoother cinematic screens. The next section leads onto discussing user interface design, the most popular form of HCI today.

2.9. User Interface Design and User Interface Standards

In this section Graphic User Interfaces (GUIs), a method of HCI, often referred to by the shortened name, User Interface (UI), are investigated. The section begins with a list of definitions and descriptions applicable to user interfaces. Following this various design considerations and approaches aimed at assisting the design and development of UIs are described, with a look into the future of UI design. Next design rules applicable to UI design are discussed. Following this the evolution of UI standards are reported.

2.9.1. Defining the term User Interface

Definitions for the term 'User Interface' are listed below.

- At a conceptual level, a computer human interface is a means by which people and computers communicate with each other, Bernard [1998].
- Leune [1995] refers to a definition by Lewis and Rieman [1994]: 'The basic UI is usually understood to include things like menus, windows, the keyboard, the mouse, the 'beeps' and other sounds the computer makes, and in general, all the information channels that allow the user and computer to communicate'.
- The UI involves the interaction between a system and its users, which often takes place in the form of concept (or message) communication, Hu et al. [1999].
- A human-computer interface is the point of contact between the computer and the computer user, Chalmers [2003].
- Graphic User Interfaces (GUI) are computer screen displays that present information in the form of icons, or images representing objects, actions, and commands, that can be directly manipulated by the user, Zanino et al. [1994]
- Myers [1995] describes the UI as, 'the part that handles the output to the display and the input from the person using the program'.

Figure 2.11 shows an example of two UIs on one screen: Microsoft Internet Explorer and Google. As a Browser, Microsoft Internet Explorer provides a gateway onto the Internet. In this case, the gateway provides access to another user interface, Google an Internet search engine, residing on servers connected to the Internet.

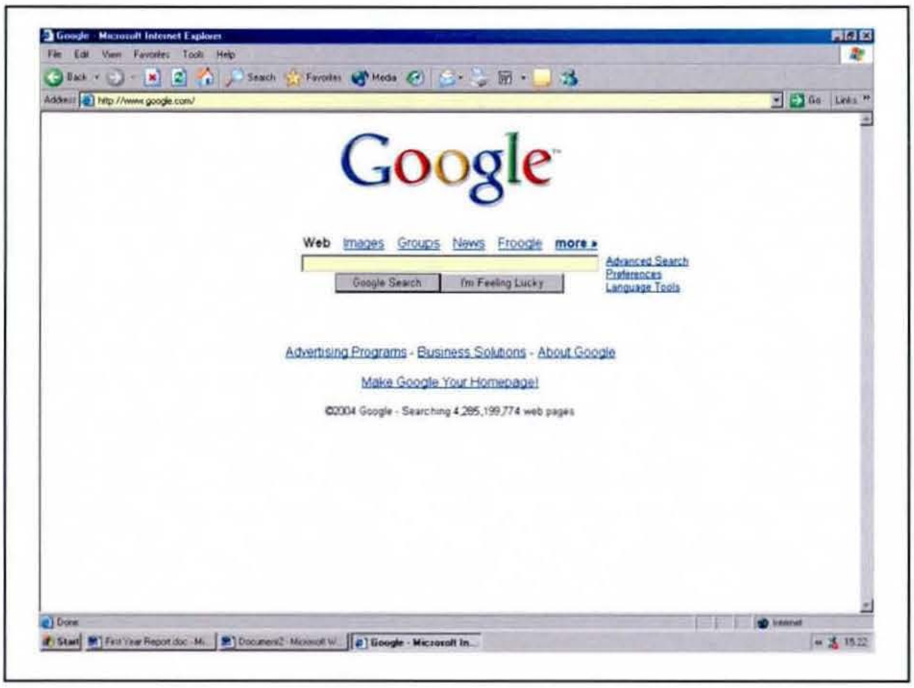


Figure 2.11. Google opened using Microsoft Internet Explorer.

2.9.2. User Interface Design (UID)

It has been quoted by Sheppard & Rouff [1994] that between 40-90% of the code making up a typical software application drives the user interface.

UID represents the top level of numerous screen design theories, identified by Chalmers [2003], to include: Screen layout, Screen consistency, Screen colours, Spatial display, Organisational methods and techniques, (Advance organisers, Outline organisers, Post organisers, Graphic organisers, Continuous organisers, Concept maps.) Each theory can be further elaborated upon by considering individual differences in computer users, e.g., Age, Gender, Level of education, affect, and motivation.

Traditionally UID is divided between presentation and dialogue. The dialogue level deals with the information flows regarding such problems as what information to handle and when. The presentation level is concerned with the problems of how to present the information to the human user, and how to transform their control inputs, Johannsen [1997b].

Zanino et al. [1994] makes the statement that, 'Users are likely to be more motivated to use a system if they can perform job-related tasks with it', i.e., it helps users with their day-to-day responsibilities.

Leune [1995] presents an iterative model developed by Preece [1993] for designing a Human Computer Interface, shown in Figure 2.12. He also suggests that breaking the task analysis into Macro and Micro, enables a design team to approach the task of developing a UI from a higher level, i.e., the number of Windows and type of information to be presented, and from a more detailed level, i.e., selecting a suitable annotation mechanism (menus, button bar, short cut keys).

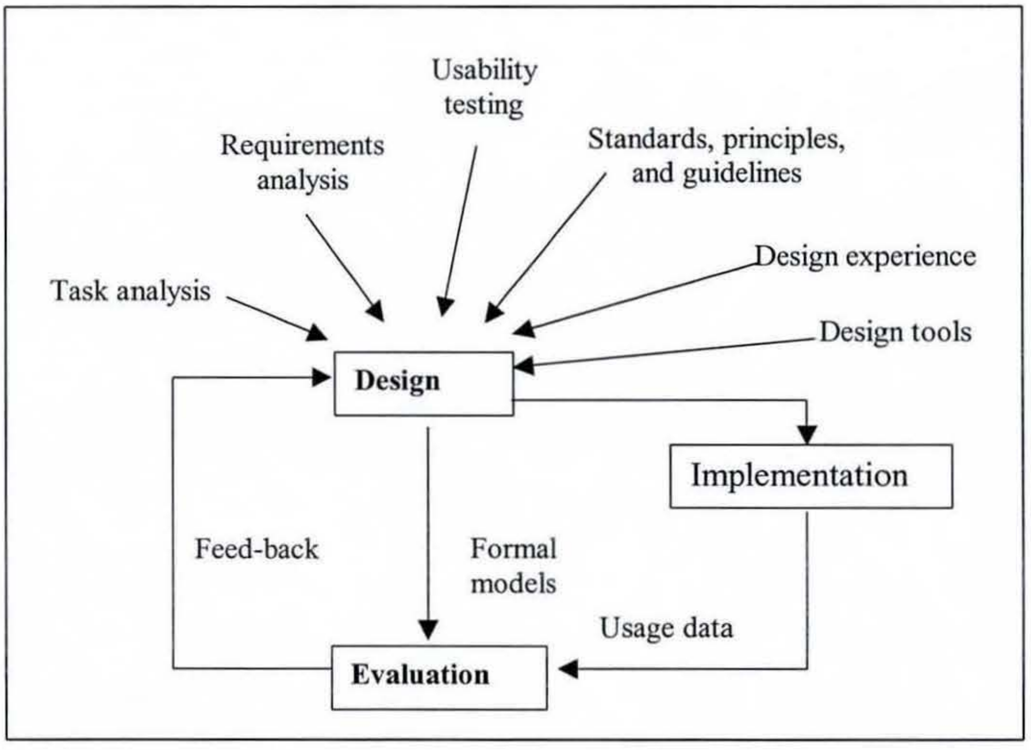


Figure 2.12. Design approach for a Human Computer Interface, Preece [1993].

Kontogiannis and Embrey [1997] identify a good interface design for human machine interaction should present system information in a format and level of detail, which facilitates the goals of the operator in solving problems. In this sense, the interface should organise and present information in a way that helps operators to formulate alternative hypotheses about the causes of a plant situation, keep mental track of their previous actions, and select appropriate strategies to control the plant. Finding an appropriate form of system representation however, is a challenging design problem since a thorough analysis of system complexity and user requirements is required. Design tool frameworks and simulation tools, notably Human Centred Design (HCD), Cognitive Engineering and iterative design, discussed in sections: 2.6, 2.7 and 2.11 offer the GUI designer possible solutions.

Jennings et al. [2002] emphasize the need for UID to present system information in a format and level of detail which facilities the goals of the person in question in solving problems. For example, a machine operator accessing a UI within a factory environment, will only be interested in data referring to the machine, while a manager accessing the same UI may be interested in a manufacturing area. Johannsen [1997a] states, 'UIs designed to satisfy multiple user classes are often referred to as multi-human machine computer interfaces'.

Myers et al. [2000] and Myers [1998] present a look into the future of UID. In the future, screens will vary in size from cell phone displays (60×80 pixels at about 5 centimetres in diagonal) up to wall-size displays. Figure 2.13 illustrates a Palm mobile device and interface. Today's UI functionality is not likely to be suitable for tomorrows technology. For example, pull-down menu bars cannot generally be used, since they may not fit on small screens, and on large touch sensitive screens they might be too high up the screen for small people to reach. There are starting to be examples of real 3D volumetric displays that will clearly require entirely different interaction techniques. Some UIs of the future will also provide high-quality speech, gesture, and handwriting recognition, 'intelligent agents,' adaptive interfaces, video, and many other technologies now being investigated by research groups at universities and corporate labs.

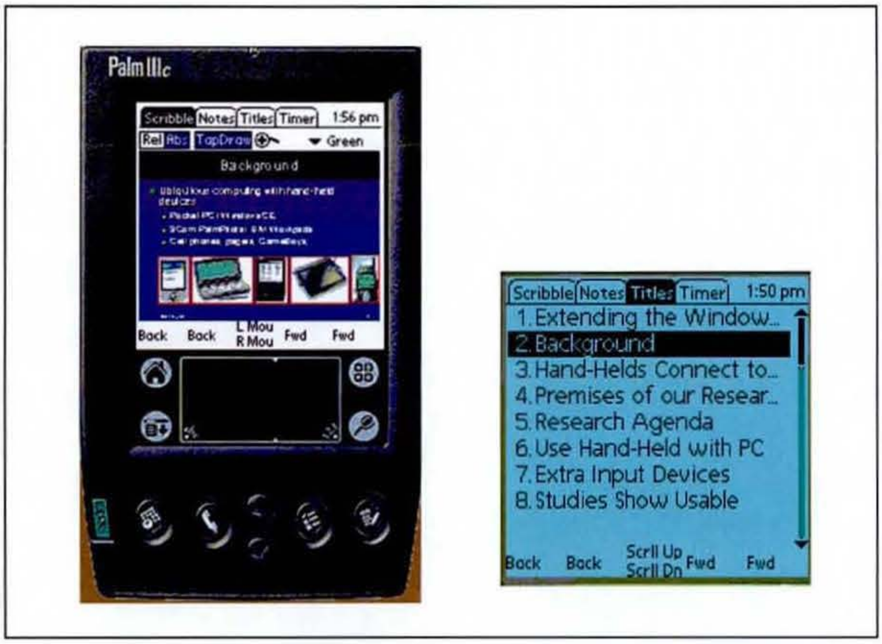


Figure 2.13. Example of a mobile device: The Palm IIIc.

2.9.3. GUI Design rules

Shneiderman [1998] and Shneiderman and Plaisant [2004] present 8 golden GUI design rules. Each rule should be interpreted, refined, and extended according to the environment GUIs are being designed for.

1. Strive for consistency.
2. Enable frequent users to use short cuts.
3. Offer informative feedback.
4. Design dialogues to yield closure.
5. Offer error prevention and simple error handling.
6. Permit easy reversal of actions.
7. Support internal locus of control, e.g., provide users with the functionality to set up personal preferences, alter the look and feel of the GUI.
8. Reduce short-term memory load.

Additional GUI design rules proposed by various authors include:

Kules et al. [2004], identified the following design rules whilst designing a public access photofinder software application:

- Incorporate distinctive and clear start up procedures for the first screen of your software application or web sites GUI, e.g., a message such as touch screen or click here to begin or enter.

- If it is important to identify registered users accessing a system, consider displaying the name or user identification, on every GUI screen for the duration of each users session.
- Provide users with a method of back stepping through their previous command actions, in the form of a return to previous action icon (graphic symbol), to be displayed on every GUI screen.
- Similar to Shneiderman design rule number 4, design the software application/web site to disengage and close, at the end of a users session. Display a message confirming the end of a users session, e.g., 'Thank you John Smith, you have ended your session'.

Norman [1983] recommends building menu driven icon direct action controls as well as command language opportunities into a UI, as this offers solutions to both the novice and expert user. Experimental results conducted by Saade and Otrakji [2004], indicate menu based GUIs to be quicker to learn, when picked up for the first time than icon-based interfaces. Function keys are another menu control method often considered suitable for advanced and expert users. Chalmers [2003] expresses the same view twenty years later from a slightly different angle. She recommends GUI screens that are simple enough in design for the novice learner, yet complex enough to sustain the interest of the expert learner.

Bernard [1998] suggests avoiding unnecessary detail and to use concise wording when presenting information through a GUI, in order to conserve screen space. If familiar data formats exist, the GUI should utilise them. Likewise labels and icons should be in a language and a diagrammatical representation familiar to the intended user group. He continues by adding a GUI should display only what information the user needs to perform the current operation, avoiding needless complexity. Information should be grouped with visual acuity (clarity) in mind. Users should be able to take in the different chunks of information at one glance to improve readability. Good techniques to aid grouping include using colour, graphical boundaries, and highlighting.

Design user interface control features to be transparent or at least non-intrusive wherever possible, making them visibly intuitive in operation. Research by Furnell [2005], identified security control feature functionality designed into MS Word XP, as requiring improvement in this UI design area.

De facto Windows UID rules include: placing the window title at the top, scroll bars on the right, close down icons at the top right, etc.

Kontogiannis and Embrey [1997] recommend considering GUI design from the psychological perspective, the role of the interface design is to represent the technical system in ways that support the process of attention, memory and decision-making.

Hu et al. [1999], presents three GUI design suggestions:

1. Use graphical interfaces rather than list-based interfaces when the goal is to provide effective system-user concept communication support.
2. A graphical interface that incorporates use of size, distance and colour may be more effective in supporting system-user concept communication than a design based on only one of these visual properties.
3. An interface design incorporating multiple visual properties may also contribute to increased user satisfaction without adding considerable cognitive load.

Leune [1995] explains that direct manipulation interfaces are object orientated in nature. Objects enable designers to separate the Human Computer Interface from an applications functional core subsystem. Object orientation in the human-computer interface allows illustration and use of real-world objects. And indeed, the objects on the screen should be modelled according to real-world entities and experiences (e.g., real world metaphors). Examples of real world objects in the form of popular icons are shown on the next page. Objects allow humans to think in the familiar terms of the application domain rather than those of the medium of computation.

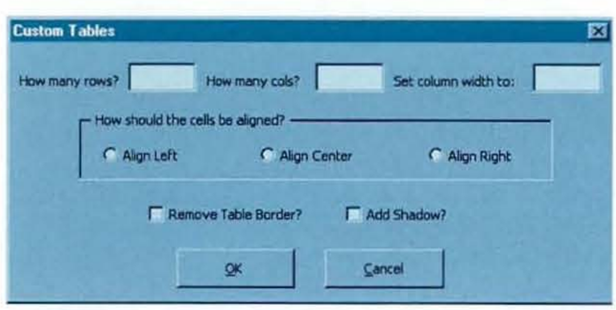
Incorporate human sensor arousal components in GUI design. Hu et al. [1999] identifies specific UI arousal components as: Size of an object, distance between an object and a viewer's attention locus (anchor), and colour and its effect upon visual arousal. He recognises that while colour may subtly vary from one culture to another, red is an appropriate candidate colour to represent important or significant objects; blue is often considered a cool colour that invites receding attention from viewers; yellow against black is associated with danger, e.g.,

Size, **IMPORTANT!!!**, Receding **DANGER**

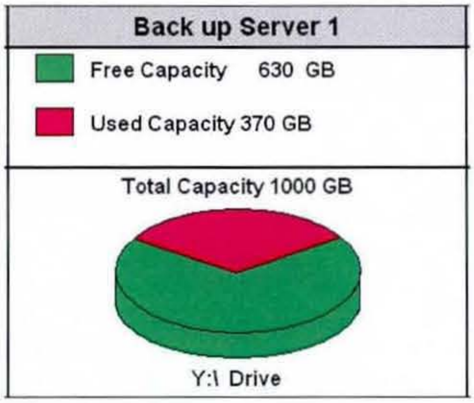
Typical UID features include:

Icons.

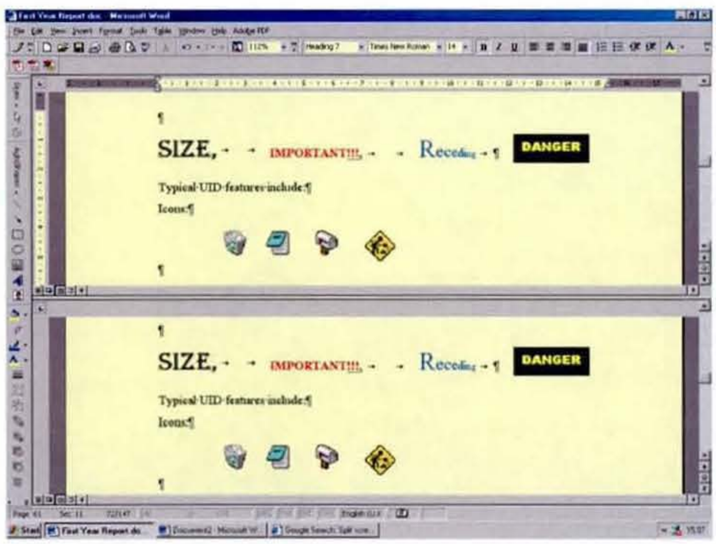
Menu bars.



Dialogue boxes.



Graphics.



Windows and split screens.

An interface that is easier to use minimises the effort associated with deciding what to do and how to do it, Lim et al. [1996].

One study has shown that designers are biased towards aesthetically pleasing interfaces, regardless of efficiency, Ivory and Hearst [2001].

Jonesa et al. [2005] recommend the use of impenetrable borders in GUI design. Their research shows icon and menu button selection times increase when located at the edge of a display screen, incorporating impenetrable borders. They recommend instructing users, via training, on the advantages of ballistic mouse movement as a method to speed up icon and menu button selection on a GUI incorporating impenetrable borders.

Hori and Shimizu [1999] examine industrial design considerations for UID. They explain that a human interface should be designed in stages taking into consideration the following conditions:

- Features of a plant: the number of operators and organisations; size, location and environment the UI/s will be placed in, quantity of information required to be displayed in order to satisfy the functional requirements of the system the UI is intended for.
- Human Factors: the ability to process information; range of visual fields or visual angle.
- Limitations of specifications: costs of displaying devices.

In their research into the effects of animated characters on anxiety, task performance, and evaluations of UIs, Rickenberg and Reeves [2000], recommend careful consideration for a user's own personal preferences and locus of control. Animated characters have their place as agents within an interface, but not every one will need or appreciate a graphical character built into their UI, such as the windows paper clip shown in Figure 2.14.

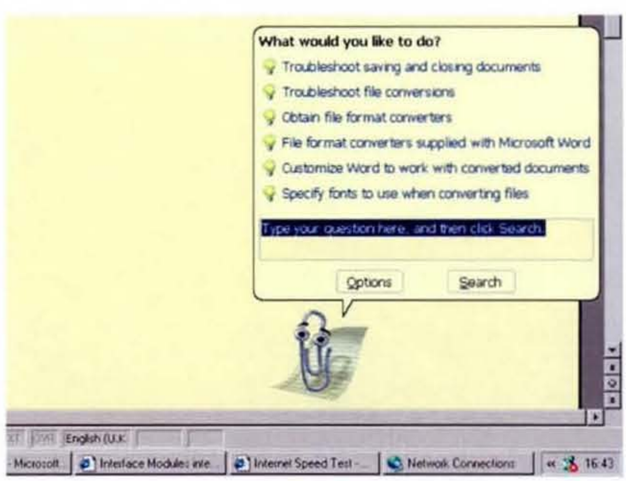


Figure 2.14. Example of an animated agent: Microsoft's paperclip.

All modern software applications provide some form of help assistance within their GUI, popularly accessible by selecting a button containing the word Help, located at the top of the screen, on the right hand side, for windows applications. Software application help assistance has the function of teaching users to operate a software applications features at their own pace. Help assistance should also offer users explanations and demonstrations on how and when to use a software applications features. Miller [2005] suggests in the future help assistance should also be designed to take into account different users cognitive learning styles.

Help assistance can be incorporated into GUIs through a variety of different techniques, some of which are listed below:

- Using an active questions and answers form available in Microsoft XP software applications, a type of intelligent software agent. For example, to get help about how to create a table, users type, 'How do I create a table', in the assistant form.
- Linking users to external web sites, which provide further help assistance for the software application in question. This might be the software vendors own web site, or a companies own web site. In the case of Royal Mail this might be the automation development and support team (ADST) web site.
- Providing ScreenTips, designed to offer users a brief explanation as to the function of buttons, icons or dialogue box options, within a GUI. Microsoft XP software applications offer this feature.
- Offering animated tutorials, that step users through a software application's introductory operational principles. Microsoft and other larger software houses offer this feature in many of their software applications.

Figure 2.15 illustrates the application of several GUI design rules incorporated into the design of a CBM systems software GUI, developed by: Meridium Enterprise Reliability Management System.

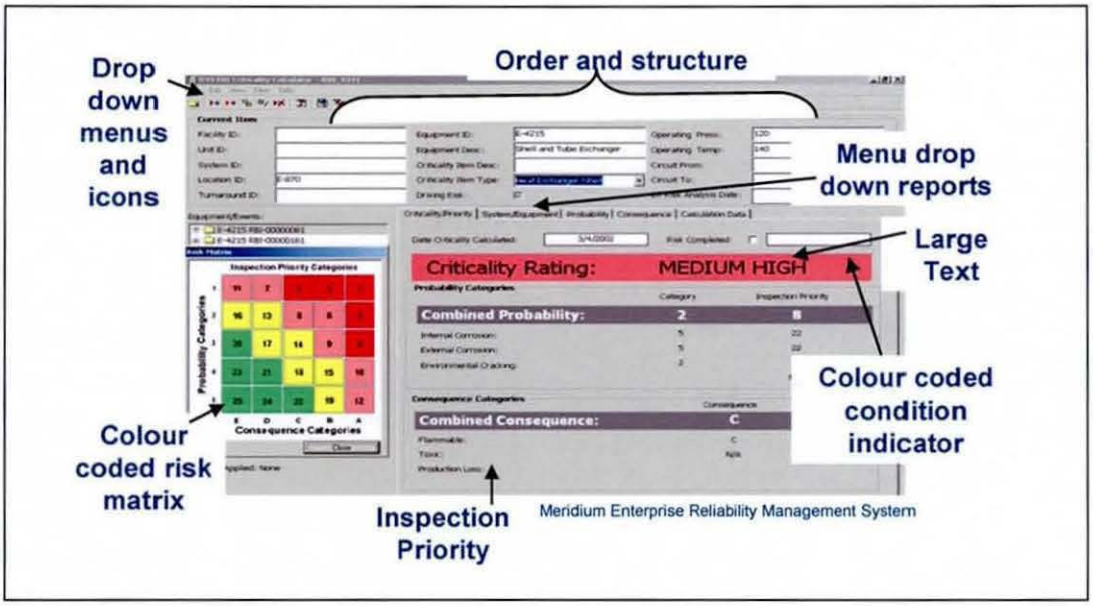


Figure 2.15. Demonstrating GUI design rules incorporated in a Reliability Management System, courtesy of Meridium Enterprise.

2.9.4. User interface standards

Historically, all modern GUIs are offshoots of the Apple Macintosh. Most application GUIs adhere to one of the three major GUI paradigms, the Apple Macintosh, the IBM Systems Application Architecture (SAA), or the X-Windowing System. GUIs usually have three major components: A windowing system, an imaging model, and an application program interface (API). The windowing system builds the windows, menus, and dialogue boxes that appear on the screen. The imaging model defines the fonts and graphics that appear on the screen. The API is the means in which the user specifies how and what windows and graphics appear on the screen. The X-Windowing System is the most popular GUI for UNIX systems, Bernard [1998].

2.9.5. Summary

Several definitions have been presented defining the meaning of UI. UID guidelines and UI standards promote good UID. Good interface design should present system information in a format and level of detail which facilities the goals of the user in solving problems.

In the future UID will be adapted to changing user requirements and advancing HCI technologies. UI standards have been slow to evolve and even slower to be accepted as de-facto. Most commercial computer applications incorporate UIs based on one of three paradigms, the Apple Macintosh, the IBM Systems Application Architecture (SAA), or the X-Windowing system.

2.10. GUIs for Internet and Mobile Applications

Design tools for web page GUI creation and mobile device GUI creation are introduced and discussed in this section.

2.10.1. Browser GUIs

More and more software systems are being designed for Browser access over the Internet, resulting in a greater need for professional web sites designed with similar interactivity and functionality to conventional commercial software applications. As the demand for commercial interactive web sites has grown, so has the quality and functionality of these web sites.

Just as UID tools emerged to speed up the process of designing GUIs for commercial software applications, so have emerged web page design tools, HTML programs, web editors, and specialised programming languages such as HTML, script code, VBScript, Java and XML, for the creation of web sites with ever greater functionality, e.g., dynamic web pages and database interactivity through a web page.

Heldal et al. [2004] makes reference to research conducted by Nielsen [2000], identifying usability as the most important consideration for Browser compatible GUIs. Usability encapsulates web site ease of use, simplicity in design, ease to remember, avoidance of decision errors and irrelevant or drawn out information and user subjective satisfaction.

New and emerging methods of Human Computer Interaction designed specifically for Browser accessible web sites, are discussed by Kumar et al. [2004], Hobart [2004], Marsico and Levialdi [2004]. The papers examine Browser GUI design issues aimed at optimising interactive experiences.

Kumar et al. [2004] explains how web sites are being designed to automatically configure their appearance and control features according to pre-defined user requirements and identified operational habits. At the same time they explain how web page personalization of this nature increases the complexity and challenge for user interface designers, increasing web design costs.

Hobart [2004] foresees the next generation of Internet applications to be capable of much more than simply rendering pages. They will be able to perform complex calculations, handle data manipulations, send and receive data asynchronously, and allow occasionally connected users to perform tasks in a mobile environment. Presentation issues like redrawing sections of a screen or displaying multiple views simultaneously will become commonplace, and all of this will be available independent of the backend architecture it is connected to.

Marsico and Levialdi [2004] emphasise the importance of web site navigation design to include:

- Selection of appropriate navigation graphics
- Enabling users to visualise their progress through a web site
- Incorporating a selection of navigation tools within a web site.

Darwin [1999] discusses Java GUI design capabilities. He describes Java as being suitable for creating many kinds of Internet compatible programs. One of the first to gather widespread attention was Web Applets, which dynamically extend the behaviour of the web Browser by being embedded in a web page. Java can also be used to make Web Servlets, background TCP or UDP servers, or ordinary GUI based desktop applications.

Onga et al. [2001] demonstrate the possibilities of developing object orientated Java-based GUIs capable of integrating with SCADA. They conclude that their GUI is portable, requires zero-installation and gives a consistent look. This enables the same GUI to be used and accessed locally over a local area network, or remotely through an Extranet or Internet, without incurring additional development or maintenance costs.

2.10.2. GUIs for mobile devices

The big difference between UIs for mobile devices, PCs and large screen displays is size. Most mobile devices have small screens between 5 centimetres by 5 centimetres up to 7.5 centimetres by 12.5 centimetres. Therefore UI designers have to be considerably more selective in their choice of information and graphics being displayed on the screen. The proliferation of mobile devices in recent years has led to several research groups emerging dedicated to developing UI tools and techniques for mobile devices.

Jonssona et al. [2003] investigated the transferability of GUIs designed for conventional desktop monitors, for use on mobile handheld small screens. There results provide cause for optimism, suggesting that while there are definitely problems in cross platform implementations, particularly with respect to ease of use, it may be possible to meet the dream of, 'write once-use on everything'.

Myers [2001] discusses issues concerning transferring of data between mobile devices and PCs. He identifies HotSync for the Palm and ActiveSync for Windows CE as technologies capable of synchronising between mobile devices and PCs.

Nichols et al. [2004] describes the development of an automatic UI template design tool, suitable for mobile devices. He explains how the interface template design tool is suitable for use with multiple platforms, including Pocket PCs, Microsoft's Smartphone, desktop computers, and speech interfaces.

2.10.3. Summary

A proliferation in commercial web sites and a gradual increase in the application of networked mobile devices, has resulted in a growing market for web page design tools, HTML programs, web editors and specialised Internet programming languages. It has also resulted in the recent creation of several research groups dedicated to creating design aids for mobile device GUIs.

Web page design tools and programming languages suitable for developing ASPs will be required for the design of an Internet CBM GUI.

2.11. User Interface Modelling, Usability Engineering, Iterative Design Techniques and Usability Testing

Modelling, Usability Engineering, Iterative Design and Usability Testing are all closely linked together, as they represent methods for fine-tuning and refining ideas and practical designs, following usability and simulation testing. Each topic is introduced and discussed in the following section.

2.11.1. User interface modelling techniques

Puerta et al. [1999] presents a case for modelling the UID process. Modelling is useful for understanding and examining issues such as how data should be split among the screen, what widgets correspond to what type of user, and how the dialogue changes according to the task and user characteristics. Without modelling tools, it may be that user-task information is kept in paper documents, or is viewable through a separate tool, or (worse) it is just in the head of the designer. The result is bound to be a number of mismatches between the designed screens and the user-task specification. In addition, revisions of the screens or of the specification can produce even more pronounced mismatches, or at the very least a cumbersome coordination process.

Model-based interface development, explained by Puerta et al. [1999], is a technology that embraces the idea of designing and developing UIs by creating interface models. An interface model is a computational representation of all the relevant aspect of a UI. The components of an interface model include sub models such as user-task models, domain models, user models, presentation models and dialogue models. Model-based interface development systems are suites of software tools, that allow developers to create and edit interface models. Many model-based systems aim at generating significant parts of a UI given a partial interface model. Some others aim at interactively guiding developers in building UIs using interface models.

One specific type of modelling technique for UID and evaluation: described by John and Kieras [1996] is Goals, Operators, Methods, and Selection rules (GOMS).

All GOMS techniques produce quantative and qualitative predictions of how people will use a proposed system, though the different versions have different emphasises, John and Kieras [1996]. The overall motivation for GOMS and other HCI cognitive modelling efforts is to provide engineering models of human performance. They predict execution time, learning time, errors, and they identify those parts of an interface that lead to these predictions, thereby providing a focus for redesign effort. They allow analysis at different levels of approximation so that predictions appropriate to the design situation can be obtained with minimum effort. They are straightforward enough for computer designers to use without extensive training in psychology, and these models are integrated enough to cover total tasks. GOMS is currently the most mature of engineering models, and can be truly useful in real world system development.

Constructing a GOMS model is a way for a UI designer to become more aware of the implications of a design. This can be important because a common design error is to focus on non-procedural issues such as screen layout or graphic design, while burdening the user with a clumsy interface. Thus, any exercise that requires the designer to think carefully about the procedures entailed by the design can help in purely an intuitive way to identify usability problems and clarify the nature of the user task, John and Kieras [1996].

Johannsen [1995] develops and presents a design methodology consisting of six knowledge modules, each designed specifically to aid the Human Machine Interface design process in a modular design approach. The six modules comprise of:

1. The goal knowledge module.
2. The application knowledge module.
3. The operator knowledge module.
4. The task knowledge module.
5. The Human Machine Interface knowledge module.
6. The design procedural knowledge module.

Figure 2.16 illustrates Johannsen's six modular design methodology.

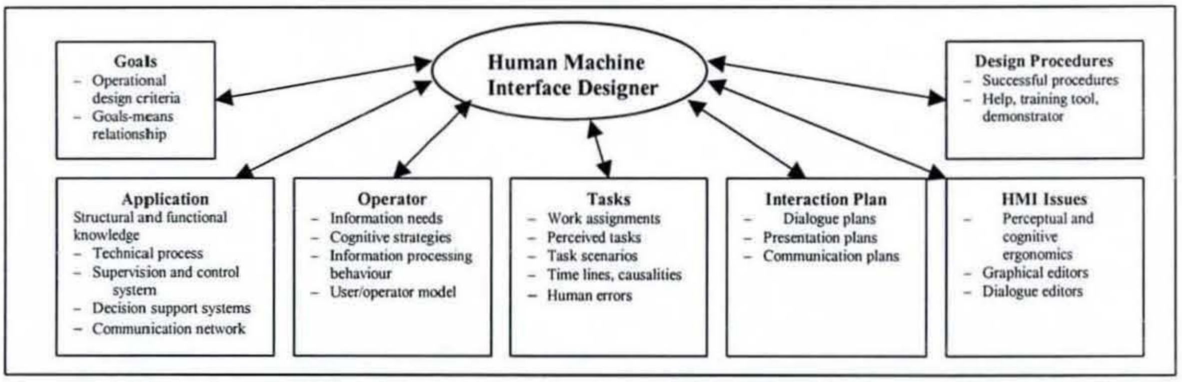


Figure 2.16. Knowledge modules for supporting the Human Machine Interface design process, Johannsen [1995]

User Hints is a modelling technique, which aims to increase awareness towards HCI design implications. Nascimento and Eades [2005] describe their User Hints framework as a tool for achieving a balance between decisions best processed and undertaken via computational methods, and decisions taken manually by a human operator/user.

Agent-orientated design is a Human Computer Interface modelling technique similar to Johnnsen [1995] design methodology. Ezzedinea et al. [2005] describes the agent–orientated design approach whilst designing a human machine supervisory interface for the public transport system in Valenciennes. The term agent in this case refers to design modules comprising the overall design. Each agent is capable of operating autonomously and collaboratively with other modules.

Using any modelling method in design entails both the cost of learning how to use the model and the time and effort to apply it to a specific Human Machine Interface design situation. Because of the large amount of detailed description involved, GOMS methodology has often been viewed as extremely time-and labour –intensive, John and Kieras [1996].

Myers [1995] refers to two prototyping tools, Director, by Macromedia and HyperCard for the Macintosh. The goal of prototyping tools is to allow the designer to mock up quickly some examples of what the screens in the program will look like. Often, these tools cannot be used to create the real UI of the program; they just show how some aspect will look. Many parts of the interface may not be operable, and some of the things that look like widgets may just be static pictures. Therefore, the interfaces must be recoded after prototyping. Most prototyping tools can be used without programming skills so they can, For example, be used by graphic designers.

2.11.2. Usability testing

Ivory and Hearst [2001] define usability as the extent to which a computer system enables users, in a given context of use, to achieve specified goals effectively and efficiently while promoting feelings of satisfaction. Usability evaluation (UE) consists of methodologies for measuring the usability aspect of a system's UI and identifying specific problems. Five categories of UE are identified below:

1. **Testing**: an evaluator observes users interacting with an interface (e.g., completing tasks) to determine usability problems.
2. **Inspection**: an evaluator uses a set of criteria or heuristics to identify potential problems in an interface.
3. **Inquiry**: users provide feedback on an interface via interviews, surveys, and the like.
4. **Analytical Modelling**: an evaluator employs user and interface models to generate usability predictions.
5. **Simulation**: an evaluator employs user and interface models to mimic a user interacting with an interface and reports the results of this (e.g., simulated activities, errors, and other quantitative measures.).

Usability evaluation is an important part of the overall UID process, which consists of iterative cycles of designing, prototyping, and evaluating. Kim [2001] promotes the importance of using usability testing to identify error prone situations or potential human errors in advance. Doing so provides opportunities for resolving human engineering deficiencies that may exist in an interfaces' design.

Ivory and Hearst [2001] suggest that automating usability testing has many potential advantages, including

- Reducing the cost of usability evaluation.
- Increasing consistency of the errors uncovered.
- Detection of usage patterns specific to common errors.

- Predicting time and errors costs across an entire design.
- Reducing the need for evaluation expertise among individual evaluators.
- Increasing the coverage of evaluated features.
- Enabling comparisons between alternative designs.
- Incorporating evaluation within the design phase of UI development, as opposed to being applied after implementation.

However automated UE is limited in its ability to identify subjective UI issues, such as user satisfaction.

Nielsen [1993] and Shneiderman and Plaisant [2004], emphasize usability testing as a primary factor in determining the acceptability and consequent success of computer software.

Nielsen [1993] recommends prototyping as a useful early usability tool. Prototyping promotes interaction among different concerned parties such as users, domain experts, and developers. It helps every one to understand the requirements and it fosters team spirit.

Archer and Tuan [1995] recommend simulation as a usability tool to evaluate human-system interface suitability. Ivory and Hearst [2001] agree explaining how simulation compliments traditional usability evaluation methods and supports automated analysis. Further discussion concerning simulation as a UE tool follows in the next section.

Park and Lim [1999] present an analytical hierarchy process (AHP) model for usability testing, shown in Figure 2.17, based on the principles of decomposition, comparative judgements, and synthesis of priorities. The proposed model consists of two phases: the pre-screening phase (expert judgement-based approach) and the evaluation phase (user-based approach). It is particularly useful when multiple criteria and several alternative interfaces are considered and when usability evaluation must be performed under limited resources. The proposed methodology enables software developers or interface designers to efficiently evaluate interface designs through multiple criteria and measures.

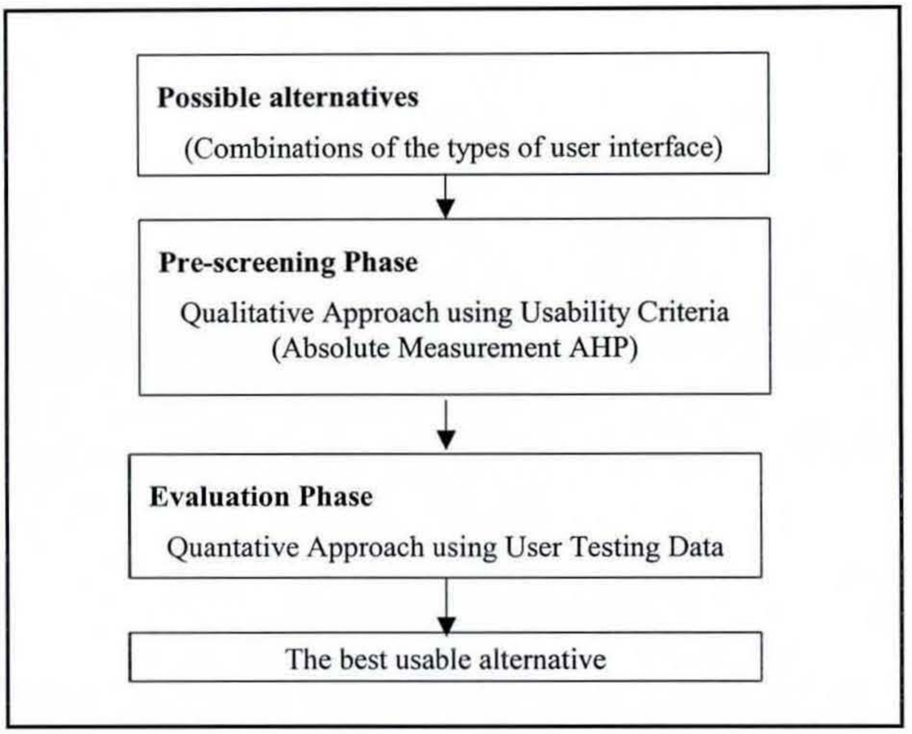


Figure 2.17. The analytical hierarchy process (AHP) methodology.

Park and Lim [1999] identify ISO 9241/10 as an international interface design usability-testing standard.

2.11.2.1. Evaluation methods

Ivory and Hearst [2001] describe various methods of usability testing with real participants. Participants use the Human Computer Interface or a prototype to complete a predetermined set of tasks while a tester records the results of the participants work. The tester then uses these results to determine how well the interface supports user task completion as well as other measures, such as number of errors and task completion time. Alternatively test data may be gathered through an automatic data logging process. Automatic data logging allows information that is easy to record but difficult to interpret (e.g., keystrokes) and information that is meaningful but difficult to automatically label, such as task completion. A further alternative requires feedback from users. Gathering subjective impressions (e.g., preferences or opinions) about various aspects of UI. Evaluators also employ inquiry methods, such as surveys, questionnaires, and interviews, to gather supplementary data after a system is released; this is useful for improving the interface for future releases.

2.11.3. Usability engineering, iterative design

Iterative design described by John and Kieras [1996], is a design process that should use engineering models and other non-destructive user testing techniques where applicable, early in the design process, to evaluate candidate designs and resolve design issues as much as possible, before investing in actual user testing.

Simulation techniques can act as useful usability engineering tools. Ivory and Hearst [2001] explain how simulation complements traditional usability engineering methods and like analytical modelling, can be viewed as inherently supporting automated analysis.
Using models of the UID, these approaches simulate the user interacting with the interface and report the results of this interaction, in the form of performance measures and interface operations, for instance. Trace-driven discrete-event simulation has been shown to produce acceptable web based usability engineering results. Trace-driven discrete-event simulation employs real usage data to model a systems usage as it evolves over time. Logged data for web based UI can be obtained from client-side logs. Evaluators can run simulations with different parameters in order to study various UID tradeoffs and thus make more informed decisions about UI implementation.

Simulation represents a valuable iterative design aid. Archer and Tuan [1995] describe how simulating and testing a UID during the design process and prior to system roll out, on a group of employees is highly recommendable. For example, systems operated using a UI, rely upon user's abilities to interact appropriately through the UI and make correct decisions. Simulating a UI therefore improves the success rate of workable UID.

Ivory and Hearst [2001] goes onto suggest that simulation methods are more difficult to use and learn than other evaluation methods, because they require constructing or manipulating complex models, as well as understanding the theory behind a simulation approach.

Interactive design was applied extensively during the upgrade of Microsoft Windows 3.11 to Microsoft Windows 95. Sullivan [1996] presents a model showing the design stages Microsoft adopted in Figure 2.18.

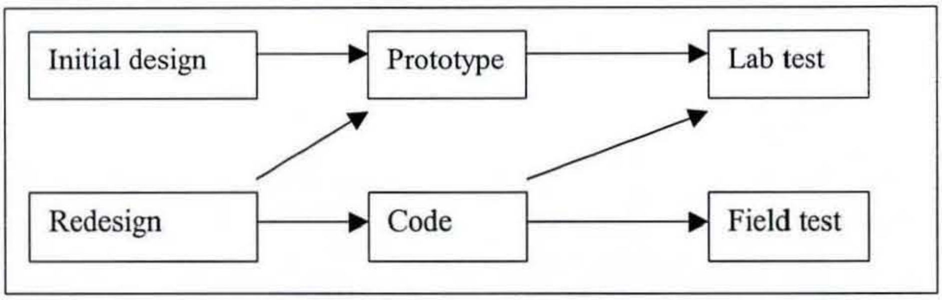


Figure 2.18. A model of the iterative design process used by Microsoft.

Sullivan [1996] summarised iterative design testing as a process of repeating or reassessing a design over and over following usability testing, fine-tuning prior to release. Besides involving potential user groups during iterative design, and usability testing, Jaspersa et al. [2004], recommend gaining an insight into how new systems can be expected to change existing working practices. They also recommend evaluating how new systems may or may not be adapted into existing practices.

2.11.4. Summary

Modelling, simulating, usability testing, and iterating, have each been discussed as methods for improving the quality and usability of a UI during design, development and testing.

Model based interface development embraces the idea of designing and developing UIs by creating interface models. Any model that requires the designer to think carefully about the procedures entailed during the design can help in purely intuitive ways to identify usability problems and clarify the nature of the users task. Prototyping and simulation can both be used as modelling techniques, allowing designers to quickly mock up an example of what the screens in the program will look like.

Usability testing enables UI designers to determine how well an interface supports the users ability to complete a task, as well as other measures such as identify number of errors and time to complete the task.

Usability Engineering and Iterative design should be used early in the design process, to evaluate candidate designs and resolve design issues as much as possible, before moving onto final testing.

2.12. User Interface Design Tools

Software tools designed to simplify and speed up the task of designing and programming UIs for software applications, known as UID tools are introduced in this section.

Interface design tools and modelling techniques have evolved in order to reduce the sophistication in both programming and human behaviour, allowing non-programmers to tackle the task of UID, Norman [1983]. UID tools aid designers in their search and management of partial interface solutions, therefore reducing the cognitive work load and thus helping to enhance overall quality of design outcomes, Kima and Yoon [2005].

Myers [1995] explains that UI tools have been called various names over the years, with the most popular being, 'User Interface Management System (UIMS).' However, many people feel that the term UIMS should be used only for tools that handle the sequencing of operations (what happens after each event from the user). Other terms like Toolkits, User Interface Development Environments, Interface Builders, Interface Development Tools, and Application Frameworks have been used.

Myers [1995] describes interface builders as interactive tools that allow interfaces composed of widgets such as buttons, menus, and scroll bars, to be placed on screen using a mouse. Interface builders allow designer to select from a predefined library of widgets, and place them on the screen using the mouse. Other properties of the widgets, can be set using property sheets. Usually, there is also some support for sequencing such as bringing up dialogues when a particular button is hit. Interface builders use the widgets from a toolkit, so they can be used to build parts of real applications. Most will generate C, or C++, or Visual Basic code templates that can be compiled along with the application code. Others generate a description of the interface in a language that can be read at run-time. Puerta et al. [1999] adds, most interface builders include code generators, which produce the basic hooks for application developers to write the code to communicate with the UI. Myers [1995] continues, although interface builders make laying out the dialogue boxes and menus easier, this is only part of the UID problem. These tools provide little guidance towards creating good UIs, since they give designers significant freedom. Puerta et al. [1999] continues by saying, 'any connection between the operations made through an interface builder and the requirements of the target users and their tasks, must be maintained in the head of the developer without assistance from the interface-building tool.' Reasons behind the success of interface builders, explained by Myers et al. [2000], is there use through graphical means to express graphical concepts (e.g., interface layout). Interface builders remove some of the initial programming skill, as they automatically create code for basic interface design activities. Reducing the speed for programmers to build UIDs. This in turn, enables more rapid prototyping and therefore, more iterations of iterative design, which is a crucial component for achieving high quality UIs. Another important advantage of tools is that they help achieve a consistent look and feel, since all UIs created with a certain tool will be similar.

Myers et al. [2000] describes toolkits as providing both a library of interactive components, and an architectural framework to manage the operation of interfaces made up of those components. A toolkit makes the programmer's job much easier and can be used as leverage to achieve the difficult goal of maintaining consistency. Thus, by achieving the goal of making the programmers job simpler, toolkits provide a path of least resistance, supporting widespread interface consistency.

Many object orientated programming languages have built in User Interface development tools, enabling software developers to quickly formulate prototype UIs, using inexpensive tools.

UID is poised for a radical change in the near future, primarily brought on by the rise of ubiquitous computing, recognition-based UIs, 3D, and other technologies. These new tools will be organised around providing a rich context of information about the user, the device, and the applications state, rather than around events. This will enable end-users programming recognition-based UIs, and the data sharing needed for ubiquitous computing. It will be important to have replaceable UIs for the same applications, to provide different UIs on different devices for ubiquitous computing, and to support customisation, Myers et al. [2000]. Generally, research and innovation in UID tools trails innovation in UID, since it only makes sense to develop tools when you know for what kinds of interfaces you are building tools.

2.12.1. Summary

User Interface Tools offer programmers an opportunity to reduce the sophistication in both programming and human behaviour when designing a GUI. Interface builders allow designers to construct UIs from predefined libraries of widgets and user interface patterns. Few UI tools provide guidance towards creating good UID. User Interface Tools for standard software applications will not be suitable, in assisting with the design of a GUI for an Internet CBM system. An Internet CBM GUI must be designed with a web page editor application or a UI tool, with web page conversion capabilities. UI tools of the future will offer designers ever-greater possibilities driven by technological advances in UID, such as ubiquitous computing, recognition-based user interaction capabilities and 3D UI possibilities.

2.13. Computer System Implementation Guidelines

It is anticipated that Royal Mail's CBM initiative could lead to an integration of its existing SAP business computer system with information from an enterprise remote CBM system. Linking two computer systems smoothly will require considerable time and effort from the organisations computer staff and all other staff in effected departments. It is not the intention at this stage to explore the entire topic of computer systems implementation, but rather introduce the topic to the reader.

A typical computer system implementation consists of the following broad steps:

1. Small scale testing, aimed at identifying and removing system errors.
2. Pilot testing. Testing the systems full capabilities on a small group of employees within the environment the system is intended for.
3. Small Scale deployment. The system is slowly introduced to other areas of the business. Dedicated trainers educate specific individuals within each area of system deployment, the aim being that those individuals take on the role of department (area) expert, or champions, and undertake all further staff training in their area.
4. Large Scale Deployment: Same as '3' but on a grander scale.

Anticipated problems and recommendations for smooth implementation of an automated diagnostic system are described by Brandon [2002]. He begins by suggesting resistance to new automated technologies is inevitable to a certain extent, and not simply because it represents change. Reasons why an automated diagnostic system may be resisted include:

- Mistrust of automated systems per se.
- A threat to expertise-based organisation status.
- Erosion of supervisory-based organisation status.
- A threat to the entire control structure within an organisation.
- The general workforce may also consider automation as a move towards the thinning of employees.

Countering the above expected resistances are a list of recommendations to ensure successful implementation:

- Make sure you understand the problem before embarking on the solution.
- Select staff with intelligence and initiative.
- Define the boundaries of the problem as widely as possible.
- Give them authority and leave them to get on with the job.

Providing knowledge of a system's capabilities, purpose and intended application through education, training and hands on experience are critical during the early stages of computer system role out. Besides people will only start using a new computer system to make or assist them, in making decisions, if they understand its intended purpose, functionality, can easily communicate with it and trust it. There is always a learning step in using software systems. If they are not regularly used, there is a serious danger that the experience needed to run them fades away, with the result that they are put aside. Dekker [1995] suggests trust in a system can be associated with acceptance. Evidence of trust in a system comes when employees are happy to stand by actions based on information taken from the system, when questioned by their superiors (managers).

2.13.1. CBM implementation guidelines

Feedback from employees within organisations who have already been through the implementation process for a CBM system, detailed in, 'A survey on CBM systems in industry', Higgs et al. [2004], enables the author to present a list of guidelines for future industrial CBM implementations, listed below:

- Obtain backing and support from top management, before implementation.
- Recognise and plan for a change in the way maintenance is applied and viewed, i.e., reassess your organisations entire maintenance approach (strategy) in every effected department.
- Select and match a system capable of doing the job, taking into consideration your own resources, and the level of employee expertise.
- Train and educate employees to appreciate the idea and philosophy behind CBM as a predictive maintenance practice. Train employees to use, understand and correctly act upon feedback from the CM equipment.

Literature published on behalf of Rockwell Automation by Spicher [2000] describes five alternative implementation guidelines:

- Document Financial Gains. Analyse and document the costs savings that are a direct result of a Condition Based Maintenance program. Including material costs, labour costs, and fuel costs.
- Upper Management Support: Senior management will be expected to explain the strategic importance of a Condition Based Maintenance program.
- Full Integration of Condition Based Practices into overall maintenance philosophy.
- Integrate Test Technologies: Integrate Condition Based Maintenance information from multiple sites.
- Assessment Process: Every three years conduct a formal assessment of your Condition Based Maintenance program. Perform a strengths, weaknesses, opportunities and threats (SWOT) analysis to assess where your CBM systems is leading.

Al-Habaibeh et al. [2003] indicate implementation guidelines vary from one company to another, dictated by the types of machines, company size and the nature of the products. For example, some companies cannot apply intelligent systems due to their high cost. Others find it difficult to extract useful information from their systems due to the complex nature of the technology involved.

2.13.2. Summary

Computer System Implementation represents the final stage in the design, development, test and implementation process. Although much of the success concerning computer system implementation is linked to the quality and accuracy of previous steps, successful implementation still requires an equal amount of thoroughness, planning and hard work in order to achieve success. Implementation guidelines have been proposed and anticipated resistances to new technologies identified, with recommendations aimed at countering such resistance. Key to successful implementation is management support and employee participation from start to finish. People will only use a computer system to make decisions if they understand its intended purpose, functionality, can easily interpret information presented by it, and operate it.

Chapter 3

3. METHODOLOGY

3.1. Introduction

Literature from twelve topics considered relevant to the research objectives have been introduced and discussed in chapter 2. Chapter 3 aims to establish the research methodology and in doing so generate a proposal for a CBM Human Machine Interface (HMI) design specification. The design specification will consist of a selection of design factors and consideration the Human Machine Interface (HMI) designer can refer and reflect upon, whilst selecting and developing suitable design ideas for a CBM HMI.

3.2. Research Direction

Section 2.6 explained the importance of involving the intended users during software design, development and testing procedures. Applying these procedures to the accomplishment of the research objectives, requires the HMI designer to identify the intended audience/user group, and discover their user and system requirements. Research activities to be undertaken should therefore incorporate liaison between the researcher and Royal Mail.

Sections 2.3, 2.4 and 2.5 explained what condition based monitoring represents, discussed the technologies available for various types of CM techniques, and explained the different architectures CBM systems can be arranged into. Discussion points presented in each section will each impact at different levels, on the design and development of a CBM HMI. Research activities should therefore firstly aim to identify and understand the CM techniques being proposed for Royal Mail, in order to tailor developmental design recommendations and decisions to their requirements. Secondly research activities should identify the extent to which CBM systems are utilised within industry as a whole, in order to generate recommendations for a generic CBM HMI proposal.

Section 2.9 introduced and discussed the topics: user interface design, design rules and user interface standards. Each topic provides the HMI designer with design guide lines, and standards to bare in mind and follow whilst developing software GUIs. CBM HMI designers with the research objective in mind, must interpret and apply these guide lines and standards to the development of a CBM HMI, for Royal Mail firstly and a generic audience secondly. Research activities should therefore be directed at identifying and understanding, which design features, both from a graphic designer perspective as well as from a software functional control perspective, to incorporate within a CBM GUI.

Section 2.11 introduced and discussed the topics: User Interface Modelling, Usability Engineering, Iterative Design Techniques and Usability Testing.
This sequence of topics describes the procedures HMI designers will undertake once they have gathered and are confident with the information acquired following the above mentioned research activities. Research activities should therefore concentrate on generating a model for a developmental CBM GUI, using existing developmental CBM GUIs already developed, for idea generation. Once the model has been developed it should be presented to the intended user, Royal Mail, for verification and further comment. Ideas and recommendations from the intended user should be applied to making model design improvements and possibly a redesign. This procedure should be followed iteratively until the CBM GUI model is considered acceptable. The researcher should next set about converting the developmental model into a working solution, using either a suitable programming language or a software engineering developmental tool, refer to section 2.10. Finally the researcher should conduct usability tests on the completed CBM GUI and make further design alterations if required.

3.3. Design Considerations Applicable to CBM HCI, Selection and Design

3.3.1. Identify user and system requirements

3.3.1.1. Identify the audience

Section 2.6 explained the importance of involving the intended users of a system throughout the design, development, and testing process for software products. Users have many of the design solutions, referred to as user and system requirements. Extracting these requirements from the intended users minds and incorporated them into a CBM HMI design, improves the chances of its acceptance and use.

Typically a CBM systems' audience includes: machine operators, technicians, maintenance engineers, shift supervisors, performance engineers, technologists, and operation managers. The HMI designer should aim to obtain user and system requirements from as many identified user groups as possible. Doing so provides a more balanced representation of user and system requirement to base design decisions on.

From a generalised perspective, operators are interested in a machines present operational condition parameters, as these determine whether the machine is operating at a desired level. Technicians and maintenance engineers are interested in all three stages, because they wish to keep machinery operational. Keeping machinery operational requires historical condition information to determine how a machine has been performing, present condition information to pin point component and or machinery weaknesses and failures, and predicted future condition information to determine how urgently maintenance is required. Shift supervisors, performance engineers and technologist are interested in all three stages, as they wish to monitor machinery performance statistics, schedule maintenance activities around operational demands, and make decisions aimed at maximising machinery conditions, in order to achieve production or capacity targets. Operational Managers are interested in maximising production and capacity output whilst minimising operational costs and satisfying commercial demands.

3.3.1.2. Designing for a generic or specific customer base

A CBM system design aimed at a generic customer base will provide a range of functions as standard, not all of which may be required by the buying customer. A tailor designed system is more likely to incorporate functional capabilities specifically tailored to a customer's requirements. Alternatively, the HMI designer may choose to tailor their CBM HMI design at a specific market or industrial group. The decision on whether to design for a generic or individual customer group should be taken early in the design process, as it influences many design decisions.

A generic CBM HMI should be designed so it can be re-programmed to a customer's own requirement with the minimum of rework costs. Factors effecting the speed and efficiency of software tailoring include: the number and complexity of user specified software alterations, the structure and understand-ability of the program code, the type of programming language, a programmers familiarity towards the program being tailored, and the programmers skill level. The generic solution must be designed to include a selection of design features considered sufficiently broad to cater for a generic customer base, whilst avoiding being overly complicated or expensive to design. The HMI designer should therefore aim to identify all the design features and functions appropriate for a generic customer base.

A custom designed CBM HMI suffers from none of the generic design challenges mentioned in the above paragraph. Custom designed CBM HMIs require/need only be designed to satisfy a specific customers requirements.

3.3.1.3. Designing for an industrial group

Identifying the industrial group a CBM system will be targeted at, assuming there is only one, will be useful for realising CBM HMI design requirements such as: language, symbols and images, terminology, and standards, applicable to the industry, for incorporation in the HMI.

3.3.2. Selecting methods of HCI suited to the CM technique

Multiple CM techniques exist for the many different situations where Condition Based Maintenance can be employed to offer predictive maintenance capabilities. For every different type of CM technique and every different application a CBM system is applied to, there exists a need for a variation, big or small to that particular CM techniques method of HCI, notably in its GUI. The HMI designer must therefore identify the type of CM technique/s being chosen, and the purpose and application the CBM system will be used for. Knowing the CM technique to be used is the first step to understanding what information will become available for manipulation and communication to the intended user group. It also provides the CBM HMI designer with an initial starting point to deciding upon the most effective method of presenting and communicating CM information. For example, vibration detection CM used on rotating machinery do not necessarily require complex multi functional GUIs for presenting information to users. A simple transducer designed to transmit warning messages at fixed vibration levels, to maintenance engineers may suffice. Warning messages of a type and form that result in the fastest response time, depending upon the location of the maintenance engineer with respects to the machinery in question. Information of this nature will be obtainable from the intended customer or group of customers.

3.3.3. Design considerations applicable to diagnostic and prognostic functional capabilities

CBM systems rely upon their accuracy to make diagnostic and prognostic decisions. Section 2.4.2 described the theory behind diagnosis and prognosis as applied to CBM systems. Presenting diagnosis and prognosis results to the intended user through a GUI and other methods of HCI, represents a critical success factor for CBM systems. User requirements investigations (refer to section 3.3.1.1) should aim to identify the most desirable methods and locations diagnosis and prognosis results can be presented to the intended users. The HMI designer should consider how to represent and communicate diagnostic and prognostic results for a single machine or multiple machines. Sections 2.9 and 3.3.7 provide useful ideas for communicating diagnostic and prognostic results to CBM practitioners.

3.3.4. Design considerations for integrated and networked CBM systems

3.3.4.1. Design considerations relevant to a CBM HMI which integrates with and presents information from multiple CBM systems

If several CM techniques are to be integrated together and viewed through one GUI, integrational design considerations must be considered. Incorporating the ability to compare and contrast data from different CM techniques into the CBM GUI may be requested as a user requirement, or considered useful from a marketing perspective by the HMI designer. Data comparison capabilities may prove useful for assisting failure diagnostic decision-making.

3.3.4.2. Design considerations for CBM systems that integrate with other Computer Maintenance Management Systems

In this case the HMI designer should consider and become familiar with the functional capabilities integrating the two systems together presents. Additional functional control features the HMI designer may be required to design into the HMI include:

- An ability to transfer or export data from the CBM system into a CMMS system's database.
- A link to jump from CBM system GUIs into CMMS GUIs and vice versa.

3.3.4.3. Design considerations relevant to localised or remote access

Identify the types of computer platforms and operating systems the CBM user interface will be made available through. Localised CBM systems are more likely to reside on one computer platform and one operating system, as they are unlikely to be networked. Remote CBM systems are more likely to be accessed through one of several computer platforms or operating systems. The HMI designer must design the software which runs the CBM HMI to operate on all the computer platforms and operating systems it will encounter.

CBM GUIs designed for access over the Internet, should be designed with GUI web design practices in mind. In this case selecting suitable web page design tools and Browser interpretable programming languages becomes a critical developmental decision. Section 2.10 introduced several programming languages for developing static and dynamic web pages.

Another design issue applicable, more so to remote accessible CBM systems, than localised, is security, especially when network access is being catered for. A few of the security measures the HMI designer might consider include: Entry to the CBM GUIs by user name and password authentication; encrypting files before transmission; and recommending the intended user have a firewall included as part of their own networking security.

3.3.5. Design considerations relevant to data management

Data management encompasses: Receiving, processing, storing, extracting further processing and displaying data. Each procedures can be associated with data movement, either into or out of a database under the control of software activated instructions. This process is referred to as data mining. Authors Kennedy et al. [2000], Jennings et al. [2002], Onga et al. [2001] describe data management issues for CBM systems capable of presenting CM information through web pages. Section 2.4.3 earlier discussed data extraction and data processing issues.

The HMI designer must acquire a knowledge and understanding towards data management and data mining, in order to realise the design features to be incorporated in a CBM HMI. Data management design features for consideration by the HMI designer are further discussed in the sections below:

3.3.5.1. Identify design features for data extraction, manipulation and presentation

Design functional features for consideration include, enabling users to perform a variety of flexible database searchers, e.g., search for data above or below a user specified value; search for data within a user specified range or time period; search for data within a specific storage location, assuming there are more than one; search for data with the same values. The HMI designer may wish to consider providing users with the ability to control the format extracted data is returned in, e.g., HTML, XML, xls, doc. txt, etc. Factors influencing this decision include: identifying compatible formats the chosen mediums used to display CM information require, and the format required in order for data analysis post processing to be undertaken. Discussion in sections 2.9, and 3.3.7 provide a variety of ideas and methods to consider for presenting CM information.

3.3.5.2. Identify design features for archiving and redistribution

Once a CBM system goes live and active, quantities of sensory data extracted from machinery being monitored will steadily or rapidly, consume storage space on the storage device/s being used. Occasionally, it will become desirable to redistribute/transfer data from one storage location to another, or delete data. This can be programmed to occur automatically. The HMI designer should therefore design features into a CBM GUI offering users control over data redistribution or data deletion. Providing users with this type of control is a sensitive issue, to be discussed with the intended customer. Access to such a control feature can be anticipated to incorporate password and username security restrictions.

3.3.5.3. Database synchronisation

Database synchronisation involves synchronising data from two or more networked (linked) databases, so that data on each database matches. This means any changes to any database will appear in all the other databases; hence potentially any site can adopt any level of control over the system. This is a useful design feature for organisations using CBM systems at multiple locations, storing CBM data on multiple databases residing on multiple storage devices, networked together. Database synchronisation may prove desirable in an organisation such as Royal Mail, where multiple CM techniques will be used to gather sensory data from multiple machines, distributed in multiple locations.

Features to be included in a CBM GUI for database synchronisation control should be restricted to authorised users, in the same way as controls for, database data information archiving and redistribution. Control features such as: down load data and synchronise, applicable to an individual downloading CBM data gathered using a portable CBM data collector; and control over the time intervals database synchronisation is performed. Additional control features would depend upon the complexity of the data synchronisation technique adopted to suite an organisations requirements.

3.3.6. Data analysis design considerations

Data analysis techniques are an essential design function for inclusion in CBM systems, because they add visual clarity towards understanding and making decisions based upon large quantities, of often hazy or unclear data. Added clarity enables CBM analysts and practitioners alike, to make maintenance and operational decisions with greater confidence and accuracy.

The HMI designer must acquire a knowledge and understanding towards data analysis, in order to realise the design features to be incorporated in a CBM HMI.

3.3.6.1. Selecting suitable and appropriate data analysis techniques to include in a CBM GUI

Data analysis techniques including: data filtering, data smoothing and data noise reduction, add visual clarity to the raw data gathered from sensors. Unseen trends, cyclical behaviour and sudden condition changes are all characteristics the data analyst has the potential of identifying, following the correct selection of a data analysis technique. Influencing factors affecting the selection of data analysis techniques include:

- **The CM technique/s being employed.** Sensory feedback from CM equipment represents a quantifiable value specific to the type of CM technique being employed, e.g., sensory feed back from Thermography CM equipment will represent a measure of temperature. Sensory feedback from Acoustic CM equipment will represent a measure of noise. Sensory feedback for Oil analysis CM equipment will include a percentage measure of foreign particles within in the oil being tested, such as metallic materials. Identifying trends, cyclical variations or sudden changes in sensory feedback, necessitates matching the data analysis technique with the type and nature of quantifiable sensory data being analysed. For example, a data analyst might choose two different types of data analysis technique to analyse sensory feedback for a thermography CM system, to what he/she would for a vibration CM system.

- **The anticipated skill level of the intended users, i.e., their ability to make accurate machinery health decisions based purely upon information taken from a CBM system.** CBM systems designed for generic applications should be designed with a variety of data analysis techniques, suitable for use by the average up to expert data analyst. Custom designed CBM systems should be designed to include data analysis techniques targeted specifically at identified (known) user skill levels, or anticipated future skill levels, following user system training and familiarisation. Besides unskilled operators are more likely to make mistakes and fail in their monitoring and diagnostic abilities than more experienced operators, Jin et al. [2004].

- **Deciding how many data analysis techniques to include in a CBM GUI.** This decision represents a compromise between providing enough data analysis techniques to enable users to make accurate diagnostic and prognostic decisions, whilst avoiding confusion and inefficiency resulting from excess data analysis for data analysis sake. For example, in an extreme case, costs incurred due to data analysis, could exceed the costs resulting from a run to failure machine maintenance policy. Only data analysis techniques which justifiably contribute to accurate maintenance and operational decisions, should be selected for inclusion in a CBM system. Examples of data analysis techniques include:
    - Fast Fourier transform (FFT)
    - Weibull
    - Mean time before failure (MTBF)
    - Nyquist
    - Waterfall spectrum (same measurement taken at different time intervals)
    - Time Waveform
    - Spectra Analysis
    - Waveforms
    - Orbits
    - Overall vibration level trends
    - Spectrum with cursors
    - The ability to plot a components condition over two or more time periods for comparison reasons

- **Making provision for alternative data analysis techniques.**
  Despite a CBM design teams efforts to match user requirements with data analysis techniques, there will almost certainly arise a user need to offer the feature enabling users to export CBM data into an external software application. In its exported state CBM data can be personally manipulated using spreadsheets, personally designed programs, or placed in a users personal database. Ideas from other software applications offering data exporting capabilities can be used as a starting point, for the HMI designer when he/she comes to designing data export controls, into a CBM GUI, e.g., those incorporated in the Microsoft Access GUI.

3.3.6.2. Identifying design features to control data analysis functions

Selectable functional data analysis controls the HMI designer should consider including in a CBM GUI include:

- Controls to select the time period users wish to analyse data between.
- Controls to select the data channel (data type) a user wishes to analyse.
- Controls for selecting the types of data analysis technique users wish to use in their diagnostic determination.
- An ability to specify whether data retrieved from CM sensors is filtered before being made available for analysis.
- Control for specifying upper and lower control limits, applicable to alarm activation conditions.
- Chart appearance controls, which allow users to alter the look and feel and shape of CBM charts and graphical displays, and possibly even change GUI descriptions and icons at a personal level.

The CBM GUI screen shown in Figure 3.1, demonstrates many of the selectable data analysis options listed above. Selectable data analysis control functions are positioned in the top left of the GUI inside a grey box. Although not visible in Figure 3.1, selectable options are included and hidden within rotating combo boxes for the following data analysis options: data channel selection, signal parameter analysis technique and type of filtering.

3.3.7. Selecting effective methods for communicating CM information

Popular methods of communicating CM information to users includes: through a computers GUI, via large overhead or office located digital display screens, via printed reports, via audible alarms, via visual alarms, and via mobile devices. Each method presents the HMI designer with different design challenges.

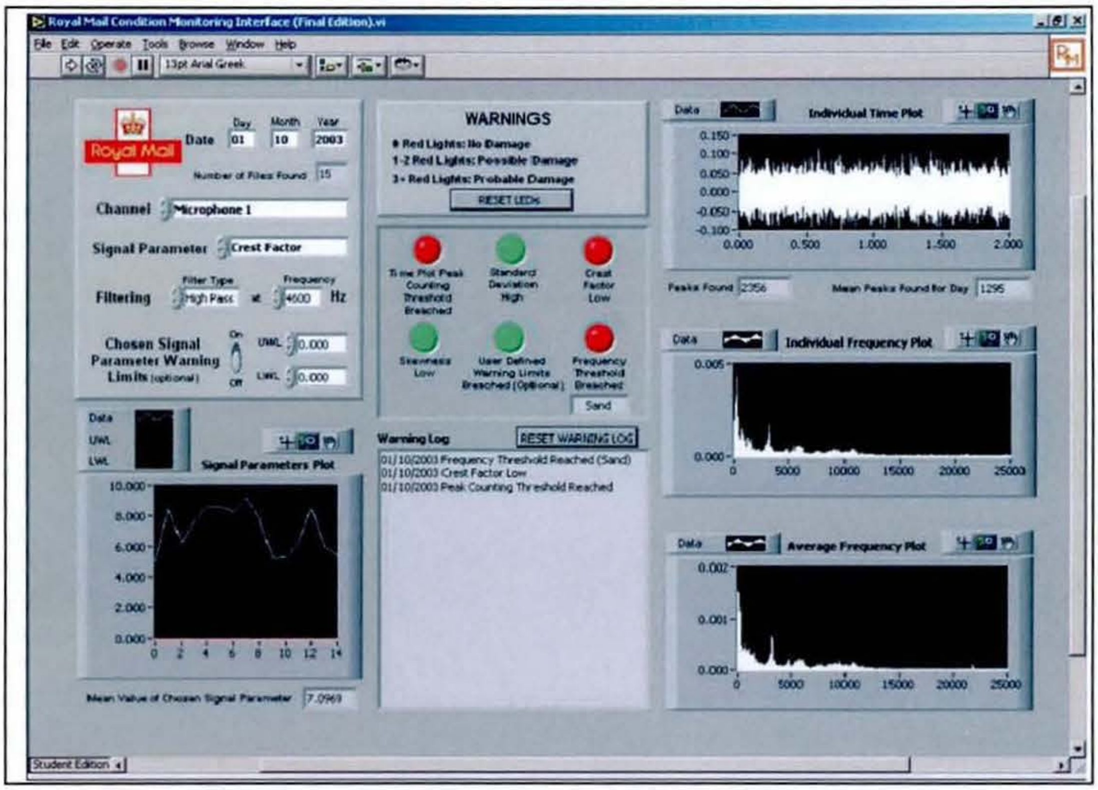


Figure 3.1. Experimental CBM GUI screen developed for presenting and analysing acoustic and vibration CM information, Walder [2004].

3.3.7.1. Communicating CM information via reports

The HMI designer should understand what purpose CBM reports have, why they are considered necessary, what makes a good and a bad CBM report with respect to report design and information content; identify the target audience CBM reports will be made available to (refer to section 3.3.1.1), identify the user requirements of the target audience, and identify the most effective method of distribution. Table 3.1 shows part of a CBM report generated following oil analysis CM test procedures, by TriboLogik.

3.3.7.2. The purpose of CBM reports

CBM reports act as a source of information for individuals interested in monitoring or knowing the health of equipment and machinery. Information contained in CBM reports reflects the health of equipment and machinery being monitored, for a predefined or user selected period of time. Knowledge acquired from CBM reports is used to make immediate and future machinery health control decisions, and or make plans for future operational demands.

Customer	David Smith Ltd.
Machine Name	ENG 1234
Received	05-APR-04
MACHINE TYPE	DIESEL ENGINE
CONTACT 1	JOHN SMITH
LUBE TYPE	ESS GALENA SAE40
REPORT DATE	07-APR-04
REPORT TIME	11:38:37
MACH MFGR	EMD
SAMPLE NO:	999-7-313-78
MACH MOD:	SD90MAC
PO NUMBER	1234

Machine Condition is CRITICAL. Lubricant Condition is MARGINAL

RECOMMENDATIONS	LOGIC
• When the exhaust back pressure is high, the engine temperature will increase since more exhaust heat must be carried away by the cooling system. • When exhaust back pressure is high engine power will decrease • because of incomplete scavenging. • To locate the cause of high exhaust backpressure, install a water manometer to the exhaust manifold, and measure the backpressure. If it is within specification, check the valve adjustment and/or valve timing. • Check radiator hoses and coolant filter. • Check adjustment and operation of thermostat fan and shutter stat. • Inspect exterior of engine for excessive dirt, grease, etc. and/or noticeable leaks. • Check coolant level. • Check oil level. • Check if radiator core is plugged or scaled, clean it and the engine. • Check for air flow restriction in radiator. • Check radiator pressure cap. • Check if shroud positioned properly so that no vacuum pockets can build up. • Check that fan blades are not broken, or bent. • Check adjustment of clutch-type fan drive. • Check drive belts for correct tension. • Book unit. • No deferral permitted • Unit not to be released running without thorough inspection. • Check oil for oxidation dirt, and high sludge content.	• Copper exceeds normal limits (>95 ppm). • High Copper indicates wear or failure of piston thrust washer, rocker arm and/or bushing and wristpin insert. • Zinc exceeds normal limits (>15 ppm). • High zinc indicates contamination of shop oil or oil added by outside source. • Lead exceeds normal limits (>35 ppm). • High lead indicates wear or failure of main bearings, conrod bearings, idler stub shaft bearings. • Tin exceeds normal limits (>20 ppm). • Piston wear tin in combination with lead or copper rise, indicates bearings wear. • Oxidation of the oil is occurring. The oxygen compounds polymerize to form viscous soluble materials (lubricant thickening) and insoluble materials (sludge and deposits). Some of the oxygen compounds are active, polar materials that accelerate rust and corrosion. • Possible causes of high viscosity: contamination soot/solids, incomplete combustion - A/F ratio, oxidation, degradation, leaking head gaskets, extended oil drain period, high operating temperature, improper • grade oil.

Table 3.1.Example Condition Based Maintenance report generated by TriboLogik.

Figure 3.2 shows a graph within a CBM report, consisting of 2 trend plots of Gs (RMS) against Time (hh:mm). The pink trend is a prediction and the blue trend is a plot of real values.

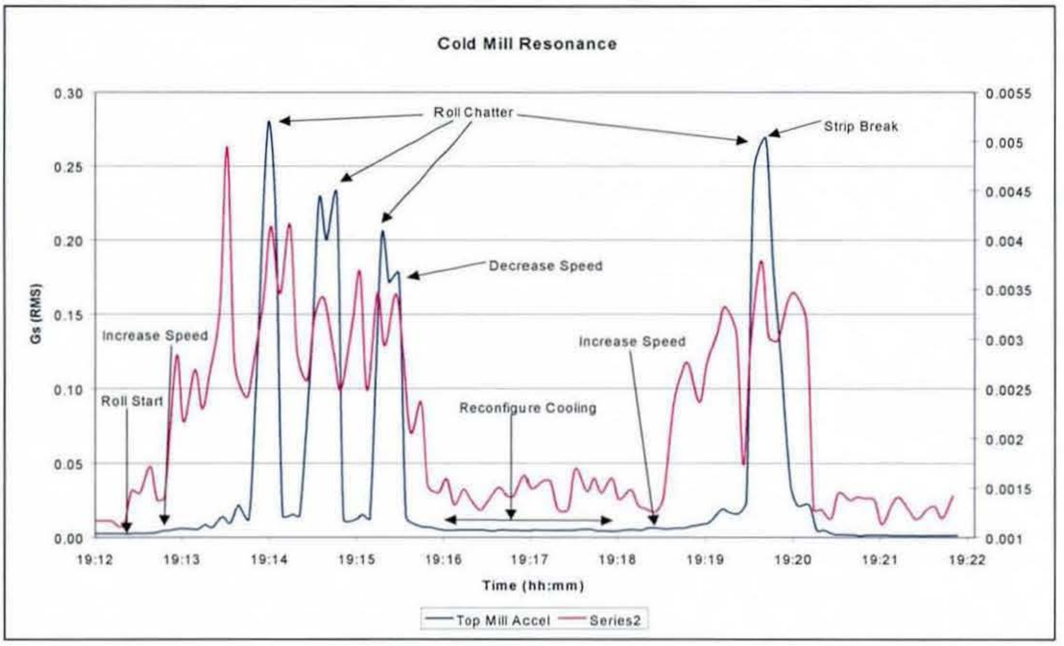


Figure 3.2. Condition based monitoring data extracted from rollers in a steel mill, exported to MS Excel and plotted. Courtesy of Marrs Inc.

3.3.7.3. Design rules for CBM reports

Determining what constitutes good report design and good presentation is a judgmental affair, dependant upon individual preferences. CBM reports should utilise graphic design techniques aimed at easy readability and quick interpretation. Reports should be designed to suite the CM technique being utilised. CM techniques dictate what information is collected from machinery, manipulated, and then presented. Different parameters are more conducive to being presented in one particular format compared to another, e.g., spectrum graphs are a suitable method for representing acoustic signals, thermal images are ideal for presenting feedback from infrared cameras, and x-y graphs are often ideal for displaying vibration measurements against time. Reports should present information identified from user requirement investigations, as aiding and/or critical towards maintenance and operational decision-making. Reports should be designed according to the intended users/s requirements. Certain GUI design rules mentioned in section 2.9.3 are equally applicable to CBM report design. Additional report design rules include:

- Presenting data in tables and graphs, rather than as a list of figures, e.g., graphical plots are easier to assess condition movements over a period of time, than a list of figures.
- Design reports with structure in mind to improve visual clarity and readability. Design techniques for creating structure include: Grouping similar information together under headings in bordered regions, underlining, bullets and numbers to differentiate lists, colour and correct use of spacing.
- Incorporate pictures and images if available to convey or emphasise a machines or components condition.
- Take all the necessary precautions to ensure information contained in CBM reports is true and accurate.
- Prioritise information contained within CBM reports according to its level of urgency. Information at the top of a report is more likely to be read immediately, and therefore should be reflected as such according to its level of priority. Alternative methods for conveying urgency in reports includes: the use of colour, large text, bold text, underlined text, highly visual text fonts, flashing text on GUIs, locating noticeable or message conveying symbols and images, next to the item of urgency, etc.

3.3.7.4. Knowing what to include in CBM reports

The content included in CBM reports should be targeted at satisfying the intended audiences personal requirements, but should include such information as:

- Displaying the movement of machinery conditions, numerically or graphically, using graphs containing upper and lower control limits.
- A comparison of like for like machines performing identical operations.
- The number of CBM system alerts generated between predefined periods of time.
- Displaying diagnostic and prognostic results, i.e., cause of failure and predicted remaining operational time, before maintenance work should be undertaken.
- An inspection list, or set of recommended procedures technicians or maintenance engineers should follow in order to identify and fix fault causes.
- Graphically displaying failure signatures.

Designing one CBM report to satisfy every user requirement is neither practical nor realistic. A more realistic proposition will be to design several CBM reports, each targeted at presenting information relevant to a particular work group, or designed to meet a particular theme or functional requirement. Methods developed to assist this process are discussed in section 2.6.

3.3.7.5. Selecting methods for distributing CBM reports

Popular methods for distributing CBM reports include via GUIs, via printed reports, email, text messaging, and voice mail. Design considerations to be considered include:

- The required response from the intended audience.
- The technological requirements necessary to achieve the chosen method.

People tend to be more responsive to situations they find familiar and understand, i.e., take a Maintenance Engineer who regularly goes through the routine of accessing his companies computer system, from a specific location. In this situation the Maintenance Engineer is familiar with following a set routine, and would therefore find receiving CBM reports through the same PC/s and display more familiar than, through a mobile phone or PDA, or on a radio, he/she had neither seen nor used previously. However, this is not to say sticking to existing tried and tested (familiar) methods of communication offers the perfect solution. Besides, existing methods of distributing and communicating information amongst maintenance and operational staff, cannot be assumed to be ideal, rather a starting point to consider during the system development process.

Identifying and appreciating when and how the intended audience wish to receive CBM reports, will also influence the chosen method of CBM report distribution. For example, Maintenance Engineers might find it beneficial to pull up or have access to CBM reports while in close proximity to machinery on the shop floor (work area), to refer to while they perform maintenance work. However, Maintenance Managers are more likely to refer to CBM reports in an office environment, or at a desk. Closely linked to this area of investigation is the issue of understanding how frequently CBM reports should and will need to be issued. Maintenance Engineers might for example, wish to gain access and print CBM reports on a flexible basis, depending upon their day-to-day maintenance activities in and around the machinery. Maintenance Managers may however only require access to CBM reports every week or month. A solution to this issue might include, enabling CBM system administrator/s manual control over when CBM reports are made visually available or issued and printed. Another closely related feature for consideration, is the provision for administrators to control what information is made available on CBM reports; refer to section 3.3.7.4. How the intended audience wish to receive CBM reports is directly linked to the format reports will be distributed in. For example, CBM reports being distributed over the Internet, must be sent in a format compatible with Internet Browsers, refer to earlier section 3.3.5

From a technological perspective, implementation costs will be considerably reduced if an organisation already has the necessary technology for distributing CBM reports. Organisations without the necessary technology immediately incur higher system start up costs and future system administrative and support costs, previously not experienced.

Security issues should also be considered when selecting the best methods for distributing CBM reports. Password and user name authentication could be used to control access rights to CBM reports targeted at different user groups. Encryption is another form of security that can be used to reduce the risk of spying. Encrypting CBM report transmissions, is only likely in military or governmental circles.

Transmission medium reliability is another factor that must be considered when choosing the desired method of CBM report distribution. For example, transmitting CBM reports along wires, cables and filaments, is less likely to encounter transmission reliability problems than wireless transmission methods, such as analogue or digital radio signals or microwaves.

3.3.7.6. Selecting suitable and appropriate alarms for CBM systems

Situations requiring human intervention, at regular or infrequent intervals during their operation, for what ever reason, tend to be designed with some form of built in or remote human attention grabbing alarm system. Alarms in this case have the same effect as a warning cry, purposely designed to attract a person's attention, and return them to inspect the system causing the alarm as quickly as possible. Alarms are essential in situations where it is unrealistic to expect human users, to be in attendance 100% of the time, at the location of the machine/s being monitored. CBM system alarms should be activated when:

- Measured machinery condition parameters exceed predefined accepted control limits.
- Measured machinery condition parameters show signs of a marked and continuous change in condition, away from normal operating conditions.
- Sudden peaks in a machines measured condition parameter values are detected.
- Continuous erratic machinery condition parameter values are detected, but not expected.

Control features incorporated within a CBM systems GUI, should offer users the ability to manually set the conditions at which alarms are activated, and the choice (if there is one) and severity of the activated alarms. Security measures such as password and user name authentication should be provided to prevent unauthorised alterations to a system's alarms.

The HMI designer should also consider the types of alarms chosen to alert CBM practitioners, and decide where to locate and distribute them. Popular alarm options include: audible alarms, visual alarms, automatically generated telephone calls, automatically generated text messaging, and automatically generated emails. McCrickarda et al. [2003] discuss different techniques for transmitting reports and messages from computer-operated systems, to networked and remote desktops and mobile devices.

Factors to consider when selecting audible alarms include: the environment alarms will be used in, the intended audience and the desired effect alarms should have. For example, noise from external alarms used in buildings located near residential areas, may carry and annoy local residents. Noise emissions should therefore be kept within health and safety regulations, and yet still be heard over other machinery. Bursts of high pitch noise or grouped pitches similar to those used by the emergency services, are more effective at gaining human (ear) attention than low pitch drawling tones. Tone variations can be used as a method of communicating both distance and condition. Alarms used on emergency vehicles generate a tone whose pitch appears to alter depending on whether the emergency vehicle is approaching towards, or departing from, a standing persons location. Audible alarms that gradually increase in volume with time or according to the severity of a condition, are popular in factory environments. Research investigating the advantages of using auditory alarms whilst tracking mistakes by machines, is discussed by Xiao and

Seagull [1999]. Additional research examining the advantages of auditory systems to compliment visual displays, has been conducted by Chen and Carlander [2003], Veltman et al. [2004], and Chen [2003].

Use of colour, strobe lighting and flashing lights, are recognised techniques for gaining peoples attention. A simple red, amber (yellow), green, colour stick is a good example of a well-used and effective visual alarm condition indicator. Visual colour coded condition indicators often associate: red with stop/warning, yellow with caution/attention, and green with advance/all clear. Singular coloured strobe or flashing coloured lights are very effective at catching a persons eye and therefore alerting them to a condition. Examples include: Yellow flashing lights on motorway maintenance vehicles, fork lift trucks and JCBs, and blue and red flashing lights on emergency vehicles.

Notification of alarm conditions via text message or email, lack the immediate attention grabbing effect created by audio and visual alarms. Techniques used to notify users that they are in receipt of new email or text messages, include:

- Sound effects, e.g., various ring tones or abrupt clashing noises.
- Messages such as: Inbox (3) *indicating 3 new messages exist in the in box*, and new message/s received.
- Icons designed to represent receipt of emails, e.g., an animated image showing a letter flying into a mailbox.
- Activation of vibrators incorporated inside a mobile device.

If text and email CBM alarm notification messages are to generate the same effects as the audio and visual alarms discussed above, alternative more immediate attention grabbing (human sensory irritant) techniques of notifying users they are in receipt of new email or text messages will be required. For example, an audible spoken message generated and continuously repeated, until the received message is opened, consisting of the words: 'Machine condition alert received', or 'Condition alert received for *name and location of the machine generating the alarm*'. Alternatively these same audio messages could be displayed on the receiving users computer or mobile displays.

3.3.8. Design considerations for a CBM GUI

Graphic User Interfaces are the most popular form of human machine interaction presently incorporated within CBM systems. Section 2.9 and 3.3.7.3 discussed methods and guidelines for achieving good GUI design.

3.3.8.1. Selecting suitable and appropriate navigational techniques to include in a CBM GUI

Choosing the navigational strategy for a GUI is a critical design decision for the HMI designer. Marsico and Leviadi [2004] discuss navigation strategies for web sites. A GUIs navigation strategy ultimately determines the ease with which users are able to link, move between and activate all the various features offered in a software application or web site. The chosen navigational strategy should channel users through a software application or web site to facilitate the anticipated goals of the user. For example, the screen sequence a navigational strategy for an imaginary CBM GUI might follow could be:

- Start up screen.
- Screens with features offering CBM practitioners an overall assessment of machinery condition.
- Screens with features providing CBM practitioners with the capability to determine whether maintenance is recommendable and its level of urgency.
- Screens with features offering possible maintenance procedures suitable for correcting the diagnosed failing item/s within a machine.
- Screens with features designed to provide CBM practitioners with links into an organisations maintenance scheduling system, e.g., a CMMS, so that maintenance can be scheduled around other jobs and operational demands.

3.3.8.2. Selecting suitable help assistance for inclusion in CBM GUIs

Methods of incorporating help assistance within a GUI were discussed in section 2.9.3 Help assistance the HMI designer should consider designing into a CBM GUI should offer advice relating to:

- Choosing the best type of data analysis technique, or variety of data analysis techniques, to use when deciding upon the present condition of a component/s being monitored within a machine.

- Why and when a CBM analyst will or may find it more useful to export data from a CBM system, into an external software application, namely a spreadsheet, in order to perform alternative data analysis techniques to those designed into a CBM GUI.
- The procedures for extracting and exporting CBM data to external applications.
- How to identify failure signatures for the machinery being monitored.
- Knowing what control limits to set for a CBM GUI, and knowing what procedures to follow.
- Knowing how to extract and compare historical CBM data against present and recent CBM data readings.

3.4. Summary

The methodology has identified design considerations anticipated to affect design decisions during the design and development of a CBM HMI. Future research and experimental work should take into account points raised in this chapter. Design considerations identified were sub categorised under eight headings, notably:

1. Identify user and system requirements.
2. Selecting methods of HCI suited to the CM technique.
3. Design considerations applicable to diagnostic and prognostic functional capabilities.
4. Design considerations for integrated and networked CBM systems.
5. Design considerations relevant to data management.
6. Data analysis design considerations.
7. Selecting effective methods for communicating CM information.
8. Design considerations for a CBM GUI.

The HMI designer is encouraged to attend to multiple design consideration at the same time where possible, in order to speed up the design and development process. However, it is emphasised that each design consideration should be thoroughly investigated.

Chapter 4

4. INDUSTRIAL REQUIREMENTS FOR CBM SYSTEMS, SOFTWARE AND GUIs

4.1. Introduction

Chapter 3 presented a design specification for designing and developing a Human Machine Interface for a CBM system, consisting of a selection of design factors and considerations the Human Machine Interface (HMI) designer should refer and reflect upon, when selecting and developing suitable design ideas for a CBM HMI. Chapter 4 will investigate and present the views from individuals within industry on CBM systems, CBM HCI, and CBM software GUIs. The objective being to appreciate and understand real life CBM system implementation and operational experiences, and identify what design features are valued in a CBM GUI.

Findings from three surveys, undertaken by the research student, each a continuation from the previous are presented and discussed. The first survey investigates the general application of CBM across industry as a whole, asking questions aimed at:

- Understand the incentives for introducing CBM systems.
- Identifying technological considerations associated and encountered.
- Understanding how CBM systems have been implemented.
- Assessing personal opinions on the reliability of CBM systems.

The second survey investigates how CBM systems should communicate and interact with the intended users, CBM practitioners. Three broad questions are asked:

- What is the most effective method of communicating CM information to maintenance engineers and other employees?
- What features should be included in a CBM user interface?

- What CBM system do you consider possess excellent HCI techniques?

The third survey continues from the second survey, at a more detailed level. Questions are targeted at understanding what CBM solution providers and CBM practitioners look for and value, in a CBM GUI and other HMI techniques. Respondents were asked for their opinion on three categories of questions, listed below.

- The level of importance they place on the incorporation of GUI design rules, discussed in Chapter 2, within a CBM GUI.
- The level of influence design features and factors identified from the second survey should impact on the design and development of a CBM software application.
- The level of agreement towards the inclusion of design features and factors linked to previous questions, have on the saleability and success of CBM systems.

4.2. Survey 1: Condition Based Maintenance Application Indicator for 2004-2005

Survey results gathered between December 2003 and June 2006, from 273 respondents, located in over 35 different countries are presented in this section. Results and conclusions from the first 157 respondent replies were submitted as a paper, Higgs et al. [2004], presented at ESDA 2004, Manchester University. The survey acts as a CBM application indicator for 2004-2005, targeting 6 key areas listed below:

1. Respondents' company information.
2. The type of CM technique/s applied by the respondents' company.
3. Incentives that led the respondents' company to implement their CBM system.
4. Technological and integration issues associated with respondents' application of CBM.
5. Implementation issues associated with the respondents' CBM system.
6. Reliability and consequential maintenance awareness issues following implementation.

A similar CBM questionnaire with fewer questions and fewer replies was conducted in 2002, published by Dunn [2002b]. Comparisons are made between both questionnaires results for those questions having a similar content.

4.2.1. Survey technique

The questionnaire was designed and distributed in accordance with the following stages:

- Select a suitable set of questions to meet the survey objectives.
- Design the questionnaire, taking into account web Browser presentation for online Internet accessibility, visual presentation, question layout, question legibility, and questionnaire length with respect to an average persons attention span.
- Select a suitable questionnaire web hosting company, taking into account hosting costs, functionality and flexibility of questionnaire design application, length of hosting time, and ease of use. www.CreateSurvey.com was the chosen provider.
- Advertise the questionnaire over the Internet using a variety of different approaches. Approaches used in this case included: Asking online maintenance magazines to advertise the questionnaire on their web sites, contacting likely respondents directly via email, and advertising on maintenance related online forum web sites: Idcon Inc. [2004], MaintenanceForums.com [2004], MRO Software Inc. [2004], Mining-Services.Com [2004], ReliaSoft Corporation [2004], SMRP [2004], Vibration Institute [2004].

Advantages of conducting a survey using the Internet are:

- Low cost hosting fee, less than £20 in 2004.
- Real time feed back.
- Access to a wide audience.
- The ability to display a controlled selection of survey results to respondents in real time.
- Personal flexibility concerning the amount of effort put into circulating the questionnaire, i.e., the Internet enables an individual to concentrate their efforts concerning advertising a questionnaire, into burst of high productive activity.
- An easier and faster method for respondents to complete and submit their questionnaire replies.

Disadvantages of conducting a survey over the Internet include:

- Failing to reach individuals within organisation who do not have Internet access or do not find time, or choose not to browse maintenance forum web sites.

- Including text boxes in an Internet questionnaire provides respondents with the opportunity to submit advertisements, rather than additional comments relevant to the question.

4.2.2. Survey results and discussion

4.2.2.1. Company information

Answers were received from an assortment of organisations and industries, demonstrating a wide application of CBM within industry as a whole. Appendix A.1, section A.1.2, provides company names and addresses for some of the companies being represented in this survey. Table A.1.1, Appendix A.1, identifies manufacturing-petroleum refining, chemicals and associated products to be the most popular industrial sector using CBM systems. The same result was true in a CBM questionnaire undertaken in 2002, Dunn [2002b]. The second most popular industrial group was classified as 'other'. An indication that a future survey of this nature could include a larger listed selection of industrial and business groups.

Responses were received from over 35 different countries, including the Americas, Europe, The Pacific Islands, Australasia, Central Asia, South East Asia, The Middle East and Africa. This is indicative of the worldwide distribution and application of CBM as a maintenance practice, and the effectiveness of questionnaire distribution over the Internet.

4.2.2.2. Condition Monitoring and non-destructive testing techniques

Survey results to the question, 'which CM and NDT technique do you apply?', represented in Table A.1.3, Appendix A.1, indicate the four most widely used CM and non-destructive testing (NDT) techniques to be: Vibration Analysis, Oil Analysis, Infra-red Thermography, and Human Senses. A similar result to the 2002 CBM survey Dunn [2002b].

Every CM and NDT technique listed as an option, has been selected by one or more respondents in reply to the question, and a further 55 additional CM and NDT methods identified, refer to Table A.1.4, Appendix A.1. Many CM and NDT techniques appear to be custom designed to the user's own requirement.

4.2.2.3. Incentives

Respondents were questioned on four motivational reasons and incentives as to why their company's introduced CBM. The four incentives are listed in Table 4.1, left hand column. Questionnaire selectable responses included: Strongly agree, agree, neutral, disagree, and strongly disagree. Respondents could also select the option, 'do not know or not applicable'. Results presented in Table 4.1 are shown in hierarchal order, from the most agreeable incentive to the least agreeable incentive. For example, 'to reduce the number of unscheduled machine breakdowns', was the most agreeable reason for implementing CBM.

Incentive for introducing CM equipment, or a complete CBM system.		Level of Agreement (% number of responses)					
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Do Not Know or NA
1.	To reduce the number of unscheduled machine breakdowns.	1.12	0.00	1.49	25.65	69.52	2.23
2.	To save money.	1.51	1.89	9.81	33.58	50.57	2.64
3.	To improve the organisations competitiveness.	0.75	1.50	15.79	33.46	46.24	2.26
4.	To adopt predictive maintenance techniques.	1.50	0.75	11.61	38.58	44.19	3.37

Table 4.1. Incentives driving businesses to introduce CBM systems.

A percentage majority of respondents selected strongly agree to all the incentives, listed in Table 4.1, left hand column. This result might have been expected, because each of the four incentives listed, represent reasons typically found in marketing leaflets, explaining why businesses should implement their CBM system. On the basis of this surveys results, such marketing talk would appear truthful.

Incentives 1 and 4, listed in Table 4.1, are loaded with motivational reasons for design considerations, when developing a desirable method of Human Computer Interaction (HCI) for a CBM system. For example, if maintenance personnel wish to reduce the number of unscheduled machine breakdowns and adopt predictive maintenance, the type of information a Human Machine Interface (HMI) should provide includes:

- A machine's live operational condition, as a measure of its health status.
- A comparison of a machine's measured live operational health status (condition), against accepted live operational conditions.

- A prediction of the remaining useful life, as a measure of time, left in an operational machine before its health status exceeds or falls below accepted measured condition parameters.
- A predicted time interval in which machinery should be stopped and maintenance and repair work undertaken.

Additional incentives for introducing CBM

Forty-four additional comments were received as reasons why respondents' businesses implemented CBM. Receiving a selection of reasons why businesses implement CBM can be expected, because the four optional selections are quite broad in nature, and will not cover specific individual organisational reasons for implementing CBM. Individual comments received from respondents, explaining why their business introduced CBM, are grouped together into the following categories: quality, production, maintenance systems and maintenance strategy and other.

Replies relevant to quality incentives

1. "QS9000 requirements".
2. "As a vital part of our manufacturing test program to assure a high quality product".
3. "Design improvements – weight reduction".
4. "To create benchmarking within the affiliate concerns".
5. "To offer a means of documenting quality repairs within our facility".
6. "Continuous improvement".

All six comments above indicate the companies in question adopted CBM to improve the quality of their products, in line with internal company quality standards, or to satisfy an independently regulated quality standard.

Replies relevant to production incentives

1. "To increase output through better reliability".
2. "For safety purposes as we operate with chemicals".
3. "Reduction of machine downtime due to avoidable failures".
4. "Reduce shutdown/repair time. Eliminate secondary damage. Enhance spare parts inventory".

5. "Too many time based works orders, which did not serve a purpose. We couldn't reduce them without other alternatives, like CM".
6. "To eliminate breakdowns as an issue. Maximises utilisation of investment and offers uninterrupted operation".
7. "Safety".
8. "Development of new production methods for old problems using new thinking".

All eight comments above present a strong production driven case for implementing CBM, including: to improve production output, to avoid or reduce the number of unscheduled failures leading to production stoppage, to maximise utilisation of investment, reduce secondary damage resulting from the failure of any one component within a system, improve spare parts inventory control, and improve health and safety.
Reducing production costs to a minimum in order to maximise production output is described by Dunn [2002a] as, 'Asset Effectiveness', the need to extract maximum profits from the minimum investment in plant and equipment.

Replies relevant to maintenance systems and maintenance strategy incentives

1. "We were carrying out a very labour intensive annual shut down and replacement program, CM reduced this dramatically".
2. "It is common sense, how else can you plan and schedule".
3. "Used as a change mechanism for tradesmen, to teach them maintenance".
4. "Interest by maintenance personnel to understand machine condition".
5. "As a strategy to enable reliability monitoring of the equipment".
6. "We previously used the services of a contractor until two years ago when we implemented our own in-house program".
7. "Because management saw others using it and wanted to show due diligence".
8. "It was an uncoordinated and not very well thought out implementation. In fact it was not an implementation, just an instrument engineer purchasing some CM equipment he had funding for in his budget".
9. "As a catalyst to change the organisations maintenance culture from reactive to proactive".
10. "To eliminate breakdowns as an issue. Maximise utilisation of investment and offer uninterrupted operation".

11. "The catastrophic failure of Narora nuclear turbine prompted the development of on-line Condition Monitoring and diagnostics. Technologies that have subsequently been installed in the power plants: Kakarpara, Gujarat and Ropar, Punjab in India".
12. "Improve running condition of machines".
13. "Better utilization of maintenance associates and other resources".
14. "To establish a comprehensive proactive maintenance program".
15. "It was a global initiative for all factories in 1990".
16. "With some of our equipment it was a regulatory requirement".
17. "Mandated by Regulations".

Each of the seventeen comments above provides an indication that CBM was introduced, because the companies in question recognised the need to alter the way they were applying existing maintenance practices. Reasons presented appear very individual, i.e., to avoid an annual maintenance shut down, improve maintenance planning and scheduling, to act as a maintenance training catalyst, monitor the reliability of equipment, follow the example set by other businesses, move from a reactive to a proactive maintenance culture, and to meet mandated regulations. Another reason for implementing CBM not commented upon, is to increase the Mean Time Between Maintenance (MTBM). In this case CBM is implemented on the assumption that the time interval between maintenance procedures increases, resulting from the introduction of predictive maintenance practices.

Replies relevant to incentives other than the above

A further 14 comments were provided, constituting mainly marketing information, from CBM solution providers.

4.2.2.4. Technology & integration

Respondents were asked whether their CBM system's incorporated one of four technological capabilities, concerning networking and integration, listed in Table 4.2, left hand column. The list of results shown in Table 4.2 are presented in hierarchal order, highest percentage majority at the top, lowest percentage majority at the bottom. For example, a percentage majority of 68.77% of companies CBM systems do not integrate with a computerised failure mode diagnostic system.

Technological capabilities of a company's CBM system.		% number of responses	
		Yes	No
1.	Does your maintenance system integrate with a computerised failure mode diagnostic system?	31.23	68.77
2.	Does your maintenance system link directly with a computerised stock reordering system?	33.83	66.17
3.	Can your CBM system be accessed through an Intranet or over the Internet?	40.37	59.63
4.	Is your CBM system connected to a network?	40.59	59.41

Table 4.2. Technological capabilities of a company's CBM system.

Nearly two thirds of CBM systems in use within industry between 2004 and 2005, were not networked and did not integrate with other computerised systems. This result suggests localised CBM design architectures are the preferred and most widely used design architecture. CM equipment within industry is therefore more likely to be encountered as a stand-alone maintenance decision aid.

Viewed from the perspective of the CBM HMI designer, each technological capability listed in Table 4.2 represents a design challenge, for consideration within a CBM HMI. For example, CBM systems that are networked may be designed with various design features included in their HMI, for data integration and data transfer. Integrational control capabilities are generally associated with accessing and transferring data from one system's database to another system's database, and passing signals or activation instructions between computer controlled devices and systems, once set criteria are reached. CBM systems whose Graphic User Interfaces (GUIs) can be accessed over the Internet or through a company Intranet were discussed in section 2.4.3. Computerised failure mode diagnostic systems take the form of knowledge-based systems and other artificial intelligent agents, incorporating algorithms capable of matching cause and effect scenarios. Computerised stock reordering systems are ordinarily associated and form part of the capabilities, offered through Computerised Maintenance Management Systems (CMMS). CBM Solution providers often make reference to their system being capable of transferring data and integrating with CMMS software.

Media used to present CM information

Remaining on the technological theme, respondents were also asked to identify which media their CBM system presented information to its users. Four popular media were provided as selectable options: charts, alarms, discrete values, and graphics and animation, as well as a text box for recording alternative media not listed. Results to this question are shown in Figure 4.1.

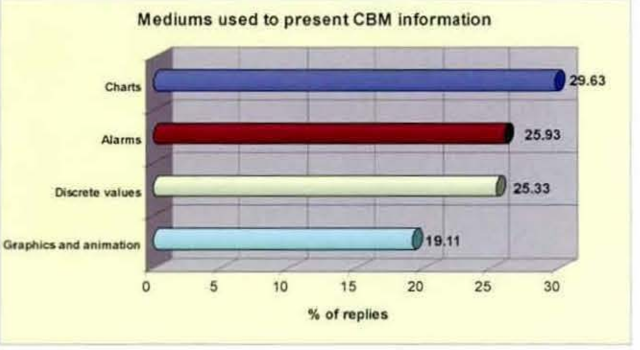


Figure 4.1. Media used to present CBM information.

Although charts received the highest percentage of replies, all four media types were similarly placed. This Implies CBM Graphic User Interfaces (GUI) should offer a variety of different media for presenting data and information to users.

Alternative media used for presenting information from CBM systems to its users is listed in Table A.1.5, Appendix A.1.5. Presenting CM information through written or computerised reports is the most popular alternative method. Suggestions to include in the content of CBM reports are: severity of faults, trends of individual fault severity, specific repair recommendation, maintenance priority, and works orders.

4.2.2.5. Implementation

The implementation approach companies have chosen for their CBM systems has been surveyed. Respondents were asked to select one option from a choice of five different methods, namely: 1) Using only internal company expertise and resources; 2) It was supplied and fitted by a vendor; 3) An external consultant was contracted; 4) A mixture of the above; and 5) Other. Results to this question are shown in Figure 4.2. A majority of 46% of respondents indicate they implemented their CBM system using a mixture of the proposed implementation approaches. Followed closely behind with 34% was the reply, using only internal company expertise and resources. The three alternative approaches all received similar respondent replies, between 5 to 7%.

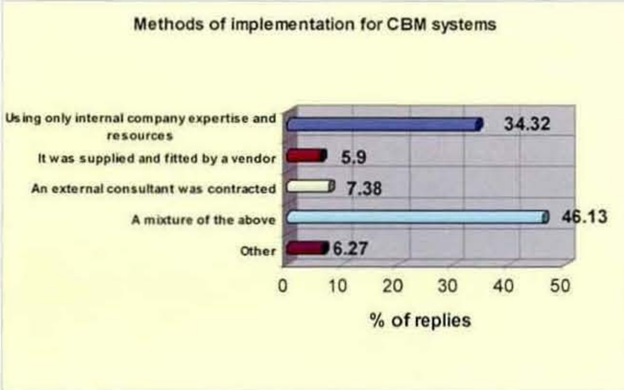


Figure 4.2. Method selected for implementing a CBM system.

4.2.2.6. Reliability

Respondents were asked to express a level of agreement towards five questions linked to the reliability of their CBM system, listed in Table 4.3, left hand column. Levels of agreement to choose from included: strongly agree, agree, neutral, disagree, and strongly disagree. Respondents could also select the option, 'do not know or not applicable'. Results presented in Table 4.3 are shown in hierarchical order, from the most reliable to the least reliable. For example, 'As a result of implementing a CBM system, it has led to further maintenance initiatives', is top of the list of reliability issues.

Responses were very positive to all questioned reliability issues, with the exception of whether the initial costs of CBM systems exceed the benefits gained. In this case an indifferent response was received, indicative of a neutral level of agreement. Question marks over the costs verses benefits for CBM systems arise because, every CBM system implementation is unique to a certain extent for each customer.

CBM system reliability questions		Level of Agreement (% number of responses)					
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Do Not Know or NA
1.	As a result of implementing a CBM system, it has led to further maintenance initiatives.	0.75	1.49	16.04	56.34	21.27	4.10
2.	Does your CBM System meet expectations?	1.11	2.59	16.67	53.70	22.59	3.33
3.	As a result of implementing our CBM system, operator and engineer awareness towards maintenance issues has increased.	1.11	2.96	16.67	47.41	30.00	1.85
4.	The CBM system has introduced predictive failure capabilities into our business, improving maintenance scheduling.	0.74	2.22	13.33	43.33	38.15	2.22
5.	The initial costs of the CBM system exceed the benefits gained.	14.81	29.26	17.78	20.00	12.96	5.19

Table 4.3. Views held towards the reliability of CBM systems.

One company may perform a smooth implementation, keeping costs down, and experience a quick measurable return and another may not. Costs will arise from material costs in terms of hardware and software; labour costs as a result of training; and production costs resulting from reduced production capacity, whilst machinery is being fitted with CM equipment.

Learning that engineer and operator awareness towards maintenance issues has increased, in the majority of cases, points towards the educational qualities CM equipment brings, in so far as understanding the operational characterises and qualities of an organisations machinery being monitored. This result ties in with the percentage majority of respondents who agree and strongly agree that, further maintenance initiatives have resulted as a consequence of their CBM system being implemented. With an increased awareness towards maintenance issues, further knock on maintenance initiatives will become visible, i.e., changing suppliers and or material types of identified problematic components, altering interval maintenance routine frequencies such as lubrication and cleaning, altering the order of maintenance procedures, and altering spare parts stock levels.

Learning that CBM systems have introduced predictive failure capabilities, improving maintenance scheduling in the majority of cases, emphasises the association between machinery CM and predictive maintenance.

4.2.2.7. Additional comments regarding survey respondents feelings towards their CBM system

As a final request at the end of the survey questionnaire, respondents were asked to provide any further comments they wished to express concerning their CBM system. Forty-four viable comments were received, which have been categorised into four areas: 1) Comments related to implementation issues; 2) Comments related to operational issues; 3) Comments related to reliability issues; and 4) Comments related to future initiatives.

Implementation guidelines

Comments associated with CBM implementation, presents a case for spending time and effort throughout the process of selecting, implementing and training staff to use CM equipment and systems, in order to improve the prospect of a trouble free introduction. Comments included:

- "Depends heavily on the skills of the technicians. Needs a lot of engineering support in the initial introduction".
- "It is important you use a technique suitable for what you are monitoring, the collection of data can be a routine, but turning it into information may not be possible, or of value".
- "It is very hard to get through to some engineers, especially the older generation".
- "The drives for increased reliability and reduced costs are strong motivators, for CBM systems. If CBM cannot be established all at once, start with what you have and move forward".
- "CBM as a tool is very powerful but you need good support from management to really make it work".
- "We have experienced difficulty in gaining maintenance personnel acceptance and support".
- "The technology is easy, but sowing the correct seeds to make company wide changes in established practices is extremely slow, hard and sometimes painful".
- "I do not believe we have gained all the benefits from implementing our Condition Based Maintenance strategy, due to a lack of training given to our in-house practitioners. A reduction in critical equipment overall velocity backs up this statement".

- "Our system has been demonstrated to work over the Internet between Australia and India, although at this stage no diagnostic data has been received remotely in real practice".
- "We are implementing our CBM system in stages, as yet no improvements have been seen".
- "We have implemented Condition Based Maintenance at a number of organisations. In some, the effort was cost-effective and productive, in others it was an expensive waste of resources. The reason programs are/are not successful in implementing CBM, has little or nothing to do with the technologies, and a great deal with the way that the program was approached within the organisation".
- "CBM implementation is only restricted by managements abilities, a major problem in industry today".
- "Organisation attitude adjustment, training, increased craft capabilities and strong management, must be in place before any CBM initiative will work. CBM requires adequate maintenance and reliability engineering practices to be in place, or its promises cannot be realized. As such, most installations are just toys rather than tools".
- "There is no substitute for adequate training, starting at the engineering stage and leading onto the operational stage for a project".
- "We have introduced CM following a piece by piece approach".

Closer examination of these comments presents an opportunity for suggesting a set of CBM implementation guidelines, aimed at assisting the smooth introduction of CBM into an organisation:

- Obtain backing and support from top management, before implementation.
- Recognise and plan for a change in the way maintenance is applied and viewed, i.e., reassess your organisations entire maintenance approach (strategy) in every affected department.
- Select and match a CM technique/s capable of doing the job, taking into consideration your own resources, and the level of employee expertise.

- Train and educate employees to appreciate the idea and philosophy behind CBM as a predictive maintenance practice. Train employees to use, understand and correctly act upon feedback from the CM equipment.

CBM operation guidelines

Comments connecting the introduction of CBM with an organisations operational decisions, and the direct effects they have over production are listed below:

- "Condition maintenance was introduced in 1987 and runs smoothly, resulting in great maintenance cost reductions. The problem for us was convincing 'New Management' of the cost benefits in continuing with our CM programme".
- "We need to continue to work on equipment reliability and not just data gathering".
- "We use a route based scheduled Condition Monitoring program for critical equipment. Shop floor personnel using vibration meters monitor other equipment. The plant personnel rely so much on the program that we are the first to be called, if any abnormality is noticed".
- "The trick in an organisation that is financially driven, resulting in a smaller maintenance workforce, is to strike a balance that allows the savings the business expects (hard savings), with the goals of maintenance in reducing downtime, increased quality and output, and maximizing equipment life, regarded by some general managers and the accounting fraternity as soft savings".
- "Focusing on failure is too restrictive; focusing on healthcare to prevent avoidable wear is better".
- "The best reliability and business benefits occur when the trades level people are trained to do the Condition Monitoring themselves".
- "Productivity improvement, cost savings, and safety for the Men and machinery".
- "It is all about rotating equipment".
- "CBM has resulted in more proactive based maintenance and machine utilisation".
- "CBM has reduced unnecessary shutdown of equipment for routine inspection".
- "CBM has been a great help in reducing/preventing unscheduled downtime".
- "CBM has improved our organisations capabilities to schedule jobs, and reduced the number of time based works orders".
- "Control issues and lack of knowledge make management and typical planners\schedulers the weak link".

- "CM leads to proactive maintenance".

Closer examination of the above comments presents an opportunity for suggesting a set of CBM operational guidelines:

- Use data and information gathered from the CBM system wisely, e.g.,
    - To monitor the reliability of your machinery.
    - To monitor the reliability of spare parts following numerous spare part replacements.
    - To assist purchase of new machinery, especially where comparison and performance are being taken into account.
    - To improve the way you schedule your production.
- Use targets to justify the benefits of a CBM system, making a comparison of the before and after implementation, e.g.,
    - Machine down time.
    - Machine output.
    - Quality of service or product.
    - Production output.
    - Machine / equipment life.
- Maintain support and enthusiasm for your CBM system by remaining focused on targets year in year out.

Overlap between implementation guidelines and operational guidelines may seem present. Ideally implementation guidelines will feed onto real life operational outputs. Orsagh et al. [2000] indicates that ideally operational guidelines for an Internet CBM system, should result in improved maintenance scheduling and reduce the machinery life cycle costs. Posting CM information on a web-site makes it readily available to all authorised personnel, improving information access, and therefore awareness towards machinery health.

Reliability issues

Six comments linking CBM directly with machinery reliability are listed below:

- "Without CM many unexpected failures would have occurred. These days unexpected failures are rare".
- "CBM has helped us take run, repair, replacement decisions on a more scientific basis".
- "As a maintenance planning tool, the 20 years of vibration based Predictive Maintenance (PdM) program has provided a benefit to cost ratio of 18.6 to 1".
- "CBM has resulted in less secondary damage to equipment, no catastrophic failures, and improved safety records".
- "A political initiative was cascaded from the head of maintenance in the continental HQ, that vibration monitoring was of little value and more decisions should be made on the basis of reliability data".
- "New management here uses Condition Monitoring purely as a "crystal ball" service, we now run to fail".

Four of the above comments place a positive view on CBM as a tool to improve reliability, and two place a negative view based on previous experience. All four positive remarks refer to the type of benefits predictive maintenance practices are expected to produce. Benefits linked to an ability to accurately track machinery performance and schedule investigative and actual maintenance, at a convenient time, before catastrophic failure occurs. The negative remarks relate to two businesses who have implemented CBM systems, but failed to achieve positive results. As a consequence both implementations have failed to gain the confidence of CBM practitioners within the companies in question.

Future CBM initiative issues

Comments concerning respondents experience with CBM and future initiatives are listed below:

- "We are always thinking of new ways to use Condition Monitoring techniques, e.g., on cranes and in pipelines".
- "Condition Monitoring of gas has been identified as the preferred maintenance system for the future of the organisation, and everything is being done to ensure that there is a fast track transition to this new system".

- "More improvements can be made to the present system".
- "CBM is a good issue in my company and we hope to extend it to others".
- "I would like to see greater implementation of CBM systems in the field at our customer sites".
- "Remote post nucleation crack detection and monitoring for Civil Aircraft - its the future".
- "Not on its own a complete answer, a RCM system, as part of a PPM setup is optimum in our case".
- "More development is needed as well as an increased awareness and usage of CBM by staff".
- "CBM is becoming more closely aligned with machine control and control systems - eventually they will probably merge".

The above comments suggest each company intends conducting future CBM initiatives within their own business or externally, by encouraging their customers to adopt such techniques. Each positive initiative originates from satisfactory results and returns following a successful CBM implementation. The challenge for business leaders when considering CBM initiatives is to keep their eyes open to this advancing technology, their brains open to opportunities and applications for its application, whilst keeping their long term financial and strategic feet firmly on the ground.

4.2.2.8. Summary

The survey acts as an application indicator for industrial usage for CBM systems between 2004 and 2005. A broad selection of industrial and business sectors are represented in this survey, from over 35 different countries. Survey results indicate CBM is most widely used within the Manufacturing-Petroleum refining, chemicals and associated products industrial sector. Vibration Analysis is the most widely used CM and NDT technique. Besides the conventional 10 identified techniques, numerous other CM and NDT techniques are identified in Table A.1.4, Appendix A.1.5.

The main incentives for implementing CBM systems are: to adopt predictive maintenance techniques, to reduce unscheduled machine breakdowns, and to save money. Additional comments indicate further incentives to be: improve product quality or meet quality

standards, various production improvement reasons, and to adopt change or improve upon existing maintenance practices.
Technological and integration trends present in today's usage of CBM systems, indicate a variety of different mediums being readily used for presenting information through GUIs. Popular mediums include: discrete values, charts, alarms, graphics and animation. Presenting CM information to users through highly visual mediums such as charts, graphics, and animation are preferred. Further comments suggest printable reports are also commonly used for passing on CBM data and information. Suggestions as to the contents for inclusion in CBM reports are bullet pointed in Table A.1.5, Appendix A.1.5.

Stand alone CM systems are presently more widely used than those connected to networks. At the present time approximately a third of maintenance systems integrate with failure diagnostic systems and / or parts reordering systems.

Two similarly popular CBM system implementation approaches emerge: 1). Using internal company expertise and resources, 2). Using a mixture of resources consisting of internal company expertise and resources, external consultants, and vendors.
A strong positive feeling exists towards the reliability of CBM systems following implementation with respects to: meeting expectations, increasing operator and engineer awareness of maintenance issues, creating further maintenance initiatives, and introducing predictive maintenance. A small majority of businesses do not believe CBM implementation costs exceed the resulting benefits.

Further comments concerning respondents' feelings towards their CBM systems, highlights four key system life cycle stages: 1) Implementation; 2) Operation; 3) Reliability; and 4) Future Initiatives. Each of these stages consists of elements representative of success or failure in a CBM system implementation and operation exercise. Time and effort is therefore recommended to understand each stage, initially from a broad subject perspective and then from a more focused customised business perspective.

4.3. Survey 2: Identifying CBM GUI Design Drivers, a Survey

4.3.1. Introduction

Findings from the first survey identified a preference amongst the majority of CBM practitioners, for receiving CM information graphically in the form of charts and automatically generated reports. Other less popular but frequently used mediums include, alarms in various forms and connotations, discrete values displayed on a GUI screen within tables or bordered areas, text messaging, and automatically generated phone messaging. The objectives of this second survey are to identify design features valued amongst CBM practitioners, for a CBM system's Human Machine Interface (HMI). Rather than set up a multi-choice online questionnaire, as was the case for the first survey, an email with three broad questions listed below was sent to those respondents completing the first survey.

1. What is the most effective method of communicating CM information to maintenance engineers and other employees?
2. What features would you like to see included in a condition based monitoring user interface?
3. Can you recommend a condition based monitoring system with what you consider has excellent Human Computer Interaction techniques?

Eighteen individuals from different organisations responded to the survey, addresses where provided are listed in Table A.2.1, Appendix A.2. Respondents did not always provide direct answers to each individual question, tending to generalise in their responses, and list those features they considered essential for inclusion on a CBM GUI. The results are therefore discussed generically, being subdivided into six influencing factors driving CBM GUI design, listed below for later discussion.

1. GUI design rules.
2. The intended audience.
3. CBM system Functionality.
4. Networking and Integration.
5. Environmental factors.
6. Tailor-ability.

Findings and conclusions to the second survey have been published by the International Journal of COMADEM, Higgs et al. [2006].

4.3.2. Influencing factors driving CBM GUI design

4.3.2.1. GUI design rules

Comments received associated with GUI design rules, earlier discussed in section 2.9.3, are split into ten distinguishable points identified and briefly discussed below:

- Keep information representation as simple as possible in order to achieve the desired affect. Avoid the need for further information manipulation. Information presented through CBM GUIs should be conducive to rapid interpretation, allowing decisions to be made in the shortest amount of time. Valued decisions are those that keep asset operational costs to a minimum, whilst maintaining the highest possible production efficiency.
- Structure and classify information in order to improve visual clarity. For example, arrange and group similar functional controls into bordered regions, under drop down menu bars and icon tool bars. Figure 4.3 illustrates this type of structure in a GUI, sold by Rockwell Automation. Information in this example has been structured using windows, tables and borders. Many of the features incorporated in this GUI design are representative of Microsoft office software applications.
- Target every aspect of the GUI design according to the intended audience. Section 4.3.2.2, discusses this issue in greater detail.
- Use recognisable and understandable icon designs for direct manipulation control. Do not reinvent icons that already exist in other popular software applications or on web sites. Popular icons incorporated in the example CBM GUI shown in Figure 4.3 include: a padlock to represent security, a printer to represent print, links in a chain to represent data transfer using Open Database Connectivity (ODBC) and a magnifying glass to represent search. Use icon descriptions aimed at the intended audience to clarify purpose and function.
- Provide a variety of help assistance functions, e.g., menu selectable function help, animated tutorials, links to commonly asked questions, links to product assistance and upgrades available from the supplying vendors web site.
- Use colour appropriately, both in the GUI design and on external attention grabbing light displays, e.g., for alarms and condition representation, consider using the

colour set used in traffic lights. Red equals: stop/warning, yellow equals: caution/attention, green equals: advance/all clear. Colours are also useful for highlighting and focussing a users attention onto specific areas of a display. The GUI in Figure 4.3 incorporates the colours red, yellow and white in the left hand window, left hand column, as a method of Condition Monitoring for components being monitored inside a PowerStation.

- Use audible sounds for GUIs and external alarms that are appropriate to the environment, the intended audience and fit for the intended purpose.
- Use recognisable graphical images where system representation is desired. Images that provide a clear modular representation of machinery and associated working assemblies. For example, the CBM GUI screen shown in Figure 4.3 incorporates recognisable images of the main components incorporated within a generator.
- Present statistical information in the most desirable medium to assist user interpretation and correct consequential decision-making. For example, plotting temperature against time on a graph with upper temperature alert control limits, is a clear understandable method of monitoring temperature variation against time. The GUI in Figure 4.3 incorporates five graphical representations or five different methods of monitoring and assessing the condition of the machinery.
- Keep GUI functionality at a level that achieves the desired result and is justifiable. Avoid including flashy functionality that adds no additional value to a users ultimate actions.

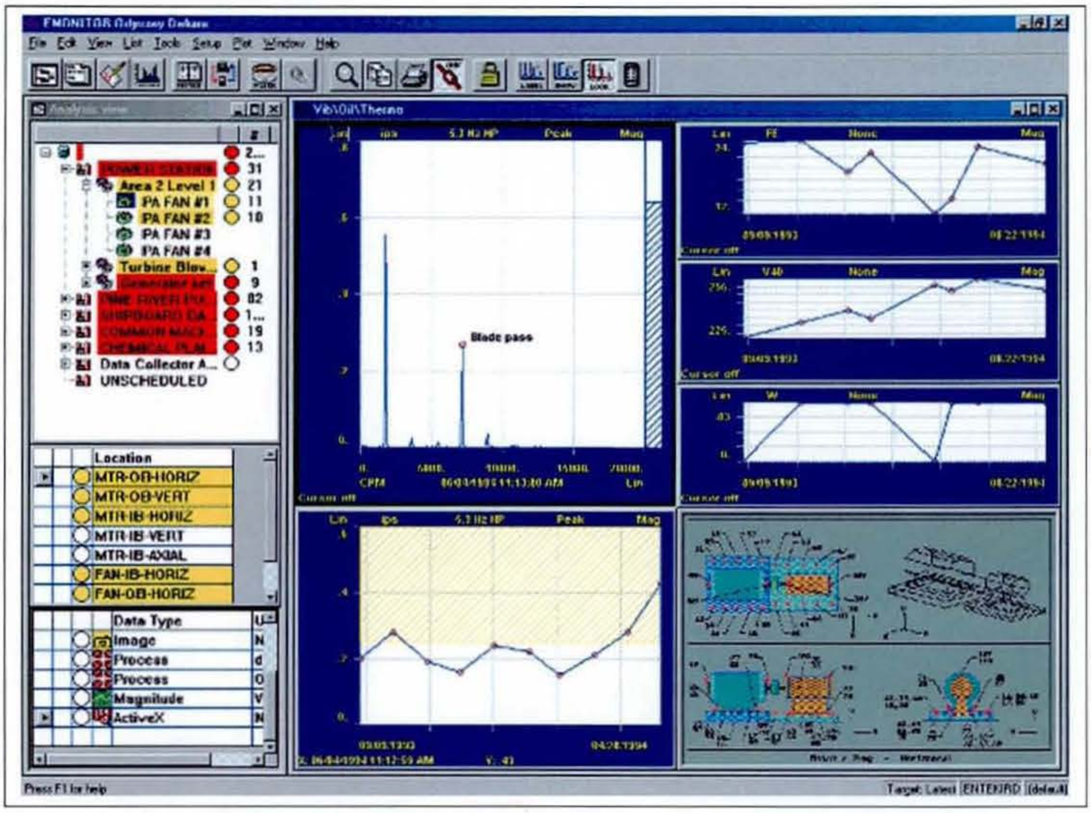


Figure 4.3. Example of a CBM GUI screen, courtesy of Rockwell Automation.

4.3.2.2. The intended audience

Four comments were received from CBM practitioners, acknowledging the importance of designing to meet the audience's requirements. Each is listed below and subsequently discussed:

- Use language within the GUI for, icon descriptions, menu options, labels, and help assistance, which is understandable by the intended audience. The intended audience are the group of individuals who make decisions based on information provided by the CBM system.
- Display CBM data in a format and medium the intended audience will understand, and be able to make correct decisions.
- Avoid using technical terminology that leads to confusion and incorrect decision-making.
- If the GUI is targeted at more than one user group, i.e., technicians, engineers or managers, use a common language acceptable by all, or section the GUI and restrict

access to different sections using password and username authentication. Sectioning a CBM GUI is a good way of sub dividing the functional capabilities of the system amongst several screens.

Further discussion explaining the importance of identifying the audience of a CBM system, in order to identify user and system requirements was earlier discussed in section 3.3.1.1.

4.3.2.3. CBM system functionality

Survey findings suggest many functional capabilities provided for in a CBM HMI are applicable and desirable for multiple different types of CM techniques. Identified functional capabilities for inclusion in a CBM HMI, are categorised into six functional area, notably: Data analysis, report generation, alarms, data archiving, displaying condition parameters, graphical machinery representation and malfunction location. Each functional capability is discussed below.

- **Data analysis**

Mechanical and electrical problems develop differently under different conditions. In order to improve the prospects for CBM practitioners in making correct diagnostics, a variety of data analysis techniques should be provided. Factors effecting the choice of analysis techniques include: the type of CM techniques being applied, the capabilities of the intended users, the computational power of the computer systems being used, and the accuracy of the sensory data being extracted by the CBM system. Factors influencing accurate diagnostics include: previous personal experience, intuition, and accurate and easily interpretable data representation. Further discussion concerning data analysis techniques was earlier discussed in section 3.3.6.1.

- **Report generation**

Reports are a valued method of communicating selective CM information, targeted specifically at an intended audience, to assist decisions based on machinery historic present and future condition. Report generation features should enable reports to be issued on demand or automatically. Automatically generated reports could be issued at pre-selected intervals, or following the detection of out of limit measured parameter values. Reports should be designed to satisfy multiple audience categories, e.g., maintenance engineers and technicians, or technologists and performance engineers, or operational managers. Provide relevant information and use an appropriate design structure offering visual clarity, suited to each audience category. Options for distributing reports include: through computers networked to the CBM system, via email, and text SMS messages. Further discussion concerning CBM reports was earlier identified in section 3.3.7.1.

- **Alarms**

Alarms are necessary for attracting people's attention and causing them to react in the minimum of time, performing remedial action as an where required. Actions to remedy for example, the detection of out of range acceptable component operating conditions. Popular alarm options include audible alarms, flashing lights, and automatic report generation. Choice of colours and audible alarm frequencies was earlier discussed in section 4.3.2.1. Reports linked to alarms should provide some indication as to the severity of the problem resulting in the alarm. For example, a report linked to an alarm might include the following message: Vibration levels exceed upper control limit by 15 percent, immediate maintenance required to avoid component failure.

- **Data archiving**

Data archiving is a useful function for recording and storing CM information at important historical events for future analysis purposes. Examples of important historical events include: following the detection and on set of failure signatures, under different operating conditions, immediately before and immediately after maintenance, etc.

- **Displaying condition parameters**

Displaying component and machinery physical condition parameters is desirable because it acts as a quick method for assessing a machines present and historic condition. Popular methods for presenting CM parameters include: numerical values and graphically. A typical graphical representation might be an X and Y graph incorporating control limits.

- **Graphical machinery representation and malfunction location**

Recognisable modular graphic illustrations, portraying the machinery being monitored, presents several possibilities for use by CBM GUI designers. Firstly they can be used as navigation aids, i.e., image hyperlinks, for moving between web pages. Secondly they can be used as a colour coded visual representation of a machines/components condition. Thirdly they can be used to quickly locate alarms.

4.3.2.4. Networking and integration

Section 4.2.2.4, identifies 40.59% of all CBM systems for 2004 and 2005 are linked to a computer network. Section 4.2.2.4 identifies 31.23% and 33.83% of CBM systems integrate with other computer systems, namely: failure diagnostic systems and stock reordering systems. Networked and integrated CBM systems require additional GUI features compared to standalone CBM systems. For example, networked CBM systems accessible over the Internet, require GUIs designed according to Internet Browser and web page design standards. Further reading describing the design and development of Internet accessible CBM systems is available from Kennedy et al. [2000], Jennings et al. [2002], and Orsagh et al. [2000].

Additional GUI features CBM software designers might include in networked and integrated CBM systems, unlikely to appear in standalone CBM systems include:

- Displaying physical condition parameters from several different CM system techniques, monitoring a single piece of machinery through one or several screens, incorporated within the GUI.
- Transferring (exporting) physical machinery performance parameters, either as raw data or statistical values, from the CBM software across into a Computer Maintenance Management System's (CMMS) database.
- Automatically generating CMMS works orders on a signal from a CBM system, following the detection of out of range condition parameter values.

4.3.2.5. Environmental factors

Environmental factors start affecting design decisions concerning CBM GUIs, in situations where access to the CBM system takes place in poor or varied environmental conditions, e.g., extremely low or high temperatures, poor lighting, space limitations, varying atmospheric conditions, etc. Environmental factors such as these influence the choice of display unit, which in turn constrain the chosen CBM GUI design, e.g., a small robust display with no more than two displayable lines of text, scrollable either up or down. Small display screens are ideal for presenting simple short text phrases and digital values, but of no use for presenting information graphically.

4.3.2.6. Tailor-ability

CBM solution providers offering off the shelf products, with a range of functional capabilities, expect to (or should expect to) tailor their CBM software GUI designs, to a customer's own design requirements. GUI design factors likely to be altered include: language and descriptions, colour schemes, direct manipulation control icons and functional capabilities. Tailoring a standard GUI takes time and costs money. It is therefore advisable to request programmers follow good programming practices aimed at limiting anticipated future rework time and cost incurred during program tailoring.

4.3.3. Summary

Condition Based Maintenance (CBM) systems come in many different shapes and sizes, dependant upon the type of Condition Monitoring being applied, and the application the Condition Monitoring system is being applied to. CBM systems may be totally independent modular systems or networked, for remote access, or integrated with other business systems. Each point influences the choice of Human Computer Interaction (HCI) selected for interacting with a CBM system. Graphic User Interfaces (GUI), text on paper, audible alarms, and colour coded condition indicators, are presently the most popular form of HCI, in use within CBM systems.

Survey results gathered from 18 CBM practitioners, identified six influencing factors CBM Human Machine Interface designers, should take account of during the design process:

1. Take account of GUI design rules.
2. Identify and understand the intended audience.
3. Incorporate GUI design features and other methods of HCI applicable to the CM systems functionality.
4. Take account of networking and integration design considerations.
5. Select methods of HCI suited to the environment they are likely to be found in.
6. Follow programming standards and select hardware that will be conducive to being tailored to customer demands at the minimum of cost.

Gathering personal opinions from CBM practitioners on preferred design features for inclusion in a CBM GUI, is one step towards developing a set of common CBM GUI design standards. Accomplishing such a goal requires a larger survey response, and a more detailed survey, incorporating more questions of a more focussed purposeful nature. Questions aimed at identifying specific GUI features for inclusion in a CBM system.

4.4. Survey 3: Placing a Value on CBM Software Design Factors and Features

4.4.1. Introduction

Survey 1 acted as CBM industrial application indicator for 2004 and 2005, identifying media for communicating CM information to users to include: charts and graphs, automatically generated reports, alarms in various forms and connotations, discrete values displayed on a GUI screen within tables or bordered areas, text messaging, and automatically generated phone messaging. Survey 2 asked respondents to identify effective methods used for communicating CM information to users, thus clarifying findings from survey 1. Survey 2 also asked respondents to identify preferred design features for incorporation in a CBM GUI. Findings from survey 2, resulted in the identification of six factors influencing design decisions during the development of CBM software, namely: 1) GUI design rules, 2) The intended audience, 3) CBM system Functionality, 4) Networking and Integration, 5) Environmental Factors, and 6) Tailor-ability. Survey 3 aims to identify the value associated with each of the six CBM GUI design and development factors, identified in survey 2. Questions asked are targeted at understanding what developers and users look for and value, when designing, buying or selling CBM software. The survey was conducted between December 2004 and June 2006. Of the eighty four replies received, eighty-one were fully complete, with three respondents failing to answer every compulsory reply question. The questionnaire consisted of seven questions. Question 1, differentiates between whether the answering respondent was either a CBM solution provider or a CBM practitioner. Question 2, asked whether respondents used or had developed a generic or custom designed CBM software application. Generic CBM software applications are those suitable for multiple different applications and customers. Custom designed CBM software applications are those designed and tailored to an individual customer's personal requirements. Question 3, asked who had designed and developed the CBM GUI, an internal employee, an external contractor, or an unknown source. Question 4, asks a multitude of questions aimed at identifying what level of importance respondents place on the incorporation of GUI design rules and CBM design features, within a CBM user interface. Question 5, asked how much influence respondents felt the list of factors driving CBM GUI design identified in survey 2, have on CBM software design decisions. Question 6, asked what level of agreement respondents placed on seven factors associated with decision-making and GUI design issues, and their affect on the saleability and success of a CBM system. Question 7, asks respondents to quantify how they rate their own CBM software's GUI, with respect to other CBM software GUIs, on the market.

4.4.2. Survey technique

A similar approach was used to design and distribute the questionnaire as that described in section 4.2.1. Exceptions include: not asking online maintenance magazines to advertise the questionnaire, not distributing any of the questionnaires by postal mail, and targeting CBM solution providers where possible. Respondents who had provided a contact email address in accompaniment to company details, during the first survey were all contacted, and asked via email to take part in this third Internet CBM survey.

4.4.3. Survey results and discussion

Results are presented using charts and tables, along with an accompanying explanation. Percentage figures given in the charts and tables, constitute the total number of replies received from both CBM practitioners and solution providers. A comparison is made between the results received from CBM solution providers and CBM practitioners.

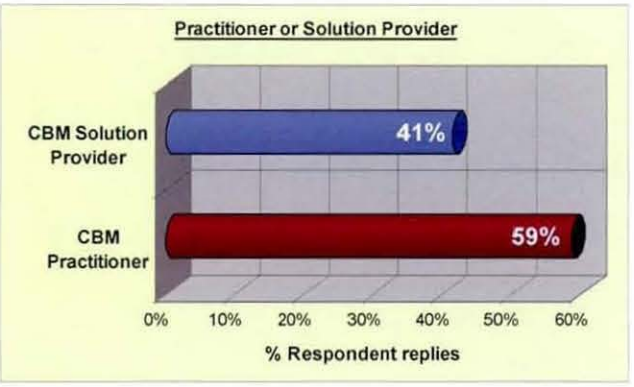
4.4.3.1. Company information

Survey replies were received from a mixed international group, representing companies located in: Australia, Britain, Canada, India, Indonesia, Italy, Germany, Malaysia, Mexico, New Zealand, Republic of Mauritius, Peru, South Africa, Sweden, Switzerland, Turkey, and USA. **Table A.3.1**, Appendix A.3, lists the participating company names and addresses.

4.4.3.2. CBM Software

Respondents were asked to name the CBM software they either used or sold. Forty-five different CBM software packages were named, some of which are included in Appendix A.3, Table A.3.1. RBMware from CSI was mentioned eleven times, making it the most popular CBM software package amongst the surveyed respondents.

4.4.3.3. Condition Based Maintenance software solution provider or practitioner



CBM practitioners form the majority of respondents participating in this survey, with a majority of 59%. A further 41% of survey respondents classed themselves as CBM solution providers.

Figure 4.4. Type of survey respondent: Practitioner or Solution Provider.

4.4.3.4. Custom designed or generically designed

A percentage majority 82% of survey respondents use or sell a generic CBM software application/s, as apposed to a percentage minority of 18%, who own or sell a custom designed CBM software application. Since a higher proportion of respondents use a generic CBM software application, it can be assumed that the results to this survey will be biased towards this set of respondents. This assumption is made on the basis that people form opinions on their own experiences and knowledge, acquired through life. Since computerised, automated and intelligent CBM systems, represent relatively new technology, CBM practitioners in particular, can be anticipated to have only had experience at using one or two such CBM systems.

Figure 4.5. CBM system design type: Custom or Generic design.

4.4.3.5. Designer of the CBM software GUI

A small percentage majority (39%) of survey respondents, identified a company employee as having designed their CBM software GUI, as opposed to 31% and 30% of respondents, who either didn't know or believe an external contractor designed their CBM GUI. A percentage majority of replies from CBM solution providers stated a company employee had designed their CBM GUI. A small percentage (4%) of CBM solution providers replied, they do not know who designed their CBM systems. CBM practitioners who have designed their own CBM GUI might be anticipated to be larger companies, as they would require sufficient capital to employ possibly extra individuals, with specialised expertise to design and program a CBM software's GUI.

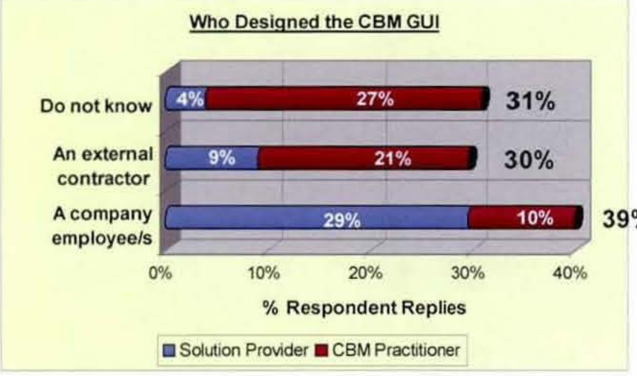


Figure 4.6. Designer of a companies CBM software's GUI: External Contractor or Company Employee.

4.4.3.6. The importance placed upon the incorporation of GUI design rules and CBM software design features in a CBM software's GUIs

Respondents were asked to rate sixteen GUI design rules and CBM software design features listed in Table 4.4, left hand column, according to one of five levels of importance. Percentage level of importance options included: Very Low, Low, 50:50, High, and Very High. If described numerically each classification would be written as follows: 0-25, 25-50, 50, 50-75, and 75-100. Results highlighted in yellow identify the level of importance voted by the percentage majority for each question.

GUI design rules and CBM software design features considered to have a very high level of importance by the majority of respondents, during the design process of a CBM GUI, listed in percentage order highest to lowest, are items 1 to 6 in Table 4.4. All GUI design rules and CBM software design features voted as having a very high level of importance, are suggested as representing rules or design features, the Human Machine Interface designer should compulsorily incorporate within a generic CBM software application.

Survey results from Higgs et al. [2004] identified popular media for presenting CM information to be graphs, charts, and reports. Items 3, 4, and 5, shown in Table 4.4 relate to and coincide with this result.

GUI design rules and CBM software design features considered to have a high level of importance, by the majority of respondents, listed in percentage order highest to lowest,

GUI design rules and CBM software design features applicable to CBM software applications.		Level of Importance (% of respondents)				
		Very Low	Low	50:50	High	Very High
1.	Providing a selection of data analysis capabilities.	0	3.70	13.58	30.86	51.85
2.	Providing a data archiving feature.	1.25	7.50	11.25	33.75	46.25
3.	The look, feel and interpretability of CBM reports.	1.23	4.94	9.88	40.74	43.21
4.	Presenting condition parameters graphically	1.23	1.23	17.28	38.27	41.98
5.	Incorporating maintenance and malfunction report generation capabilities.	2.47	6.17	14.81	34.57	41.98
6.	Incorporating password and user name authentication.	6.17	9.88	17.28	29.63	37.04
7.	Screen structure and information classification.	0	9.88	14.81	56.79	18.52
8.	Language with respect to legibility.	0	7.50	18.75	55.00	18.75
9.	Using Windows in the GUI design.	1.23	7.41	19.75	49.38	22.22
10.	Navigation techniques.	0	2.47	18.52	46.91	32.10
11.	Provide drop down menus.	2.50	12.50	25.00	46.25	13.75
12.	Colour coding designed to reflect machinery condition.	6.17	8.64	19.75	43.21	22.22
13.	The use of tables.	0	17.28	29.63	43.21	9.88
14.	Providing users with the ability to control the appearance and functionality of CBM GUI control features.	0	24.69	27.16	35.80	12.35
15.	Text Size and font type.	7.41	24.69	39.51	24.69	3.70
16.	Icons and icon design.	6.25	20.00	33.75	27.50	12.50

Table 4.4. Importance placed on the incorporation of different GUI design rules and CBM software design features.

are items 7 to 14, listed in Table 4.4. All GUI design rules and CBM software design features, voted as having a high level of importance, are suggested as representing rules or control features, Human Machine Interface designers should consider important, but not mandatory to incorporate within a generic CBM software application.

GUI design rules and CBM software design features considered to have a 50:50 level of importance by the majority of respondents, listed in percentage order highest to lowest, are items 15 and 16 in Table 4.4. All GUI design rules and CBM software design features voted as having a 50:50 level of importance, are suggested as representing rules or control features Human Machine Interface designers should consider, but spend less time and effort meeting, compared to other more highly rated design issues.

None of the sixteen GUI design rules or CBM software design features listed in Table 4.4, were voted by the majority of respondents to have a low or very low level of importance, during the design process of a CBM GUI. GUI design rules and CBM software design features, with less than a 50:50 level of importance, are suggested as being considered but requiring less time and effort in satisfying, compared to more highly rated issues.

In addition to the questioned list of sixteen GUI design rules and CBM software design features, respondents were also given the opportunity to identify additional rules and control features, they personally considered important during the design of a CBM GUI. Forty additional comments were received, categorised into seventeen headings listed in Table 4.5.

Each categorised heading in Table 4.5 is listed in rank order (highest first) according to the number of comments received. In the event where a chosen category listed in Table 4.5, left hand column, is the same or closely associated with existing GUI design rules and CBM software design features, listed in Table 4.4, the associated item number/s are identified in the right hand column, Table 4.5.

Nine of the GUI design rules and CBM software design features listed in Table 4.5, are similar or the same as one or more of the sixteen listed in Table 4.4. The top four items listed in Table 4.5 are associated with GUI design rules or CBM software design features,

Additional categorised user specified GUI design rules and CBM software design features, applicable to a CBM software application.		Number of respondent comments received relevant to this category	Rule or feature linked within Table 4.4
1.	Software design features that allow data to be exported or imported between software applications.	7	2
2.	User friendly logical and easy to operate user interface, e.g., easy to use navigation techniques.	7	10
3.	Provide appropriate data analysis tools to suite the type of CM technique being applied.	4	1
4.	An urgent method of communicating machinery defects and deviations from trends.	3	5 and 13
5.	Enable users to access CM information through Internet web pages.	3	New rule/feature
6.	Automatically distinguish and represent machinery condition according to the criticality before anticipated failure, and machine importance relevant to the process / production line.	2	1 and 13
7.	Design the CBM software to receive and process data from multiple different types of CM techniques, and multiple machines.	2	New rule/feature
8.	Provide automated data screening and automated fault diagnostics.	2	1
9.	Design CBM software to align with the major ICS software applications.	2	New rule/feature
10.	An error protection feature for back stepping through user actions.	1	New rule/feature
11.	3D representation of machinery and machinery condition.	1	New rule/feature
12.	The ability to generate machinery condition and maintenance reports.	1	4
13.	Provide users with an ability to make a selection from a group of GUIs. This selection might include user interfaces designed specifically for a particular operation or designed for a specific user group.	1	14
14.	Incorporate a feature for automatic machinery identification verification.	1	New rule/feature
15.	Identify user requirements when designing a CBM GUI at the level of the intended user.	1	New rule/feature
16.	Design the CBM system to operate through a single central database.	1	New rule/feature
17.	Design CBM software GUIs to present machine condition information in a self explanatory format and media	1	3,5,7,8,12, 13 and15

Table 4.5. Categorised additional GUI design rules and CBM software design features presented by survey respondents.

listed in Table 4.4, voted by majority to be high or very high in importance. Adding the new GUI design rules and CBM software design features to the original sixteen, creates a list of twenty-four from which the CBM software designer can work with. Repeating the survey for these additional eight rules and control features, would prove useful in determining their perceived level of importance.

4.4.3.7. The amount of influence GUI design rules and CBM software engineering decisions have whilst designing CBM software applications

Finding from Higgs et al. [2006] identified six design considerations anticipated to influence the Human Machine Interface designer, when designing a CBM GUI, notably: 1) GUI design rules, 2) The intended audience, 3) CBM system functionality, 4) Networking and integration, 5) Environmental factors, and 6) Tailor-ability. Table 4.6 presents survey respondents' results, identifying the level of influence each of the six design consideration and an additional seventh: 'The CM technique', is perceived to have whilst designing a CBM GUI.

	Influential CBM GUI design consideration	Level of influence (% of respondents)				
		None	A Little	50:50	Quite a lot	Completely
1.	The CM technique.	1.23	8.64	22.22	48.15	19.75
2.	Networking and integration.	1.35	4.05	21.62	45.95	27.03
3.	Designing the software to be tailored to multiple customers' demands.	2.70	10.81	22.97	45.95	17.57
4.	The intended functionality of the CBM software.	1.25	6.25	13.75	43.75	35.00
5.	Satisfying the intended audiences' requirements.	0	6.25	26.25	43.75	23.75
6.	Environmental issues, e.g., location of displays / monitors.	3.70	27.16	38.27	19.75	11.11
7.	Following recognised GUI design rules.	1.27	13.92	37.97	39.24	7.59

Table 4.6. Perceived level of influence GUI design rules and CBM software engineering decisions have whilst designing CBM software applications.

None of the design factors listed in Table 4.6 was voted by the majority, to completely influence design decisions for a CBM GUI. Five design considerations were voted by the majority to influence CBM GUI design decisions, quite a lot. Listed in percentage order highest to lowest, these include items 1 to 5. Design considerations listed in Table 4.6, voted as having quite a lot of influence, are suggested as being important but not mandatory for considerations by CBM system and software developers, whilst designing CBM software.

Two design considerations were voted by the majority to influence CBM GUI design decisions, according to the 50-50 level. Listed in percentage order highest to lowest, these include items 6 and 7, listed in Table 4.6.

None of the design considerations in Table 4.6 were considered by percentage majority vote, to have less than a 50:50 level of importance.

4.4.3.8. The level of influence CBM software capabilities are perceived to have on the saleability and success of CBM software

Respondents were asked to consider and rate seven CBM software design considerations, listed in Table 4.7, according to the amount of influence each has on the saleability and success of CBM software. Each of the considerations was selected under the assumption that they all influence the saleability of CBM software, and can be considered as a cross representation of the previous items listed in Table 4.4 and Table 4.6.

Results presented in Table 4.7 show two design considerations, voted by majority, to strongly influence the saleability and success of CBM software. Listed in percentage order highest to lowest, they are items 1 and 2. It is suggested both items be considered compulsory by CBM software designers, when designing a generic CBM software application.

A further five design considerations listed in Table 4.7, were voted by majority to influence the saleability and success of CBM software. Listed in percentage order highest to lowest, they are items 3 to 7. It is suggested CBM software designers consider items 3 to 7, to be important but not mandatory for inclusion or consideration, whilst designing a generic CBM software application.

CBM software design consideration		Level of agreement (% of respondents)				
		Strongly Disagree	Disagree	Neutral	Agree	Strongly agree
1.	Correct interpretability leading to accurate maintenance decisions.	0	1.23	4.94	39.51	54.32
2.	The reliability and quality of the programming language driving the CBM software.	0	11.11	22.22	32.10	34.57
3.	Presentation of condition parameters using maintenance and performance reports.	0	2.47	19.75	58.02	19.75
4.	Visually appealing GUI screens.	0	2.47	27.16	55.56	14.81
5.	Presentation of condition parameters using charts and graphs.	0	1.23	13.58	51.85	33.33
6.	The ability to tailor the GUI design to users/customers requirements.	3.75	10.00	32.50	35.00	18.75
7.	Enabling users to manually alter the appearance of the GUI and its associated features.	7.41	22.22	29.63	32.10	8.64

Table 4.7. Level of agreement associated with the saleability and success of CBM software.

None of the listed seven-design considerations received a majority percentage vote, from respondents strongly disagreeing or disagreeing, it influences the saleability and success of CBM software.

In addition to the questioned list of seven CBM software design considerations, respondents were also given the opportunity to identify additional considerations they personally felt affect the saleability and success of CBM software. Nineteen additional comments were received, categorised into nine headings listed in Table 4.8. Categorised items are listed in rank order highest to lowest, according to the number of comments received. In the event that a chosen category from the left hand column, is the same or closely associated with design considerations listed in Table 4.7, the associated item number/s are identified in the right hand column.

Consideration believed to affect the saleability and success of CBM software		Number of respondent comments received relevant to category	Design consideration linked with from Table 4
1.	Out of box user friendly user interfaces.	4	New consideration
2.	Miscellaneous comments.	4	NA
3.	After sales support, including maintenance, and software upgrades.	3	New consideration
4.	Marketing and Sales effort.	2	New consideration
5.	Design the CBM software so that it can be integrated with other computer applications and can be modified to operate on more than one operating system.	2	New consideration
6.	Tailor the software to customer demands.	1	6 and 7
7.	Design the software so that users can personally alter the look and feel of specific features provided in the GUI.	1	6 and 7
8.	Providing statistical analysis tools within the software, for defining frequency bands for analysis purposes and standard control charts for each frequency band.	1	New consideration
9.	Providing a database editing utility for removing false or corrupt data from the population	1	New consideration

Table 4.8. Additional categorised considerations believed to effect the saleability and success of CBM software.

Two of the design considerations listed in Table 4.8, items 6 and 7, are the same or associated with items 6 and 7, found in Table 4.7. Both considerations concern software tailor-ability issues.

Designing CBM software to be, 'out of box user friendly', received the highest number of additional comments. Software considered out of box user friendly would be assumed to adhere to many GUI design rules, discussed in section 2.9.3. CBM software designed to integrate with other computer applications and operate on more than one operating system, received two additional comments. Software capable of integrating with other computer applications, can be assumed to incorporate file and data transfer and sharing capabilities.

Software capable of operating on more than one operating system, will be programmed in a multi platform operate-able language. Considerations 3 and 4, Table 4.8, do not concern CBM GUI design as such, but rather the actual sales and marketing effort put in by the CBM solution provider, and the after sales support and maintenance offered, following the sale. Broadly speaking, both of these considerations affect the saleability and success of products universally.

4.4.3.9. How do respondents rate their existing CBM software's GUI

A percentage majority of 40% of respondents rate their CBM software's GUI design as being good and 37% very good, in comparison to alternative systems on the market. Only a small percentage of respondents (5%) considered their CBM GUIs to be poor or very poor, compared to other software. Solution providers have a greater tendency to rate their CBM GUIs designs, higher than CBM practitioners. Such a result must be anticipated, because rarely does a sales person (e.g., a CBM solution provider) consider his or her own merchandise, negatively compared to competitors merchandise.

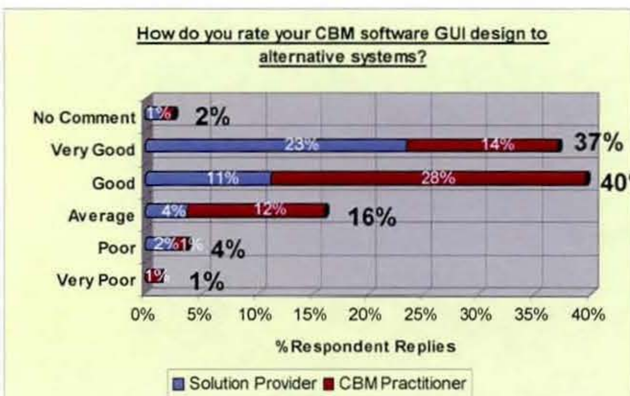


Figure 4.7. Identifying the quality of CBM software's GUIs with alternatives.

4.4.3.10. Comparison of survey results

Although not presented graphically or numerically for all the results, opinions from CBM solution providers and CBM practitioners did not vary to a great extent for the entire survey. A noticeable few exceptions included:

- More CBM solution providers (76%) place a high or very high level of importance on the use of colour coding to reflect machinery condition, compared to 58% of CBM practitioners.

- More CBM solution providers (74%) believe tailoring the design of CBM GUIs to customer requirements, has a high or very high level of influence over CBM software design decisions, compared to 58% of CBM practitioners.
- More CBM solution providers (74%) agree or strongly agree, the reliability and quality of programming affects the saleability and success of CBM software, compared to 62% of CBM practitioners.

The lower percentage vote from CBM practitioners for the three bulleted cases above, is suggested as being attributable to a higher level of ignorance amongst this group, towards the complexities of GUI design and human computer interaction.

Sections 4.4.3.6, 4.4.3.7 and 4.4.3.8, provided a measure of the importance and value several CBM software design considerations, issues relevant to GUI design rules, and various CBM system software design features, have on CBM software design and CBM system success. Each result is grouped together and presented below, categorised highest to lowest according to its perceived level of importance or value:

Proposed CBM software design and development rules and guidelines:

Considered to be <u>very high in importance</u> or value

1. Design each GUI with correct interpretability of CM information, leading to accurate maintenance decisions in mind.
2. Design CBM software with a selection of data analysis capabilities, suited to the CM technique being employed.
3. Incorporate a data archiving feature as an option in CBM software.
4. Design CBM reports with look, feel and interpretability in mind.
5. Design CBM software to present condition parameters graphically, e.g., using charts and graphs.
6. Design CBM software to incorporate maintenance and malfunction report generation capabilities, so CM information can be presented using performance reports.
7. Design CBM software to incorporate password and user name authentication.
8. Design CBM software using reliable, quality programming techniques and standards.

Considered to be high in importance or value

9. Consider screen structure and information classification whilst designing CBM software GUIs.
10. Design CBM software to incorporate visually appealing GUI screens.
11. Use appropriate language that is legible to the intended audience in the CBM software GUI.
12. Design the structure of CBM software to incorporate windows.
13. Take into account the CM technique being employed when designing the CBM software.
14. Provide easy to use navigation techniques in the CBM software's GUIs.
15. Design CBM software GUIs to incorporate drop down menus.
16. Take into account networking and integration opportunities and requirements whilst designing the CBM software.
17. Anticipate having to tailor CBM software to users/customers requirements.
18. Design the CBM software with the intended functionality of the CBM system in mind.
19. Design the CBM software to satisfy the intended audiences requirements.
20. Design CBM software GUIs to incorporate colour coding to reflect machinery condition.
21. Design CBM software GUIs to make use of tables where appropriate.
22. Provide users with the ability to control the appearance and functionality of CBM GUI control features.

Considered to be average in importance or value

23. Use text size and font type appropriately in CBM software GUIs.
24. Take into account environmental issues, i.e., location of displays / monitors.
25. Whilst designing CBM software follow recognised GUI design rules.
26. Use icons and icon design appropriately in CBM software GUIs.

Additional issues suggested by respondents, requiring further investigation to determine their level of importance

27. Provide software design features enabling data to be exported or imported between a CBM software application and other software applications.

28. Design CBM software GUIs to be user friendly logical and easy to operate, e.g., out of box user friendly, easy to use navigation techniques.
29. Design an urgent method of communicating machinery defects and deviations from acceptable trends into CBM software GUIs and other media.
30. Design CBM software to enable users to access CM information through Internet web pages.
31. Consider the after sales support, including maintenance, and software upgrades, at the design and development stages of a CBM software application.
32. Design CBM software to automatically distinguish and represent machinery condition according to the criticality before anticipated failure. Take into account the level of importance the machine being monitored represents if it fails and is unable to function.
33. Design the CBM software to receive and process data from multiple different types of CM techniques, and multiple machines.
34. Provide automated data screening and automated fault diagnostics into CBM software.
35. Consider the marketing and sales strategies anticipated at the design and development stages of a CBM software application.
36. Design CBM software to align with the major ICS software applications.
37. Incorporate an error protection feature for back stepping through user actions within the CBM software's GUIs.
38. Use 3D representation of machinery and machinery condition in CBM software GUIs.
39. Provide users with an ability to make a selection from a group of GUIs. This selection might include user interfaces designed specifically for a particular operation or designed for a specific user group.
40. Incorporate a feature within the CBM software for automatic machinery identification verification.
41. Design the CBM system to operate through a single central database.
42. Design CBM software GUIs to present machine condition information in a self-explanatory format and media.
43. Providing statistical analysis tools within the software, for defining frequency bands, for analysis purposes, and standard control charts for each frequency band.

A certain degree of association and repetition can be detected amongst the forty-three items above. This occurs because some items form part or need to be incorporated in procedures undertaken to satisfy the condition of others. For example, designing CBM GUIs to be out of box user friendly, logical and easy to operate, requires the CBM software designer to take into account items: 9, 10, 11, 14, 15, 17, 19, 20, 22, 23, 24, 25, 26, 37, 38 and 39, from the above list of forty-three. Shneiderman and Plaisant [2004] discuss methods for creating user friendly GUIs for various software applications in greater detail.

4.4.4. Summary

The objective of this survey has been to identify a set of GUI interface design guidelines, for use and consideration by CBM software designers and solution providers alike. Each guideline is intended to make the Human Computer Interaction design process for a CBM GUI run smoothly, resulting in a product fit for purpose and therefore more saleable.

Section 4.4.3.10 groups together all the CBM software design features and other issues assessed in the survey, to form a list of proposed CBM software design and development guidelines. Items 1 to 26 are arranged according to survey respondents perceived level of importance and value. Guidelines 1 to 8 are considered to have the highest level of importance and value. It is therefore suggested they be considered mandatory during the software design and development process. Guidelines 9 to 22 are consider to be high in importance and value. It is therefore suggested they be considered important but not mandatory during the software design and development process. Guidelines 23 to 26 have an average level of importance and value. It is therefore suggested CBM designers consider these items not to be important but still requiring consideration. Guidelines 27 to 43 level of importance and value is undetermined, because they represent respondent suggested additional comments. A further survey is required to determine the importance and value for guidelines 27 to 43.

Identifying whether survey respondents know who designed their CBM software's GUI, does not provide any indication as to whether the respondents themselves were involved, or whether they have personal software GUI development experience. Future surveys of this nature would find it useful to extract such information, because individuals with personal experience at software development and CBM GUI design in particular, provide a very good indication of existing professional practices and expectations. Comparing professional developers practices and expectations against users practices and expectations, exposes areas for product improvements.

Further evidence justifying the proposed CBM software design and development guidelines, will be achieved by applying them whilst designing and developing a CBM software application. Once designed the CBM software's GUI should be put through a set of usability tests, aimed at assessing its acceptability in meeting users requirements. Ideally individuals with previous experience at designing CBM software should be asked to undertake such an exercise. The experience and knowledge of professional CBM software designers makes them ideal candidates in accessing the relevance and accuracy of each guideline.

Chapter 5

5. IDENTIFYING ROYAL MAIL'S CBM HCI USER REQUIREMENTS

5.1. Introduction

The following section describes maintenance activities presently undertaken within Royal Mail (RM). Information presented was gathered via telephone interviews, email exchanges, face-to-face interviews, and walk around guided tours at several different mail centres. The section begins with an explanation of RM's maintenance practices in 2005, moves on to describe their user requirements for a CBM system, and then discusses suggested and anticipated RM CBM GUI and HCI user requirements.

Understanding RM's existing maintenance practices and identifying user and system requirements falls in line with recommended HCD, HF principles and User Profiling procedures, discussed in section 2.6. Gaining an appreciation of RM's maintenance practices helps the HMI designer, develop design ideas for CBM HMI more likely to be accepted by RM, the intended customer.

5.2. Information Gathering Techniques

Information gathering was conducted over a two-phased period, prior to RMs 2004 organisational restructuring and after the restructuring. This distinction is considered necessary because personnel changes occurred at RM following restructuring, and in some cases maintenance practice alterations have been initiated. Figure 5.1 provides a schematic of the information gathering techniques employed. Information gathering techniques used prior to the organisational restructuring included:

- Round table discussions between Professor Jo Coy, heading up RM's strategic maintenance activities (at the time) and Simon Weston, Maintenance Team Leader (MTL), at the Mechatronics Research Centre, Loughborough University.

- Recorded telephone interviews with an MTL from Leeds mail centre and a Lead Technologist from Swindon.
- Email discussions with a Lead Technical Analyst from Swindon.
- Face to face interviews with an MTL from Leeds mail centre, an Area Shift Maintenance Engineer (ASME) and union representative from Leeds mail centre, a Maintenance Shift Team Leader (MSTL) from Beeston mail centre, an Area Maintenance Manager (AMM) from Heathrow World Wide Distribution Centre (HWDC), and the SAP SDMM Manager from Swindon. Each face-to-face interview was recorded using a Dictaphone and the subsequent information written up as minutes. The minutes in each case were emailed to the providing source for verification and additional comment.

Following the appointment of Gary Stubbs as Maintenance Director, and the introduction of Matt Jenkinson, Northern Territorial Maintenance Manger, to the Royal Mail University Technology Centre, further information gathering exercises commenced, with:

- Face to face interviews with four Area Maintenance Managers, at Manchester's mail centre and Leed's mail centre. In each case a Dictaphone was used to improve the accuracy of the minutes, as described previously.

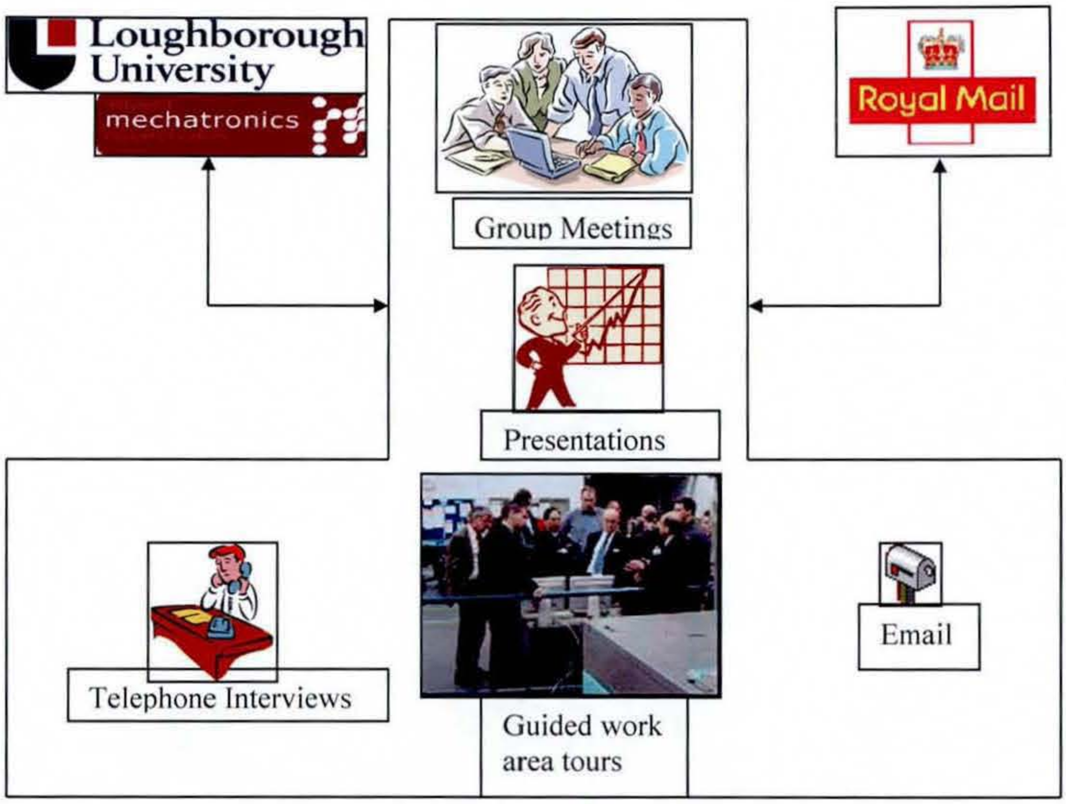


Figure 5.1. User requirements information gathering techniques.

5.2.1. Direction of questioning

Other than the original project brief, no further external assistance was received to direct the line of questioning adopted.

The first set of questioning was aimed at gaining a broad perspective of RM's maintenance practices. An MTL and a Lead Technologist from Swindon were both separately asked to describe how RM organises its maintenance activities. This open ended questioning technique was considered necessary to gain a quick overview of existing maintenance practices. The second set of questioning involved asking three individuals, a MTL, a MSTL, and an ASME, ten questions (refer to Appendix A.1, section A.4.1.1), targeted at understanding RM's requirements for a CBM systems HMI, incorporating access to Royal Mail's Computer Maintenance Management System (CMMS). Following on from these investigations a Lead Technical Analyst, with experience at remote diagnostics of Integrated Mail Processing (IMP) machines, was asked to describe remote diagnostics of IMP machines. The incentive behind this investigation was to determine whether the practice of remote diagnostics should impact upon design and development decisions for a

CBM system and its GUI. Further consequential questioning involved asking the SAP SDMM manager to describe the history behind the implementation and evolution of RM's chosen CMMS, SDMM, a maintenance module from SAP, defined as: Service Delivery Materials Management. Additionally the SAP SDMM manager was asked questions, refer to Appendix A.1, section A.4.1.2, concerned with design and development issues likely to effect the integration of the SAP SDMM system, with a future CBM system.

The third set of questioning, included in Appendix A.1, section A.4.1.3, following Royal Mail's reorganisation, was conducted amongst four Area Maintenance Managers. Questions and discussion was targeted at clarifying information previously gathered describing RM's maintenance practices and identifying specific user requirements for a CBM systems' method of HCI.

5.3. Royal Mail's Maintenance Personnel

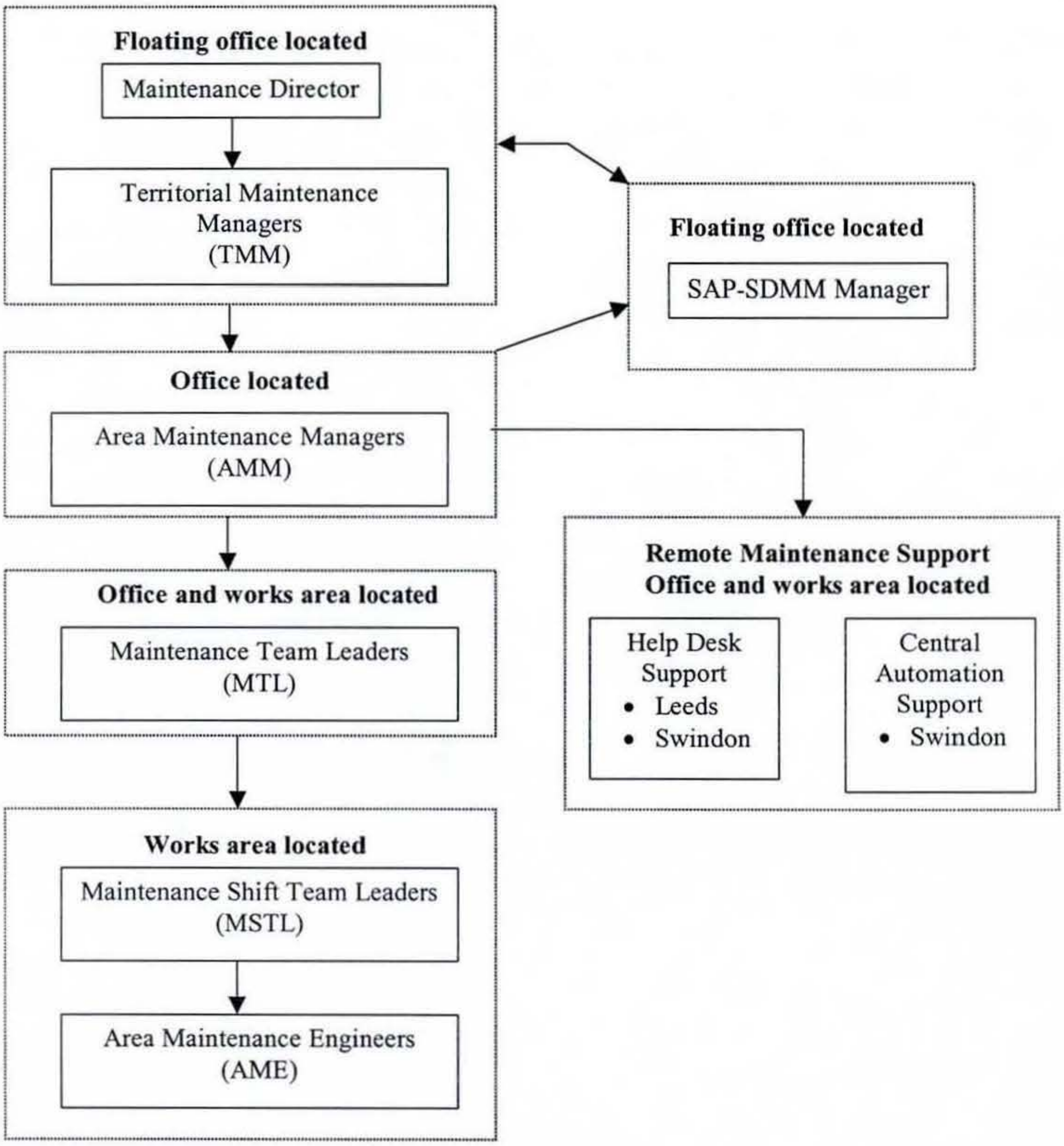


Figure 5.2. RM's maintenance staff hierarchy.

The tables below briefly define the job responsibilities for each of RM's maintenance personnel, listed in Figure 5.2.

Personnel	**Maintenance Director**
Brief explanation of present job responsibilities	
• Establish RM's maintenance strategy. • Identify and request a maintenance budget aimed at satisfying RM maintenance strategy. • Coordinate and manage the activities of TMMs aimed at meeting accepted maintenance strategy and budget targets. • Report to the Managing Director.	

Table 5.1. Responsibilities of the Maintenance Director.

Personnel	**Territorial Maintenance Manager (TMM)**
Brief explanation of present job responsibilities	
• Monitor the performance of mail centres maintenance activities within their designated region. • Discuss and coordinate strategic maintenance improvements with AMMs. • Control and manage the maintenance budget for their designated region. • Identify and instigate maintenance strategies aimed at improving the availability and performance of mail sorting machinery for their designated region. • Report to the Maintenance Director.	

Table 5.2. Responsibilities of a Territorial Maintenance Manager.

Personnel	Area Maintenance Manager (AMM)
Brief explanation of present job responsibilities	
• Meet maintenance strategies requested by their TMM, i.e., instigate and manage maintenance practices designed to sustain sorting machinery and make it available for operation. • Control and manage the maintenance budget for their mail centre. • Ensure procedures are in place for meeting European health and safety regulations. • Monitor and compare the performance of sorting machinery within their mail centre with other mail centres. • Identify sorting machinery considered to be operating below performance targets, and instigate procedures to improve the situation. • Monitor the performance of MTLs. • Report to the TMM.	

Table 5.3. Responsibilities of an Area Maintenance Manager.

Personnel	Help Desk Support
Brief explanation of present job responsibilities	
• Provide firstly telephone and secondly hands on assistance and advise on difficult or unknown maintenance problems, to all of RM's mail centres. • Update and add information to the Automation Development & Support Team (ADST) Intranet site. • Know who to contact if a maintenance problem cannot be solved over the telephone by themselves. • Report to AMMs.	

Table 5.4. Responsibilities of Help Desk Support.

Personnel	**Central Automation Support**
Brief explanation of present job responsibilities	
• Provide the service of keeping the computerised system controllers, incorporated within IMP machines, in operational condition. • Perform remote diagnostics and resolve where possible IMP machine computer system controller problems. • Monitor and report system problems and performance information for IMP machines back to AMMs.	

Table 5.5. Responsibilities of Central Automation Support.

Personnel	**Maintenance Team Leader (MTL)**
Brief explanation of present job responsibilities	
• Keep sorting machinery in operational working condition. • Ensure all health and safety regulations are followed by ASMEs and MSTLs. • Monitor the performance of sorting machinery within their mail centre. • Identify and determine the reasons for any sorting machinery considered to be operating below performance targets. • Monitor and record the performance of MSTLs and ASMEs. • Plan labour requirements around shifts and holidays. • Report to the AMM.	

Table 5.6. Responsibilities of a Maintenance Team Leader.

Personnel	**Maintenance Shift Team Leader (MSTL)**
Brief explanation of present job responsibilities	
• Same responsibilities as ASME. • Over see the actions and advice ASME. • Report to the MTL.	

Table 5.7. Responsibilities of a Maintenance Shift Team Leader.

Personnel	Area Shift Maintenance Engineer (ASME)
Brief explanation of present job responsibilities	
• Keep sorting machinery in operational working condition. • Provide a hands on maintenance service for all sorting equipment. • Follow all health and safety regulations, in order to avoid jeopardising ones own and other peoples safety. • Follow all the necessary administrative duties, designed to record and register an individuals maintenance activities and working time. • Report to the MSTL and MTL.	

Table 5.8. Responsibilities of an Area Maintenance Engineer.

5.4. Royal Mail's Maintenance Practices

RM has adopted the practice of standardising equipment, machinery and working practices. As a consequence standardised maintenance routines are followed every day by maintenance personnel within mail centres throughout Britain.

Maintenance adds no value to RM's products and services because it consumes money through labour and spare parts, and often requires production to be stopped or slowed down, reducing optimum operational output. However, without maintenance potentially very expensive component/s failure/s would occur leading to process stoppages and or reduced quality of service. Keeping maintenance time to a minimum should therefore be viewed as a value adding opportunity for improving RM's competitiveness and ultimately its profits.

Maintenance is scheduled between similar time brackets at each of RM's 73 mail centres across Britain every day. Other than external cleaning and maintenance that does not involve the automatic triggering of a machines' stop switch, maintenance is scheduled to occur whilst mail-sorting machinery is not in operation. Maintenance time intervals are governed by inward mail and outward mail sorting times, which occur across RM's network, referred to as the pipeline, at similar times every day. Sundays and Monday mornings are popular times for more time-consuming maintenance jobs.

Maintenance routines are controlled by a preventative maintenance system driven by the release of Asset Care Schedules (ACS). ACS are recommended descriptive maintenance routines to be completed on a day by day basis, by Maintenance Shift Team Leaders (MSTL) and Area Shift Maintenance Engineers (ASME). Each ACS originates from recommended manufacturer preventative maintenance guidelines, and subsequently derived or calculated routines. Techniques used by RM to calculate and derive preventative maintenance schedules include: failure mode effect analysis (FMEA), product to failure (PF) curves, bath tub product life curve analysis, Reliability Centred Maintenance (RCM), and approved maintenance design alteration requests. ACS are centrally controlled and stored on SAP SDMM, RM's computer maintenance management system (CMMS). Included amongst the ACS are several predictive maintenance practices including: listening for bearing noise, knocking, and out of the ordinary noises using the human ear, testing sorting machinery bed plates for vibration, checking belt tensions, and checking motor temperatures.

Holroyd acoustic emission health checking devices, a stand alone acoustic CM unit, for monitoring acoustics in the bed plates of sorting machinery, have been trailed within Royal Mail. Information gathered from bed plate acoustic emissions, provides an opportunity for assessing the condition of pulleys and drive motors, incorporated within the vicinity of the bed plate location being measured. Although the practice still exists, it has not become a standardised maintenance routine, due to reliability issues, discussed in Coy [2003]. Clavis belt tensioning units are another CM technique trialed at RM. Belt tensioning checks using the Clavis belt tensioning unit, have been accepted as a standard maintenance routine, because they are quick and easy to perform. Clavis belt tensioning units help maintenance staff, fit and monitor the tension levels of belts, used extensively in automated sorting machinery. Other than preventative and predictive maintenance, corrective maintenance, e.g., sudden failures, are attended to as and when they occur. Alternative CM techniques under investigation at a developmental level include:

- Acoustic emission CM of multiple bearings, Salvan [2004].
- Thermal imaging CM of belts, bearings and belt drive motors, Al-Habaibeh et al. [2003].
- Vibration Condition Monitoring of belts, Notini [2005].
- Belt surface degradation CM using image recognition.

Maintenance engineers are often faced with multiple tasks during their shift, having to make a decision on what maintenance work should be done immediately, what maintenance work can wait, i.e., is not priority, and what maintenance work can not be completed without assistance. Factors driving their decision on this matter include:

- Machine availability, i.e., whether the machine is in operation (sorting mail) or stopped and available for the required amount of time, it will take to perform the maintenance.
- Spare parts and tooling availability, i.e., are spares in stock to enable the maintenance job to be undertaken and are the required tools available for the job to be performed.

Timing of maintenance is a critical factor because it should not prevent or hold up mail sorting operations. In the event of machine failure leading to prolonged downtime, it becomes the responsibility of the Operations Manager to inform Royal Mail Engineering Services, Swindon. Engineering Services have the ability to perform remote diagnostic capabilities on Integrated Mail Processing (IMP) machines, and call in emergency maintenance staff from other mail centres or administrative offices, in order to resolve problems in the minimum of time. The central operational role played by Engineering Services, implies a need to develop new maintenance practices with their joint understanding and co-operation.

Figure 5.3 illustrates using a flowchart, a simplified representation of the sequence of processes and decisions MSTLs and ASMEs follow during their shifts.

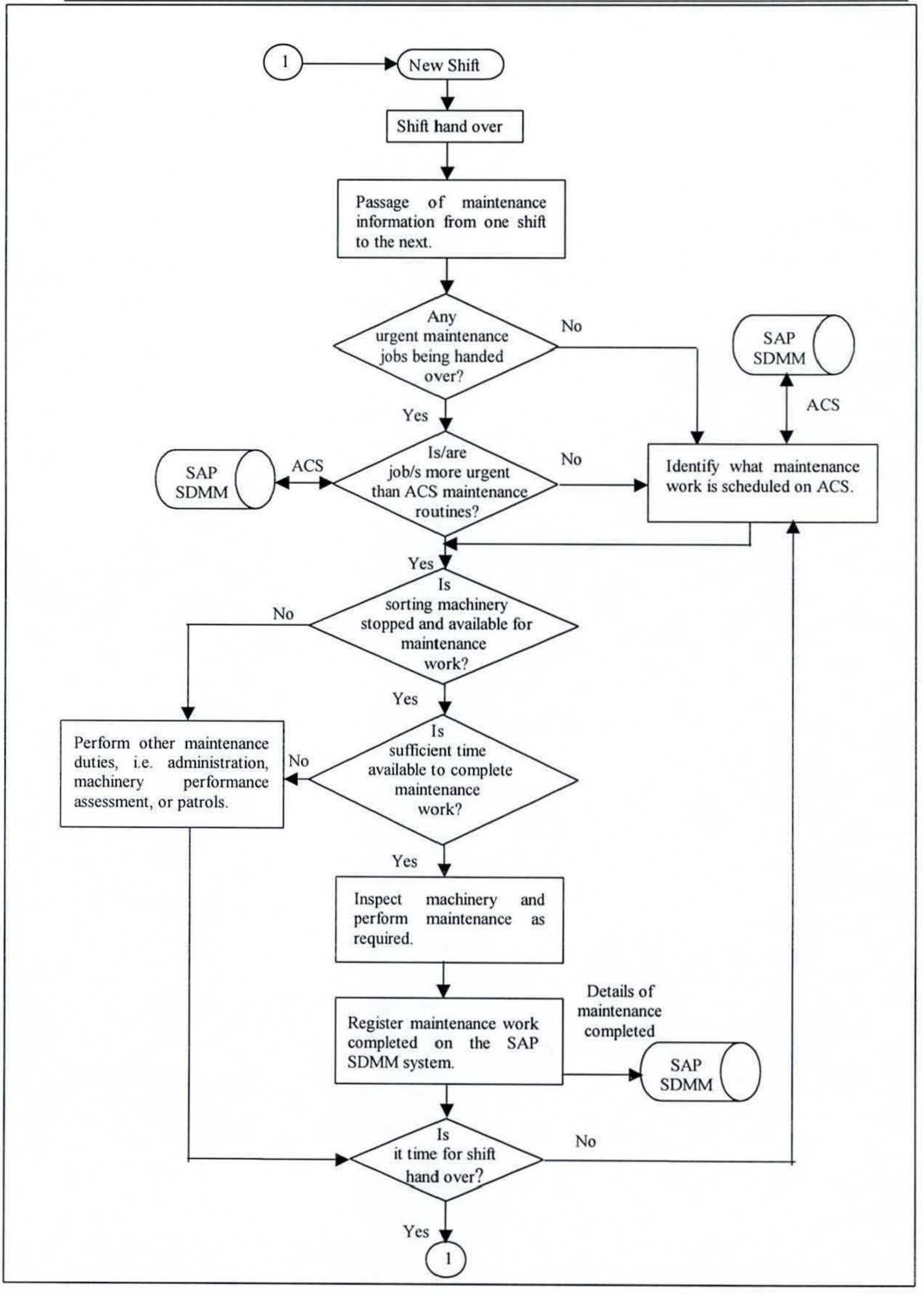


Figure 5.3. Flowchart illustrating the simplified sequence of events performed by MSTLs and ASMEs within Royal Mail.

On completion of each maintenance task, engineers are required to record details of the work completed, their personal ID, the time taken to complete the task, a general description of the maintenance task completed, and if applicable replacement part details; onto Royal Mail's SAP SDMM business computer system. SAP is a German acronym for: Systeme, Anwendungen, Produkte in der Datenverarbeitung; in English: Systems, Applications and Products (in Data Processing). Figure 5.4 shows an example of the SAP SDMM GUI screen for registering malfunction reports.

Initiatives being led by Royal Mail's Heathrow worldwide distribution centre (HWDC), aimed at reducing maintenance administrative time include, using bar code technology and wireless transmission. Mobile devices with built in scanners have been employed to catch data including: Personnel ID, machine ID, component ID, working time, and work completed. The captured data is transmitted wirelessly to the mail centres custom selected CMMS, avoiding the need for Maintenance Engineers to manually enter the same data at a later stage through a PC key board. This initiative highlights the importance of matching computer systems with human needs in a fast and efficient style.

Other than the SAP SDMM computer system, additional software applications utilised to aid maintenance decision-making include:

- RM's own Intranet site called, Automation Development & Support Team (ADST).
- The Automatic Data Capture (ADC) system.
- PROMOS, an MS Excel application consisting of multiple macros.
- The North Eastern Interim Data System (NEIDS).
- IMP operation control terminals.
- The IMP remote access system (RAS).
- HolisTech, a Computer Maintenance Management System (CMMS) used at Heathrow Worldwide Distribution centre (HWDC).
- Microsoft Excel.

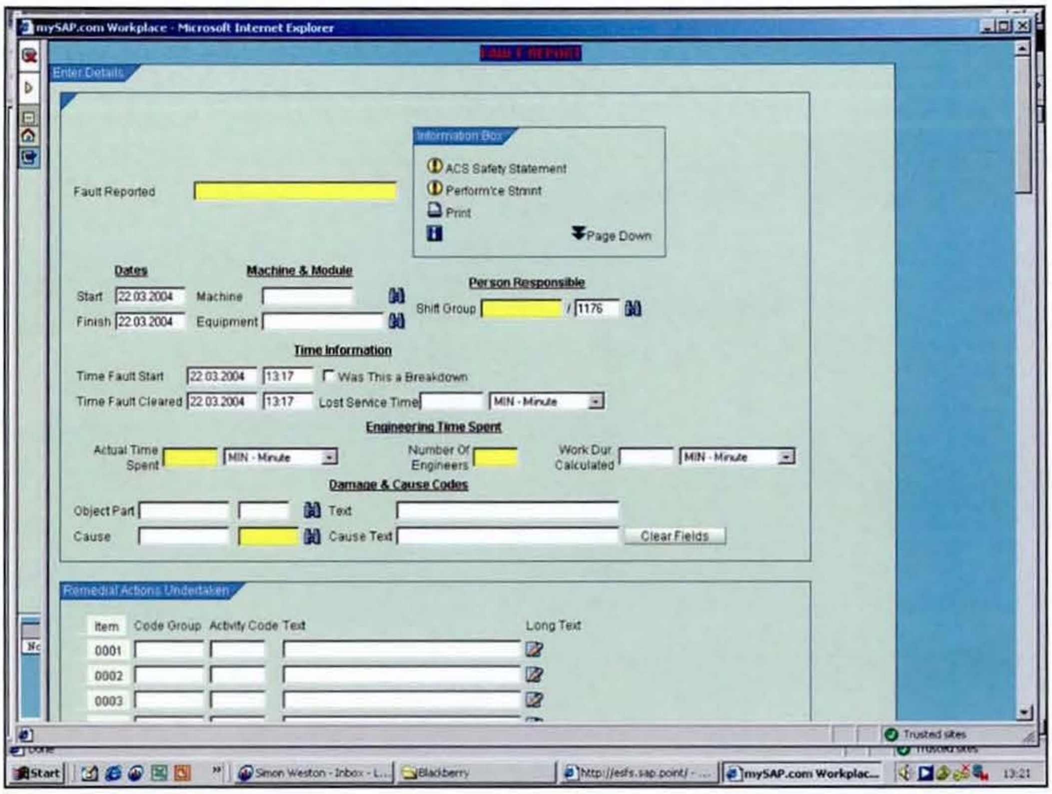


Figure 5.4. One of the SAP maintenance system screens used by RM maintenance engineers.

Table 5.9 below summarises the main applications each software application is used for, identifies the group of users who use the software, and identifies whether each software application is networked or stand alone.

Software Application	Main Applications	Users	Networked or standalone
SAP SDMM	Royal Mail's central Maintenance Management Computer System. Recording, managing and outputting maintenance information. Analysing maintenance performance and outputting results. Assisting with maintenance scheduling, costing, labour planning and inventory control.	All maintenance staff.	Fully networked. Accessible from any Royal Mail site with the necessary equipment and access rights.

Table 5.9 continued on next page

Software Application	Main Applications	Users	Networked or standalone
ADST	Storing and sharing up to date records of maintenance tips, tricks, and advice. Storing lists of maintenance best practices. Storing digitised machinery maintenance manuals. Storing an up to date list of RM's adopted machinery maintenance procedures. Storing up to date information on equipment build, replacement parts, quality of parts and suppliers.	All maintenance staff.	Fully networked. Accessible from any Royal Mail site with the necessary equipment and access rights.
ADC	Monitoring and comparing day and weekly performance figures, for IMP machines and LSMs, within each mail centre.	All maintenance staff.	Fully networked. Accessible from any Royal Mail site with the necessary equipment and access rights.
PROMOS	Monitoring and comparing weekly and monthly performance figures, of one or more mail centres against another.	MTLs and above	Fully networked. Accessible from any Royal Mail site with the necessary equipment and access rights.

Table 5.9 continued on next page

Software Application	Main Applications	Users	Networked or standalone
NEIDS	Stores and displays performance figures for LSMs. 'NEIDS TV' displays the number of letter item jams and letter address readability rate, for each LSM. NEIDS integrates with ADC, enabling performance figures from LSM, to be transferred for viewing over the ADC and PROMS systems.	All maintenance staff.	Networked between mail centres.
IMP operation control terminals	Setting up, controlling and monitoring IMP machines. The control terminals operational log report is often referred to by maintenance staff and operators alike, because it provides access to recorded system error or malfunction messages.	Operators, MTLs and below.	Standalone for each IMP machine.
The IMP remote access system (RAS)	Performing remote diagnostics of IMP computerised control systems. Reconfiguring and rebooting IMP computerised control systems.	Lead Technical Analyst, and Technical Analysts	Networked to the remote access system, independent of other RM networks.
HolisTech	HWDC's exclusive CMMS. Recording, managing and outputting maintenance information. Analysing maintenance performance and outputting results. Assisting with maintenance scheduling, costing, labour planning and inventory control.	Maintenance staff at HWDC	Networked within the HWDC. Not accessible from other mail centres.

Table 5.9 continued on next page

Software Application	Main Applications	Users	Networked or standalone
Microsoft Excel	Used mainly for creating personalised maintenance decision aid spread sheets, e.g., maintenance scheduling, labour requirements, holiday planners, and mail centre performance figure spread sheets.	MTL and above	Fully networked. Accessible over RMs network, to the agreed upon level of license holders.

Table 5.9. Computer software applications used to assist maintenance decision-making.

From a CBM system design perspective, it will be useful to know whether each of these computer systems will continue to be used, once CBM systems have been put in place. It will also be useful to determine whether any benefit is to be had, from linking CBM software to any of these computer systems. Benefit refers to an improvement in the way maintenance decisions or activities occur, with respects to efficiency (speed and cost) and accuracy.

Maintenance activities undertaken within Royal Mail are judged upon sorting machinery operational performance, following maintenance procedures, and all costs directly attributed to maintenance activities, including labour costs and materials costs. Sorting machinery operational performance is judged against:

- The number of item jams per hour.
- The percentage of item addresses accurately interpreted within a specified time.
- The number of mail items passing through the sorting equipment.
- The percentage of mail sorted automatically.

Performance targets are locally set, yet follow similar trends to the rest of the country. For example, York mail centres targets in 2004 were:

Machine de-Tris a Trasseur (MTT)	14000 letter items per jam 72.13% read rate 32779 through put
Letter Sorting Machine (LSM)	7000 letter items per jam 97.57% read rate 27400 through put
Culling Facing Classing (CFC)	2858 letter items per jam 91.04% read rate 21790 through put

5.5. Design Requirements for a CBM system

The introduction made reference to papers by Coy et al. [2001] and Coy [2003], explaining RM's decision to invest in CBM research. Subsequent sections within the literature review have discussed maintenance approaches, CM and its associated technologies, and the strategic impact a predictive maintenance initiative could have on RM's existing maintenance practices. Each discussion items goes someway to anticipating likely CBM system design requirements. Presented below in table format are CBM system design requirements identified by maintenance personnel, during interviews described in section 5.2. Each system design requirements is categorised into one of four tables:

1. Table 5.10: Predictive Decision-making Requirements.
2. Table 5.11: Requirements Linked to Maintenance Decision Assistance.
3. Table 5.12: Integration Design Requirements.
4. Table 5.13: System Design Requirements.

5.5.1. Predictive decision-making requirements

Reference	User requirements	Applicable Users
1	Accurately judge the amount of time sorting machinery can be reliably operated before it needs to be stopped for maintenance.	**MTL** **MSTL** **ASME**
2	Automatically recognise anticipated component/assembly failure signatures, and generate an alarm system designed to notify ASMEs or MSTLs.	**MSTL** **ASME**
3	Knowing or anticipating how sorting machinery will perform during known periods of high mail volume.	**TMM** **AMM** **MTL**

Table 5.10. Predictive decision-making requirements.

5.5.2. Requirements linked to maintenance decision assistance

Reference	User requirements	Applicable Users
1	ASMEs, MSTLs, and MTLs, ideally want a maintenance scheduling system that prioritises maintenance tasks and provides an indication of the time available to complete the task.	**MTL** **MSTL** **ASME**
2	If a CBM system is to be accepted, it must enable maintenance engineers to identify deteriorating equipment and machinery conditions as they arise; and assist them determine what corrective action should be taken to resolve the problem. Having completed maintenance actions suggested by CBM systems, maintenance personnel must witness the machinery move back into acceptable operating conditions, if their confidence is to be gained.	**AMM** **MTL** **MSTL** **ASME**

Table 5.11 continues onto next page -

Reference	User requirements	Applicable Users
3	Compare the condition of sorting machinery against machinery performance. Such comparisons open the way forwards to improving maintenance scheduling, identifying substandard components, and optimising operational conditions to maximise component life expectancy.	**AMM** **MTL**
4	Suggest possible causes for deterioration in component/assembly condition.	**AMM** **MSTL** **ASME**
5	Provide help assistance on predictive maintenance practices and CBM systems on the ADST Royal Mail web site.	**TMM** **AMM** **MTL** **MSTL** **ASME**

Table 5.11. Requirements linked to maintenance decision assistance.

5.5.3. Integration design requirements

Reference	User requirements	Applicable Users
1	Integrate CBM systems with other maintenance systems other than SAP SDMM, e.g., HolisTech and ADC.	**AMM**
2	Enable CBM systems to transfer or export data into SAP SDMM. Doing so will enable ACS to be automatically generated as a consequence of a CBM system detecting out of tolerance conditions, or erratic operating condition movements.	**MTL** **MSTL** **ASME**

Table 5.12 continued onto next page -

Reference	User requirements	Applicable Users
3	Provide the functional capability to export data generated by CBM systems, for analysis against IMP and LSM performance data. Such a capability presents the opportunities to compare equipment condition against overall machinery performance.	**AMM** **MTL**
4	The capability to export CBM data into MS Excel spreadsheets for personal data analysis calculations.	**AMM** **MTL**
5	CBM system implementation on an organisational level, should be networked (integrated) country wide, enabling like for like machinery Condition Monitoring comparisons.	**TMM** **AMM**

Table 5.12. Integration design requirements.

5.5.4. System design requirements

Reference	User requirements	Applicable Users
1	Associate causes of failure with existing known and understood causes of failure, i.e., bearing vibration = noise; worn bearing = increased pulley temperature; Loose belt = increased belt vibration; Loose belt = a need for tensioning or belt elasticity failure; worn belt = shinny surface = reduction in address read rate, etc.	**MTL** **MSTL** **ASME**
2	ACS works order requests, generated automatically by a CBM system, should be inspect a specific machine or component, rather than change or repair a component or subassembly. Inspection is a more realistic proposal, because detected machinery condition deterioration, might be the result of knock on factors from other equipment and parts within a machines integrated system.	**MTL** **MSTL** **ASME**

Table 5.13 continued onto next page -

Reference	User requirements	Applicable Users
3	You would need to identify a bench mark set of conditions from which to compare all follow on condition sets, during machinery operation. Bench mark machinery operating conditions should be selected to take into account different types of mail, different mail sorting volumes flowing through the pipe line, and different atmospheric conditions.	**AMM**
4	CM techniques designed to monitor electric motors should be designed to take into account increased torque and possibly increased temperature, during machine start up. They should also account for long periods of high volume mail processing, or mail items that create a lot of friction as they are processed.	**AMM**
5	You must identify what your CBM system will measure and then determine the best technique to represent and present the information, as a measure of the machines condition.	**AMM**
6	Provide a facility for displaying the number of CBM system alerts, generated within a user selectable periods of time, for one or more sorting machines.	**AMM** **MTL**
7	A CBM system should sell itself if it is to be accepted at RM, i.e., it must be seen as having a purpose, otherwise it will fail.	**AMM**
8	Response time of the CBM system in all its functions should not exceed user accepted patients levels, e.g., approximately 5 to 10 seconds for adults. If response times do exceed these levels, a suitable message should be displayed on the screen informing users to be patient. Such an event might occur when a time-consuming data analysis feature is activated.	**MD** **TMM** **AMM** **MTL** **MSTL** **ASME**

Table 5.13 continued onto next page –

Reference	User requirements	Applicable Users
9	Identify all critical equipment, CBM predictive maintenance practices, will prove more effective than preventative maintenance practices, i.e., reduce asset costs and lengthen machinery longevity. More opportunities exist for predictive maintenance initiatives using CBM at HWDC than any other mail centre. HWDC differs from all other mail centres because it incorporates more machinery, of an automated nature, in more combinational mixes than any other.	AMM MTL

Table 5.13. System design requirements.

User requirements presented in tables 15 to 19 differ from those above because they represent possible design solutions as much as user requirements. Each recommended solution or user requirement is categorised into one of five tables:

1. Table 5.14: GUI design Requirements.
2. Table 5.15: Information Communication Requirements.
3. Table 5.16: CBM system Hardware Suggestions.
4. Table 5.17: CBM Alarm Design Suggestions.
5. Table 5.18: CM information Accessibility Requirements.

5.5.5. GUI design requirements

Reference	User requirements	Explanation behind user requirement
1	Providing access to every computerised maintenance system presently used by Maintenance Engineers through one common user interface.	It could save an engineer time, because he/she would be able to assess machinery performance information from any networked PC.
2	Design methods of HCI to be as simple as possible.	Levels of computer literacy vary amongst Royal Mail Staff, due to the huge difference in staff back grounds and ages.
3	Display CM information in a numerical format using understandable units on CBM GUIs, and on printable reports, e.g., motor temperature, bearing vibration levels, belt tension or belt speed.	Provides maintenance personnel with a spot check reference, on actual equipment condition.
4	Present data analysis results in a format that can be easily learned, correctly interpreted, and used to guide maintenance decisions.	Data analysis techniques are only useful if the resulting information improves a persons understanding of a situation, resulting in better judgmental decisions.
5	Include Pareto analysis as a data analysis technique within a CBM software.	Where deterioration in equipment condition is uncertain or reasons for a drop in sorting machine performance is uncertain, Pareto analysis could speed up cause identification.

Table 5.14 continued onto next page –

Reference	User requirements	Explanation behind user requirement
6	Provide the option for presenting equipment wear rates as a linear graphical representation.	Linear graphical representation is arguably the easiest interpretable method for representing changeable units, against a measure of time.
7	Use diagrammatical methods to represent the condition of each module incorporating CM equipment, for each IMP, within a mail centre. Use diagrams that portray IMP machines split up according to individual modules. Use colour coding as the method for representing the condition of each module within each IMP machine.	Provides a fast and visual method of gauging the working condition of equipment linked to the CBM system, for every IMP in every mail centre.
8	Provide the functional capability to click on an IMP diagrammatical representation and zoom in on individual pieces of equipment being monitored. Provide a variety of data analysis tools suitable for analysing individual components.	This functional capability will enable maintenance personnel to visualise and home in on suspect or problem equipment quickly.
9	Offer the functional ability to compare the condition of each IMPs within a mail centre, i.e., how does IMP 1 compare against IMPs 2,3, & 4 etc.	Useful for machinery performance comparisons, and creating equipment condition benchmarks.

Table 5.14. GUI design requirements.

5.5.6. Information communication requirements

Reference	User requirements	Explanation behind user requirement
1	Display the likely hood of equipment failure along with the level of urgency before a machine requires maintenance. Do so using graphical and numerical methods.	Provides maintenance personnel with a gauge to schedule and make preparations for future maintenance. Acts as a maintenance prioritisation scale.
2	Using graphical or numerical methods, include the functionality to display a comparison of a machines existing condition against accepted (bench marked) normal conditions. E.g., a graphical plot showing a machines live moving condition plotted between predetermined acceptable control limits.	It will improve maintenance decision-making, because maintenance personnel will be able to gauge the present condition against acceptable conditions.
3	Avoid producing lots of numerical data, likely to confuse and loose people. The CBM system should automatically perform all the number crunching in the back ground, presenting only the most easily interpretable information.	Makes for easier interpretation, and increases the probability maintenance decisions will be correct.
4	Present through printable reports or reports presented through digital display units, a prediction of the anticipated maintenance work (corrective action) necessary to repair/replace identified failing equipment.	Improve maintenance scheduling, inventory control, and labour requirements planning. Potentially acts as an ACS trigger.
5	Present through printable reports or reports presented through digital display units, anticipated consequential effects to other components or machinery or plant or the business, resulting from failing equipment within a machine.	Helps maintenance personnel place a level of urgency on future maintenance tasks.

Table 5.15 continued onto next page –

Reference	User requirements	Explanation behind user requirement
6	Provide the optional request within a CBM GUI or report print to, display the number of CBM system alerts generated within a user selectable period of time.	To provide a method of judging the performance of equipment and equipment set up, and potentially the quality of previous maintenance work.
7	Include in printable reports or messages displayed through digital display units, a list of critical components that might be the cause of deteriorating equipment/machinery condition.	Helps maintenance personnel pin point the causes of failure/s, and therefore schedule or perform appropriate maintenance action.
8	Include in printable reports or messages displayed through digital display units, an indication as to the type of failure or anticipated failure process.	Helps maintenance scheduling.
9	Following the detection of deviations from acceptable normal machinery operating conditions (failure signatures), present based upon anticipated trend movement calculations (a data analysis technique), an indication of a machines remaining useful life, using graphical or figurative methods.	Provides maintenance personnel with a gauge to schedule and make preparations for future maintenance. Acts as a maintenance prioritisation scale.
10	Included on CBM report prints, and or visual display units: An indication of the amount of time machinery can be reliably operated for, before it needs to be stopped for maintenance, e.g., remaining belt life, time till pulley replacement, remaining useful life for motors, etc.	It provides a clear guide as to when machinery is in need of maintenance. It should prevent unnecessary maintenance and avoid running machinery till failure.

Table 5.15 continued onto next page –

Reference	User requirements	Explanation behind user requirement
11	Using graphical or numerical methods, include the functionality to display a machines recent condition movements against historical condition movements.	It will improve maintenance decision-making, because maintenance personnel will be able to gauge recent machinery condition movements, against previous recorded historical condition movements.

Table 5.15. Information communication requirements.

5.5.7. CBM system hardware suggestions

Reference	User requirements	Explanation behind user requirement
1	Use low specification robust PCs or dumb terminal for communicating CM information to maintenance personnel on the work area. Avoid spending extra money on high specification computer equipment if it is not necessary, and easily broken.	Avoid unnecessary expenditure, avoid introducing inappropriate display units and expensive computers onto the work area.

Table 5.16. CBM system hardware suggestions.

5.5.8. CBM alarm design suggestions

Reference	User requirements	Explanation behind user requirement
1	Design CBM systems to automatically generate alarm messages requesting the attendance of maintenance shift personnel, at machinery who's CBM system has detected out of tolerance conditions. The alarm message could take the form of an email, or a flashing message on a digital display unit. Alternatively it could activate a mobile devices ring tone or vibrator.	ASMEs and MSTLs are often found in their office, just off from the work area. Issuing alarm messages to PCs located in their office is a good way of attracting their attention.
2	Use elevated coloured lights embedded within sorting machinery to represent the condition of sorting machinery. A three colour coding system, as used in traffic lights would suffice. Acceptable machinery conditions = green light. Changeable or wayward machinery conditions = yellow light. Out of limit machinery conditions = red light.	Traffic light visual condition indicators are a proven technique widely accepted within industry. Colour coded condition indicators are already well established at RM.

Table 5.17. CM alarm design suggestions.

5.5.9. CM information accessibility requirements

Reference	User requirements	Explanation behind user requirement
1	Provide access to CM information in administration offices, for access by all levels of maintenance staff. Link the CBM system into RM's network and make CM information accessible through PCs.	Office based maintenance staff will require access to CBM system information.

Table 5.18 continued onto next page –

Reference	User requirements	Explanation behind user requirement
2	Provide access to CM information within close proximity to machinery. CM information might be provided via reports that can be printed and taken to the machine being worked on. CM information could be made available through a computer or computer screen/display located near machines. CM information could be made available through mobile devices carried around by maintenance personnel. e.g., PDAs, mobile phones or wireless laptops.	If CM information acts as an aid in identifying and correcting a problem, it will prove useful to access such information whilst attending to a maintenance job.

Table 5.18. CM information accessibility requirements.

Many user requirements are not specific to designing a CBM GUI, as they concern the design of the CBM system as a whole. They should not be dismissed however, because ultimately they will determine whether the chosen method of HCI, will directly or indirectly lead users towards satisfactory interaction with the CBM system.

User requirements relating to the operation of the CBM system, that are influenced by external factors, other than graphic design and web design considerations, fall outside the scope of this research projects time allowance. They should however form part of further work aimed at developing the CBM system and its method of HCI, for Royal Mail.

5.6. Anticipated Implications From Introducing CBM systems at Royal Mail

The introduction and integration of a CBM system with the SAP SDMM, offers an opportunity for automatically generating ACS requests on the command of a CBM system. Taking this a step further, it becomes feasible to consider automatically generating inventory level checks, and tool management checks, on the detection of failure signatures by a CBM system. This level of integration presents the opportunity for maintenance scheduling based on prediction, leading to tighter inventory control possibilities.

Feed back from the SAP SDMM manager (refer to Figure 5.2) identified the realistic possibility of tying CM information, supportive of malfunction reports, with malfunction report entries. Supportive CM information might consist of any one of the many techniques used to represent a machines condition, e.g., thermal images, a series of data values, data presented graphically, data presented in tables, automatically or manually generated Condition Monitoring reports, etc. He suggested: "CM information could be made accessible within the SAP SDMM module through the use of an external application executable folder. External executable folder refers to CM information supportive of a malfunction report, capable of aiding and assisting maintenance decisions, packaged and saved into folders. Each packaged folder could be represented within the SAP SDMM malfunction report in question, with an appropriate folder icon symbol. On selection (mouse click) the folder would open using a suitable automatically selected or manually selected software application."

Experience gained from adapting the SAP SDMM module into Royal Mail, provides a strong indication of the challenges and resistance future technological initiatives, such as predictive maintenance in the form of CBM systems can expect. Resistances such as:

- Personnel dislikes towards changing from familiar working practices that are accepted, to new unfamiliar working practices.
- Personnel difficulties towards learning to operate new technology, e.g., a new unfamiliar computer system.
- Personnel frustrations towards the time consuming systematic nature of entering data into a computer systems database.

Resolving these resistances in a large organisation with a wide geographical spread, such as at Royal Mail, requires continuous management backing and determination, and a coordinated nationwide implementation approach. Resistance towards Royal Mail's Computer Maintenance Management System (CMMS) is declining, in line with increased personnel familiarisation with its operation. Evolutionary alterations to the GUIs provided for interacting with SAP SDMM, resulting from staff complaints, have also helped to reduce system implementation resistances.

5.7. Summary

Predictive maintenance in the form of autonomous Condition Monitoring, has been anticipated to reduce maintenance costs and increase longevity of RMs automated sorting machinery, Coy et al. [2001] and Coy [2003]. Four different CM techniques are being investigated for their suitability and application, as predictive maintenance practices for use on RM's IMP machines and LSMs:

- Acoustic emission CM of multiple bearings.
- Thermal imaging CM of belts, bearings and belt drive motors.
- Vibration Condition Monitoring of belts.
- Belt surface degradation CM using image recognition.

Interviews conducted with RM's maintenance personnel, have identified a list of user and system requirements, for inclusion in a networked nationwide CBM system and desirable methods of HCI. Each user requirement requires further scrutiny to determine its priority, achievability and practicality. Further discussions with maintenance personnel at RM are recommended, to determine identified user and system requirement priorities. Further investigation into the technologies driving the CM techniques being considered namely, data management, data mining and data presentation, are suggested in order to determine the achievability of each suggested user and system requirement. Findings from the latter and an understanding of the design, development and implementation costs, and anticipated usability for each of the user and system requirements, are necessary to determine their practicality.

5.8. An Analysis of GUIs Developed by Previous Royal Mail University Technology Centre Projects

Research projects undertaken by the Royal Mail University Technology Centre, Loughborough University, concerning Condition Monitoring (CM), has resulted in the development of four separate CM techniques: 1) Bearing acoustic emissions detection; 2) Bearing and motor temperature detection; 3) Belt vibration detection; and 4) Belt surface condition detection. Each technique is designed to detect and monitor phenomena associated with sorting machinery component failures, collecting data automatically on a continuous basis. Artificial intelligence incorporated within each system utilises heuristic knowledge in order to analyse sensory data, for the prediction of faults. Monitoring takes place continuously whilst the machines are in operation. CM information is displayed through graphs, as numeric values and images. Linked together each project aims to satisfy Royal Mail's desires to create an autonomous CBM system.

Human Computer Interaction is provided through GUIs adopted to satisfy system design requirements. Discussion below critically analyses three of the CM techniques GUIs, with respects to design, presentation, visual appearance, complexity and functionality. The intentions being to learn from ideas incorporated in each individual system's GUIs, and apply the knowledge to development decisions for an integrated CBM GUI.

5.8.1. Intelligent Condition Monitoring of multiple bearings in a high speed system: Application to mail processing machines

Salvan et al's. [2004] acoustic CM system, has been developed with the intension of monitoring mail sorting machine bearing conditions. Two UI screens are provided, shown in Figure 5.5, and Figure 5.6. The GUI is designed to act as a maintenance decision aid, providing maintenance engineers and technically minded individuals with sensory feed back on the condition of a group of mail sorting bearings, located within pulleys and a drive motor. Pulley bearing condition information is presented through 7 graphs, to the right of screen 1, Figure 5.5.

On examination both GUIs shown in Figure 5.5 and Figure 5.6 are technical in appearance and content. Correct understanding and application of the developed CM techniques, requires instruction and training. When faced with a new software front end UI, users quickly form an immediate impression of screen layout, design and visual appearance, simply by interpreting what they see. For example, in the case of Salvan's [2004] GUI, screen 2 could be interpreted as follows: Grey border, green back-ground, an image on the left hand side of the screen, which appears to represent a graph with x and y axis, a 3 by 7 grid of numeric boxes located to the left of the screen, with column and row identifiers; a further two numeric boxes with identifiers immediately above, and two (what appear to be) green (often associated with go and OK) and red (often associated with stop or warning) action control buttons, immediately below the grid, at the bottom right of the screen. Without any form of interaction with the UI, an image of the computer system's likely application and capabilities is formed through simple observation. Understanding how the human mind interprets visual images and objects, and starts formulating ideas for possible interaction and usage scenarios, is discussed in the theoretical subjects, Schema Theory, discussed in section 2.7, Human Computer Interaction (HCI), discussed in section 2.8, and user UID, discussed in section 2.9. Learning to operate screen 1 as the designer intends, may well not become apparent without considerable instruction and an understanding of the systems function. The UI does not therefore represent an example of intuitive design. As with most things in life, once a user becomes clear towards a systems purpose and functionality, so it becomes easier to correctly utilise the provided method of human computer interaction. Teaching users to operate a Human Computer Interface, becomes a matter of providing users with a level of instruction appropriate to a users needs (refer to section 2.6), using group or/and one to one training sessions, encouraging individuals to teach themselves, and promoting continued learning. For example, instructions provided in the thesis, Salvan [2004], offers an explanation for the GUI screens 1 and 2 functionality. Screen 1 presents condition data from three tie-clip microphones, connected to the acquisition unit inside a LSM, used extensively in mail-sorting centres. Users specify the date period top left, they wish to extract data for examination, DD/MM/YYYY format. Two pictures (bottom and top view), middle left, represent the individual items being monitored. Each rotating element is numbered to assist maintenance engineers in associating the right condition with the right element. To the right side of the GUI is a series of seven graphs portraying the counting (activity) for each element. Counting, y axis, represents an evolution of the acoustic activity for a given pulley, and time x axis, a measure of hours. High counting values indicate greater likelihood of worn or damaged bearings. In this case '6' is taken as the upper limit. Counting values above the upper limit indicates a requirement for immediate maintenance. The green start button, bottom left of screen 1, activates the Condition Monitoring system, starting data extraction and analysis, for the selected time period. Before starting data extraction and data processing, the system needs to be correctly set up using screen 2. The red close button, bottom left of screen 1, stops the data extraction and analysis process.

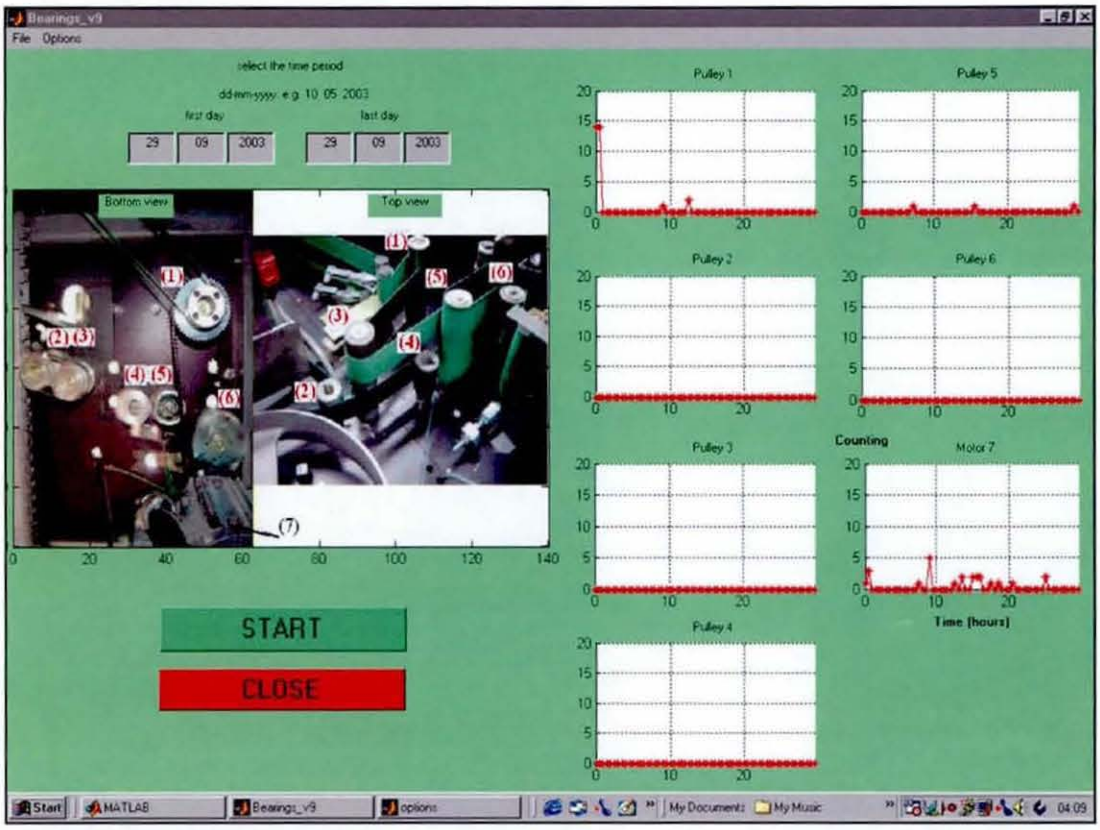


Figure 5.5. An intelligent Condition Monitoring System's GUI, screen 1. Salvan [2004].

Selecting the options button in the upper left tool bar, screen 1, opens up screen 2. From the file address box, upper right, users specify the file location to extract sensory data for data processing. The two boxes immediately below file address, length 'a' (cm) and length 'b' (cm), represent distances a) and b) on the graph, left of screen 2. Lengths 'a' and 'b' represent the distance between the three tie clip microphones. The two columns under x-axis and y-axis, right of screen 2, represent the co-ordinates for all 6 pulleys and the motor with respect to sensor 1 (microphone 1), units centimetres. The column under 'Element diameter (cm)', right of screen 2, represents the diameter for each pulley and motor, units centimetres. Once all values and coordinates have been entered correctly, clicking on the green confirm button, bottom left, screen 2, feeds the values into the system and trains the internal neural network (NN) for acoustic source location purposes. Finally clicking on the red close button, bottom right of the screen, returns to Screen 1.

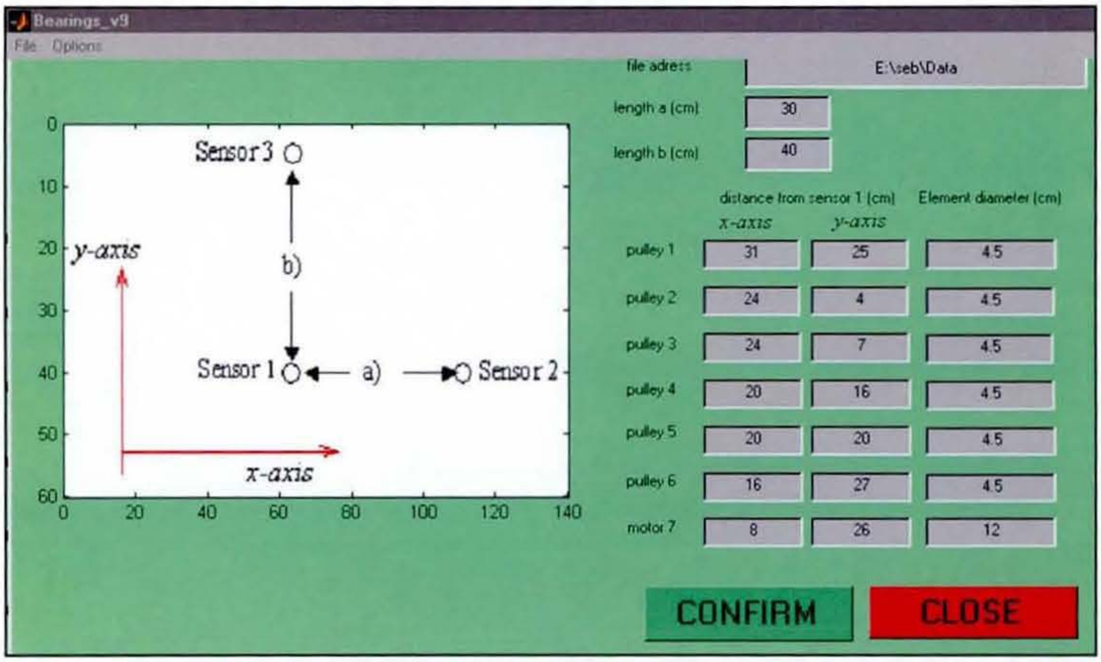


Figure 5.6. An intelligent Condition Monitoring System's GUI, screen 2. Salvan [2004].

5.8.2. Condition Monitoring of transport belts

Notini et al. [2003] describes a developmental CM system designed to monitor the condition of sorting machinery drive belts. The systems experimental GUI shown in Figure 5.7, enables data analysis using information from one of three types of CM techniques: Belt slippage CM, Belt temperature CM and acoustic emission CM. Having selected a CM type, users are presented with a series of data analysis techniques to select from, a series of data scaling options, the period data will be analysed between, and threshold selectable values. An altogether much more complex and flexible set of functions compared to Salvan's [2004] GUI. A considerable amount of technical knowledge, understanding of data processing techniques and experience of the machinery being monitored will be required, if correct and appropriate decisions are to be taken based on information presented via the GUI. This necessitates the need for users with experience in Condition

Monitoring and interpretation of data analysis. Novice users can be anticipated to require extensive training in order to use this GUI as intended.

Many UID rules identified in section 2.9 are broken in the GUI presented in Figure 5.7, e.g., its dull grey background creates a lacklustre appearance. The screen appears cluttered, failing to show any obvious signs of grouping amongst radio buttons, combo boxes and indicators. Information is tightly packed together at the top of the screen presenting an unbalanced appearance. A small font size text with the same style is used throughout the UID, making it difficult to distinguish between any of the text on the screen. Technological terminology is used extensively for numeric boxes, control boxes and radio button descriptions. Good for expert or well-versed users, but of little use for novices or non-technical users. On the positive side, numerous data analysis options are available on one screen, avoiding the need to jump around UI screens, in order to conduct a thorough analysis of belt condition. The data analysis trend graph and threshold condition indicator appears more prominent, than other information on the GUI. This is essential because the trend graph and condition indicator, act as the main method for communicating CM information to users. Both graphs incorporate legible units for their x and y-axis coordinates. An easy to understand worldly traffic light colour scheme provides a visual indicator for belt condition. Coloured threshold lines on the trend graph, offers users a clear indication of condition movements within threshold limits. The prediction function creates a clear visual representation of future predicted condition movements, based on the users selected method of extrapolation.

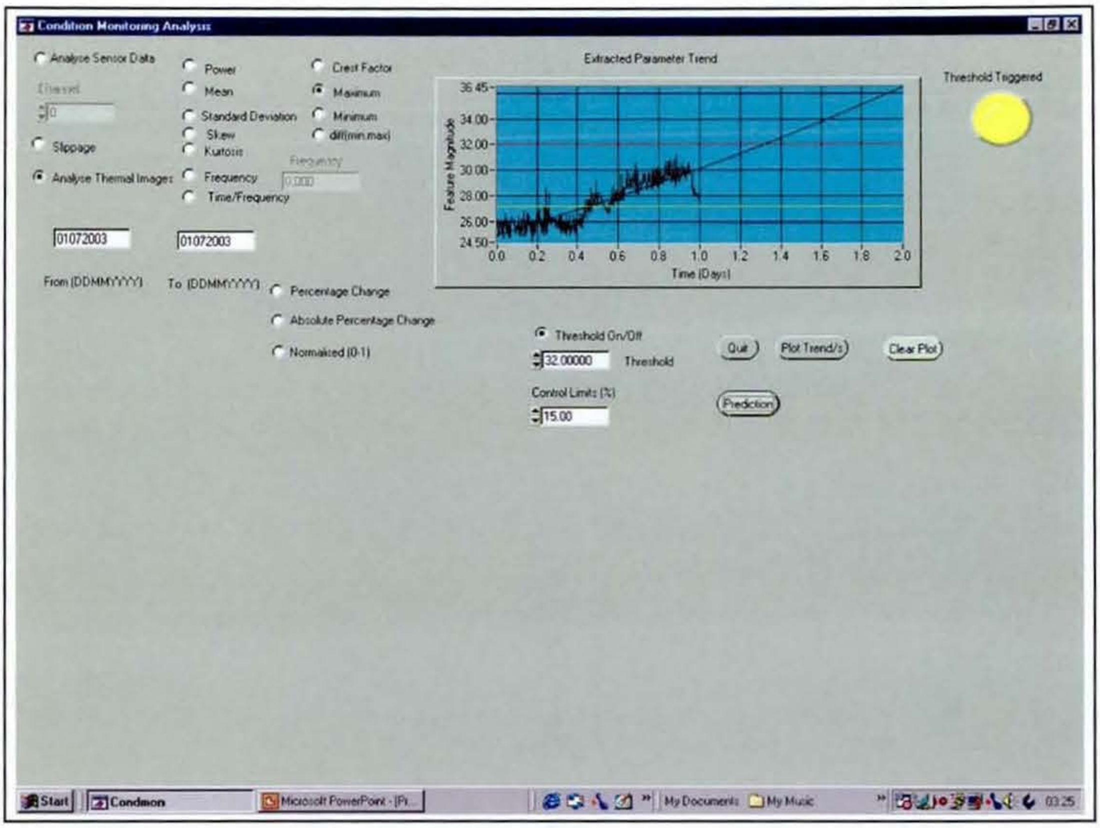


Figure 5.7. Belt Condition Monitoring user interface, Notini et al. [2003].

5.8.3. Integrated thermal imaging CM system

Al-Habaibeh et al. [2003], describes the application of an autonomous low-cost infrared imager, for monitoring Royal Mail LSMs. Figure 5.8 and Figure 5.9 display the GUIs developed for this system. Mechanical and electrical systems generate thermal energy during normal operation, enabling a thermal imaging camera to distinguish between normal and abnormal conditions. For example, excessive heat is normally associated with a deviation from the normal operating condition, evidence of a suspect problem developing. Al-Habaibeh's intension is to provide maintenance engineers and interested staff at Royal Mail, with thermal sensory data in the form of images and graphical plots, to aid predictive maintenance decision-making.

GUIs in Figure 5.8 and Figure 5.9 present an initial professional appearance, incorporating grouping of associated interface control functions, the use of graphical icons, a suitably sized graphical plot with x and y units for data analysis purposes, manual control functionality over the graphical plot, including: scale, line colours and size, plot back ground colours, thermal image size, data extraction data storage controls; manual control functionality over the thermal image plot including: image size, image resolution and orientation, image storage and extraction; manual controls for thermal camera set up, a help button and a quit button.

Negative aspects in the GUI design include confusing unclear descriptive identifiers, located next to buttons and control boxes such as, 'AI', 'AI-Counts', 'Counts', 'Saved sampling period', 'number of samples', 'sampling rate (frame/sec)', 'Ch1, Ch2 ....Ch7'. An excessive amount of information is provided on both GUIs in Figure 5.8 and Figure 5.9, confusing and intimidating for novice and intermediate users, but perfectly acceptable for the expert user, who doesn't want to jump between screens in order to complete a task.

In comparison with Salvan [2004] and Notini [2005] GUIs, Al-Habaibeh incorporates more manual controllability over the look and feel of the decision aids (graphical plot and thermal image), and the hardware (infrared camera, data storage device, and additional sensory device inputs.). Al-Habaibeh's GUI doesn't incorporate as many methods to analyse sensory data as Notini's GUI. Al-Habaibeh's GUI represents a development tool, being complex in design, requiring explanation and instruction before a user would be able to make full and correct use of its functionality.

Figure 5.8. Thermography Condition Monitoring GUI. Screen 1, Al-Habaibeh et al. [2003].

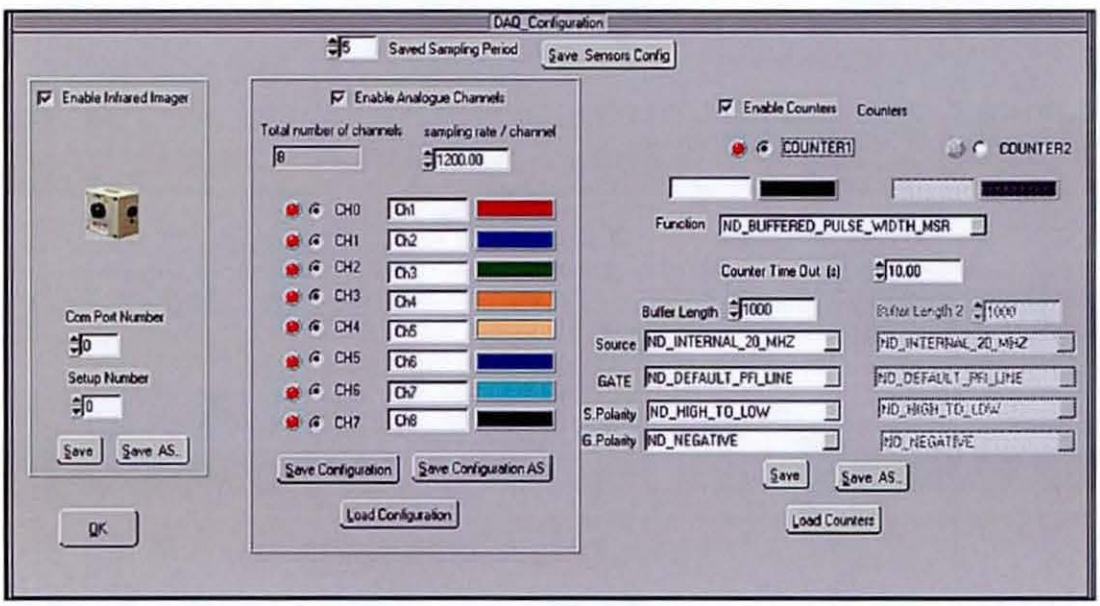


Figure 5.9. Thermography Condition Monitoring GUI. Screen 2, Al-Habaibeh et al. [2003].

5.8.4. Analysis of remotely captured machine health data

Further analysis of bearing acoustic signals gathered during Salavan [2004] research, has been completed by Walder [2004], a recent under graduate at Loughborough University. His investigations compare different data analysis techniques, aiming to identify the most suitable analysis technique for identifying loose bearing assemblies and sand contaminated bearing sleeves. Identified data analysis techniques are incorporated into a single screen GUI developed using LabVIEW from National Instruments, shown in Figure 5.10. GUI operating instructions are included in Walder [2004].

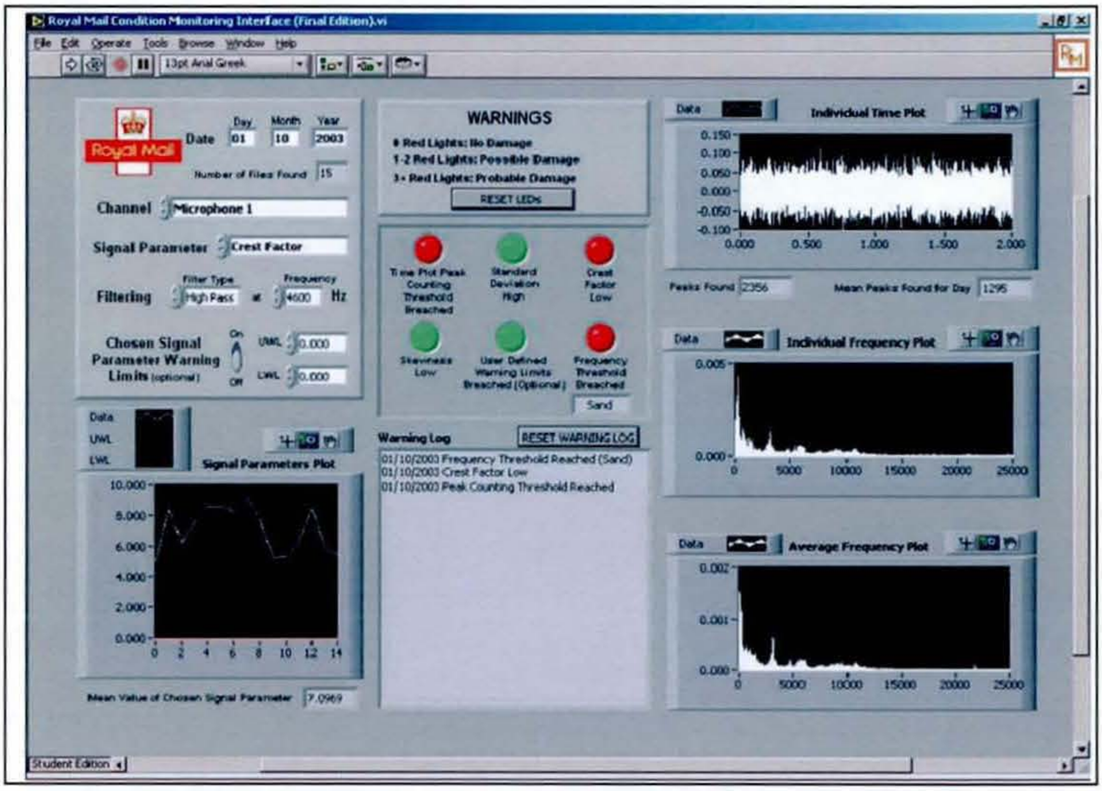


Figure 5.10. Experimental CBM GUI screen developed for presenting and analysing acoustic and vibration CM information, Walder [2004].

Walder [2004] takes advantage of the UID tools provided within LabView, creating a bold evenly distributed and spaced interactive GUI. Control features are packed into a box positioned to the top left of the screen. Each feature is labelled with an appropriate description, in an easily legible font of a suitable size for normal human vision. Controllable features include: the date period data is to be analysed between, the type of channel (sensor) data has come from, a selectable list of data analysis techniques, a choice of data filtering techniques, and selectable upper and lower control limits. Screen space is saved through the use of combo boxes and radio buttons. Combo boxes are provided for selecting the users preferred data analysis technique, channel selection and filtering selection. Four labelled charts offer users four signal analysis alternatives. Each chart offers users built in size and view options, enabling users to zoom in on a specific portion of a graphical plot, or zoom out for examination of a plotted area over a longer period. Located within the centre of the GUI, Figure 5.10, are a set of six-condition indicators in the form of Light Emitting Diodes (LEDs) and a warning log. Instructions above the LEDs provide an indication of bearing condition. Each LEDs colour is linked directly to known condition based parameters, determined when the user conducts a data analysis run routine. Normal condition parameters result in a green LED colour, and out of range parameters result in a red LED colour. Out of range conditions result in the automatic generation of a message within the warning log, indicating a possible component condition problem. In this way the GUI takes on the role of an instructor. None of the other GUIs under comparison incorporate this level of component condition detail. Adding the intended organisations logo into the GUI creates a sense of company product ownership, i.e., designed for and owned by Royal Mail.

5.9. Summary

Design, presentation, visual appearance, complexity and functionality have been discussed for four CM GUIs, developed by members of the Royal Mail University Technology Centre, Loughborough University. Results provide sufficient material for recommending a list of design features for inclusion in CBM software's GUIs.

- Provide access to adequate help assistance and tutorials, within a CBM software's GUIs.
- If charts are used for displaying process parameters, offer a full range of manual user plot appearance controls. Controls enabling users to alter line, back ground, chart and warning control indicator colours. Provide maximise and minimise chart buttons, provide zoom in and zoom out buttons, and an ability to vary between panoramic or compact chart views.
- Incorporate calendar drop down selection boxes and/or text boxes, for specifying the date data is to be extracted between for analysis.

- Where appropriate provide upper and lower manual selection chart control limit settings.
- Offer a drop down expandable file Browser, as a method for selecting data files to be extracted for analysis, or location for saving data and image files.
- Group like for like controls into bordered or boxed areas on the screen. For example, all chart appearance controls to be located together, data analysis selection controls located together, start, stop, save and load buttons located together, etc.
- Use drop down combo boxes instead of radio buttons to avoid presenting a cluttered screen appearance.
- Use clear text of an appropriate size and font style for all labels. Vary size or strength of label text to emphasise label importance, in the same manner as headers in a word processed document.
- Use label description language suitable for the profile of the intended users. Further discussion on User Profiling is provided in section 2.6.4.
- Incorporate colour coded component condition warning indicators into the GUI. Link the warning indicators to the results for data processing run routines. Use a selection of colours within the indicators indicative of known human associated responses, by the intended user group, e.g., red = warning or stop; yellow = caution; green = ok or go. Use an appropriate number of colours to suite the number of different conditional responses. The 3 warning colours suggested above might not be adequate. In which case further colours could be added, or alternatively more than one warning indicator light might be necessary, as is used in Figure 5.10.
- Incorporate a warning log report otherwise known as an automatic condition report generator, similar to the idea presented in Walder [2004]. Link the function of the log warning report directly to the results of data analysis run routines, and the warning light indicator/s. Information to be automatically generated on the report might include: discrete condition parameter values; the type of data analysis performed; date and time data analysis performed; the time period data has been analysed between; user identification information (ID); level of the severity of the detected component condition anomaly, with respect to whether maintenance action is required immediately or in the near future; a descriptive reason of the detected change in condition, i.e., sensory data at 75% of the upper limit, a sudden change or

movement in component condition sensory data, an irregular component condition sensory signal, etc.

At this stage each CM techniques GUI developed or under development for sorting machinery at Royal Mail, shown in Figure 5.5 to Figure 5.10, represents a developmental design rather than saleable commercial products. It is very doubtful whether any of these designs could be picked up by the average maintenance engineer at Royal Mail and used to make accurate and well-judged maintenance decisions. A fact largely attributable to the decision not to use Human Centred Design, Human Factors principles and User Profiling, prior to designing each interface. Reassessing each user interface's design at this stage using Human Centre Design principles, Iterative Design techniques, and Usability Testing would highlight many of the already discussed design shortcomings.

Chapter 6

6. CONCEPTUAL DESIGN

6.1. Introduction

Previous chapters constitute interpretation and discussion, following information-gathering exercises. This chapter presents a conceptual design for a CBM GUI based upon earlier findings, guidelines, previous examples, and user requirements investigations. Ideas incorporated in the conceptual design are targeted at Royal Mail, the main industrial sponsoring organisation. The chapter begins by describing the initial design considerations namely, identifying the design architecture, selecting a desirable method of HCI, selecting a prototyping tool, and deciding upon a structure for the CBM web site. Further design ideas on a web page-by-web page discussion basis follow. Influencing factors driving each design idea, are referenced and discussed.

6.2. CBM Design Architecture

A remote CBM system architecture, residing on an Internet or Intranet server, accessible through Browsers, is the chosen solution for the conceptual design. Differentiations between CBM design architectures were discussed in chapter 2, section 2.5. Reasons favouring this design architecture, identified as user requirements in chapter 5, include:

- Providing users with access to CM information via a networked computer system, linking all machinery being monitored using CM equipment.
- Providing a system that integrates with existing maintenance software presently used by personnel at Royal Mail.
- Further reasons favouring an Internet design architecture are presented in section 2.5.3.

6.3. Selecting a desired method of Human Computer Interaction

A standard computer display screen of regular size, connected to a personal computer capable of running an Internet Browser over a high speed Internet link, acts as the chosen form of HCI. A standard mouse and standard keyboard are also selected.

6.4. Selecting a Prototyping Tool

Visual Web developer 2005 Express Edition, from Microsoft, has been used to construct the conceptual design. The software was selected because it offered the capability to generate active server pages (ASPs), was ideal for individuals with limited programming capabilities, and proved relatively easy to construct a set of prototype CBM GUI web pages. Reference to and discussion concerning ASPs is presented in chapter 2, sections 2.4. and 2.5.3. Alternative web design software capable of producing ASP web pages, notably Macromedia, a Dreamweaver product, would have proven equally suitable.

6.5. Web Site Design Structure and Navigation

The chosen design structure for the CBM web site, provides users with access to the majority of CBM system functionality requirements identified from survey two, section 4.3.2.3. It is also heavily influenced by user requirements listed in section 5.5. Each distinguishable functional requirement forms and is represented as the first layer within the web site structure, illustrated in Flow Diagram format, shown in Figure 6.1. Subsequent layers comprising the lower level structural elements, fall below these top layers. Categorising the web site into distinguishable layers, compliments a logical web site drill down navigational process.

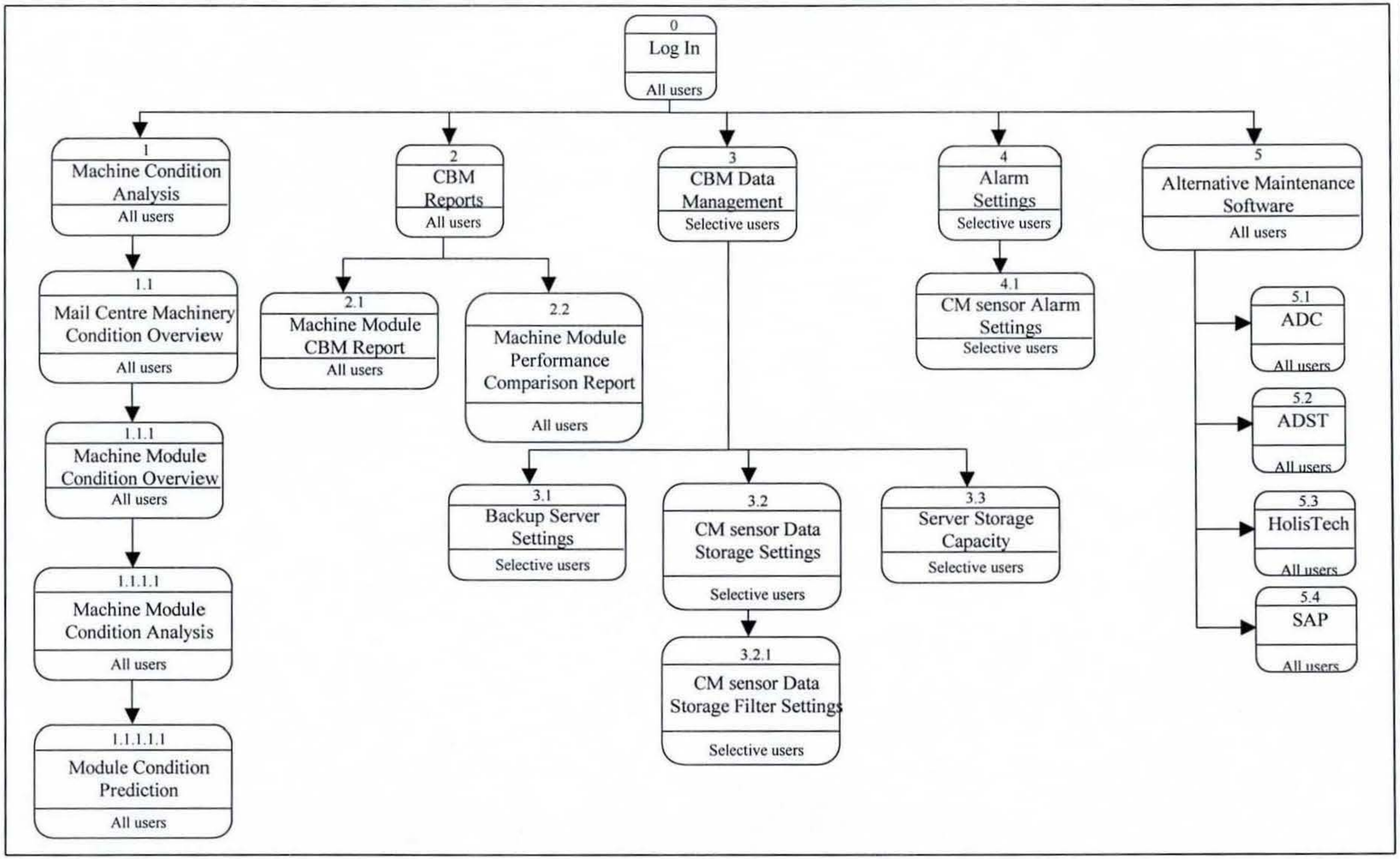


Figure 6.1. Flow diagram depicting the hierarchal structure for the CBM web site.

A 'Log In' web page provides the top layer for the CBM web site structure, followed by five expandable categories listed below:

1. **Machine condition analysis.** Provides an automatic and or manual capability to access machinery health monitoring and predicted remaining useful machine life information, for a user's chosen Mail centre.
2. **CBM reports.** Provides an automatic and or manual capability to generate CBM reports for one or many machines, linked to CBM systems.
3. **CBM data management.** Provides the capability to set up automatic CM sensory data management features, along with the capability to manually control the storage and movement of CM sensory data, stored on databases.
4. **Alarm settings.** Provides a manual capability to select and specify control limits and alarm types, activated automatically once equipment being monitored by CM equipment enters control limits.
5. **Links to alternative maintenance software.** Links to other software regularly used by maintenance personnel at Royal Mail.

6.5.1. Navigation

Navigation is considered to have a high level of importance when designing a CBM GUI, refer to section 4.4.3.6, Table 4.4. Suggestions for good web site navigation were proposed in section 2.10.1 and section 3.3.8.1. Drop down selectable menu buttons grouped together in a menu bar, positioned at the top of each web page, demonstrated in Figure 6.2, provide the main method of navigation. Each drop-down-menu is headed with a title, derived from the first level items incorporated in the CBM structure, refer to Figure 6.1. The words comprising the titles for the drop down menus have been chosen for their anticipated ease of interpretability.

Figure 6.2. Web site navigation bar.

The navigation bar is mouse activated. Moving the mouse cursor across any of the menu buttons, containing an arrowhead to its right exposes further selectable buttons, each of which represents a 'hyperlink' to further web pages, demonstrated in Figure 6.3.

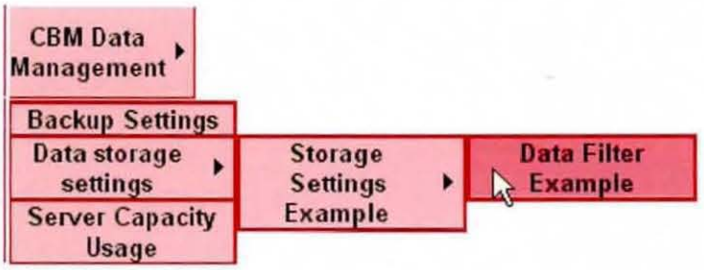


Figure 6.3. Expandable drop down menu.

Additional web site navigation techniques include selectable hyperlink images, positioned in and around individual web pages, illustrated in Figure 6.4, and user name and user type, authentication web access to specific web pages.

Figure 6.4. Hyperlink images used for web site navigation.

6.5.2. Login screen

Issues influencing the design of the Login screen include: Ease of use; user familiarity; security; user type screening; and web Browser functionality. A Log In box designed to receive: 'User Name' and 'Password', shown in Figure 6.5, constructed using ASP instructions, forms the chosen design solution. Evidence supporting this design choice are discussed in sections 2.5.3 and 3.3.4.3.

Figure 6.5. Log In Box incorporated in entry-level screen.

6.5.3. Machine condition analysis

The machine condition analysis section of the web site structure, represented as '1' in Figure 6.1, provides users with access to:

- Live and historic machinery health monitoring information.
- Predicted machinery health information.
- A selection of data analysis techniques, to assist the process of predicting future machinery health.

Access to machine condition analysis web pages, is initiated through the drop-down-menu button titled, 'Select mail centre', refer to Figure 6.2.

6.5.3.1. Mail centre machinery condition overview

The mail centre Machinery Condition overview is represented as 1.1. in Figure 6.1. The objective of this web page is to intuitively display the condition of each mail-sorting machine, for a user selected mail centre; an objective included as a user requirement in section 5.5.5. Factors influencing the chosen design include:

- Providing a recognisable user familiar solution.
- Incorporating recognisable colour coding to portray machinery health conditions; recommended in section, 2.9.3, 'GUI Design rules', and considered to have a high level of importance amongst survey respondents, refer to section 4.4.3.6, Table 4.4.
- Visual clarity leading to easy interpretation.
- Portraying the live condition of every machine being monitored using CM equipment on one screen.
- Providing a rapid method of drilling down from the overview condition perspective to lower more detailed machinery condition information.

An image of the web page is shown in Figure A.5.1, Appendix A.5. The web page is designed to act as a template, incorporating the following self-populating items:

1. The location of the mail centre, incorporated within the title bar.
2. Colour coded images designed to portray live machinery condition, demonstrated in Figure 6.6.
3. Machinery condition activated labels, which identify the condition status of a machine, demonstrated in Figure 6.6.

4. The number of machines illustrated on the template, and thus the size of the table containing each mail centre's machinery condition overview.

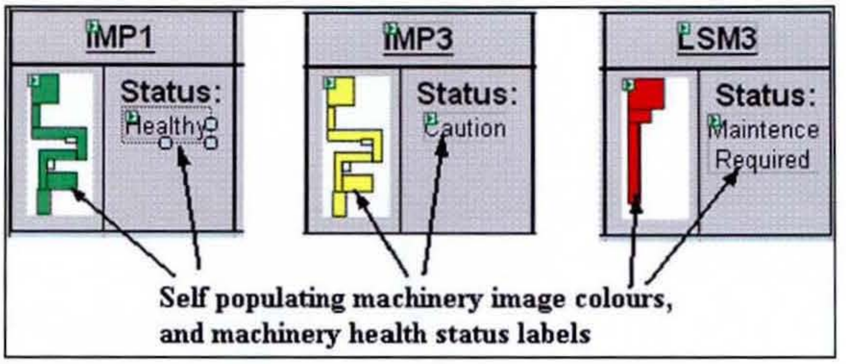


Figure 6.6. Colour coded images portraying a machine's overall condition.

6.5.3.2. Machine module condition overview

The machine module condition overview web page is represented as 1.1.1. in Figure 6.1. The web page displays the condition of a sorting machine's modules; identified as user requirements included in section 5.5.5. The design communicates modular condition using colour coding and semi circular condition instrumentation dials, demonstrated in Figure A.5.2, Appendix A.5. The worst performing or most deteriorated component dictates the presented condition for each module, since an average value would be of no use. Factors influencing the chosen design include:

- The first three bullet points listed as influencing factors in the design of the, 'Mail centre machinery condition overview'.
- Communicating live sensory conditions from the most deteriorated component within a module, for each type of CM technique in use.

The web page is designed to act as a template, incorporating the following self-populating items:

1. The location of the mail centre and the name of the machine being investigated, incorporated in the title bar.
2. A colour coded representation of the machine being investigated, demonstrated in Figure 6.7.
3. Animated colour coded semi circular condition indicator dials, demonstrated in Figure 6.8.

4. A live value displaying the most deteriorated component within a module being measured using CM equipment, demonstrated in Figure 6.8.
5. The size of the scrollable table containing each of the animated colour coded semi circular condition indicator dials.

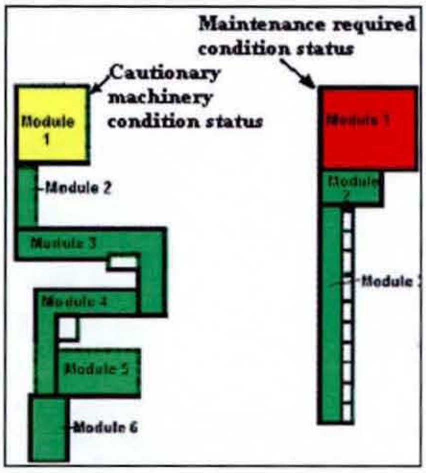


Figure 6.7. Colour coded modular condition representation.

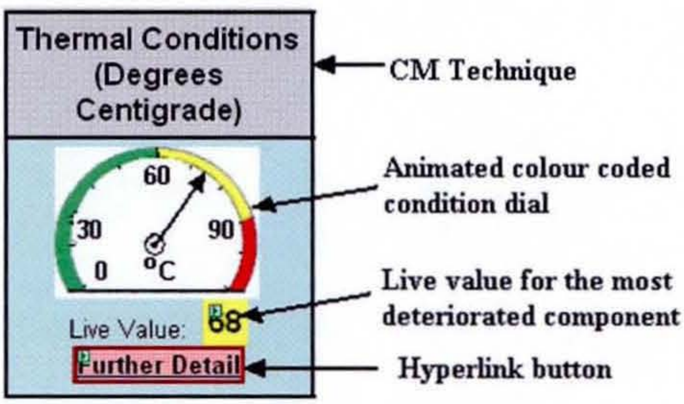


Figure 6.8. Animated machinery condition indicator dials.

6.5.3.3. Machine module condition analysis

The machine module condition analysis web page is represented as 1.1.1.1. in Figure 6.1. The objective of this web page is to graphically display live, historical, and predicted component condition movements, for sorting machine modules. These objectives are included as user requirement listed in sections: 5.5.1, 5.5.5, and 5.5.6. Figure A.5.3, Appendix A.5 shows an image of this screen. Factors influencing the chosen design include:

- Results from Surveys 1, 2 and 3, which present the same message: 'Machinery health monitoring information should be presented graphically, using control limits'.
- Results from survey 2 and 3, which recommend the inclusion of a selection of data analysis techniques within CBM software.
- Following the example of existing CBM software designs, described by numerous authors including: Lopes et al. [2002], Lee [2001], Orsagh et al. [2000], Salvan [2004], Al-Habaibeh et al. [2003], Notini [2005], and Walder [2004].

The web page is designed to act as a template, incorporating the following self-populating items:

1. An x-y axis graph, with upper and lower colour coded control limits, showing live and recent CM sensory data movements, demonstrated in Figure 6.9.
2. An x-y axis graphical prediction, anticipating future component condition movements, based upon recent historical machinery trends, demonstrated in Figure 6.10.
3. The predicted amount of time before a machine's most deteriorated component operating condition enters lower control limits and upper control limits.

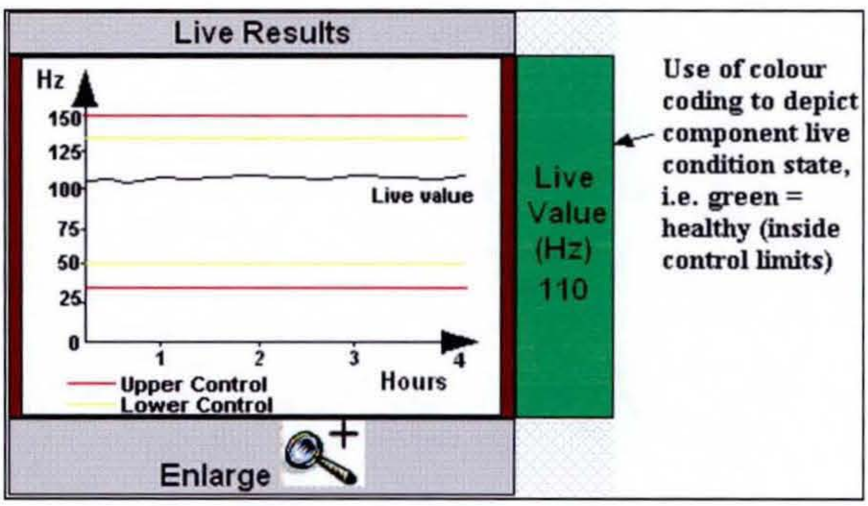


Figure 6.9. Graph showing live and recent component condition movements.

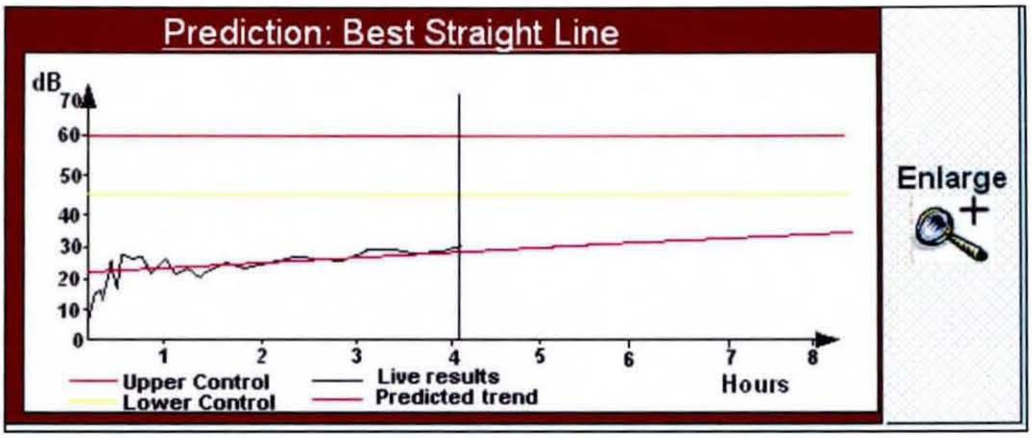


Figure 6.10. Graph showing a best straight-line prediction.

Additional graphical objects incorporated on this page include a selection of data analysis options, demonstrated in Figure 6.11, a pair of calendars for making date data selections, demonstrated in Figure 6.13, and colour coded labels, showing a prediction for the calculated length of time before the most deteriorated component enters lower and upper control limits. Selecting a data analysis option and clicking the submit button, generates a new graph in place of the prediction best straight-line graph. For example, selecting standard deviation generates a graph showing the standard deviation, for data gathered during the previous 24 hours.

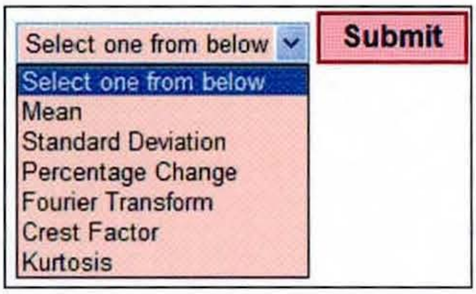


Figure 6.11. Data analysis drop down combo box.

Both graphs incorporated on the web page are relatively small in size, and could prove difficult to read. Controls for viewing an enlarged version of both graphs are therefore provided in the form of a selectable icon, titled 'Enlarge', as seen in Figure 6.9 and Figure 6.10. An image of the enlarged live results graph is shown in Figure A.5.4, Appendix A.5. To the left of the enlarged graph, is a hyperlink titled, 'Transfer data to MS Excel'.

Clicking the hyperlink activates ASP programming code, that extracts the data constituting the graph, builds it into an MS Excel format document, and offers users a file location in which to save the file. Incorporating the capabilities to transfer CBM data into MS Excel format documents, so that they may be exported, is a user requirements listed in section 5.5.3.

6.5.4. CBM reports

Providing users with the ability to generate CBM reports in a CBM GUI, was found to be very important, in the eyes of industrial maintenance personnel, refer to section 4.4.3.6, Table 4.4. Equally as important is the look, feel and interpretability of CBM reports. Section 3.3.7.1 discusses CBM reports in some detail, providing useful ideas and suggestions to assist the CBM report design process, including: explaining the purpose of CBM reports, suggesting design rules to follow whilst designing CBM reports, suggesting what to include in CBM reports, and suggesting methods for distributing CBM reports.

Two CBM reports are included in the conceptual design: a sorting machine module report, and a performance comparison report, represented as 2.1 and 2.2 in Figure 6.1. Access to both reports is provided through the navigation bar under the header, 'CBM Reports', illustrated in the adjacent image. 'Module Reports', provides users with access to a CBM report generator and subsequently CBM reports. 'Performance Comparisons', provides users with access to a CBM report generator and subsequently a CBM performance comparison report.

6.5.4.1. CBM report generators

The CBM report generator provides users with the capability to manually select parameters from which CBM reports will be constructed. Two CBM report generators are included in the conceptual design, located between 2 and 2.1/2.2 in Figure 6.1. Images of each CBM generator are shown in Figure A.5.5 and Figure A.5.6, Appendix A.5,

The chosen design solution provides users with lists of selectable parameters for defining the contents of a CBM report, converting a users selection into a database query, similar to a structured query language (SQL) request, extracting the requested data from database/s and constructing a new web page, containing a users CBM report. Drop down lists constructed using active server page programming instructions, are the chosen parameter selection design solution, demonstrated in Figure 6.12. Drop down lists utilise screen space very efficiently, are an established familiar design, and offer users a quick method for making a selections from small to medium sized lists.

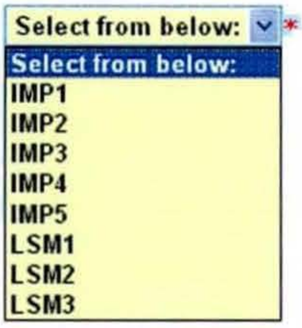


Figure 6.12. Drop down list provides a choice selection for data base queries.

The choice of selectable options provided in the CBM report generators includes: mail centre, Machine Type, Machine Module, Condition Based Monitoring Technique, and Data Date Extraction period. With this choice of options, users can generate CBM reports for machine module's at any mail centre. Interactive calendars provide an intuitive method by which users specify the period data will be extracted between, illustrated in Figure 6.13. Calendars are used similarly throughout the CBM web site design.

Figure 6.13. Interactive calendars for date period selection.

Additional features incorporated in the machinery comparison performance report generator, Figure A.5.6, include:

1. A drop down list for choosing the type of CBM performance comparison.
2. A second list of selectable options, so that users can compare the results from one set of options against another.

6.5.4.2. Condition Based Monitoring Reports

Contents incorporated in section 3.3.7.1 along with user requirements, contained in section 5.5.6, have influenced the design of the two CBM reports, provided as examples in the conceptual design. Images of each CBM report are shown in Figure A.5.7 and Figure A.5.8, Appendix A.5, The first CBM report example is intended to enable users to gauge the present and future condition for a component. The second CBM report is intended to enable users to compare the CBM performance of one component against another or several others.

The first CBM report example shown in Figure A.5.7, comprises four distinguishable parts. Firstly a table identifying the parameters to which the report is constructed from, located at the top of the page. Secondly an x-y axis graph incorporating control limits, demonstrated in Figure 6.14, showing condition movements for the most deteriorated component within the module selected, for the duration of the user selected time period.

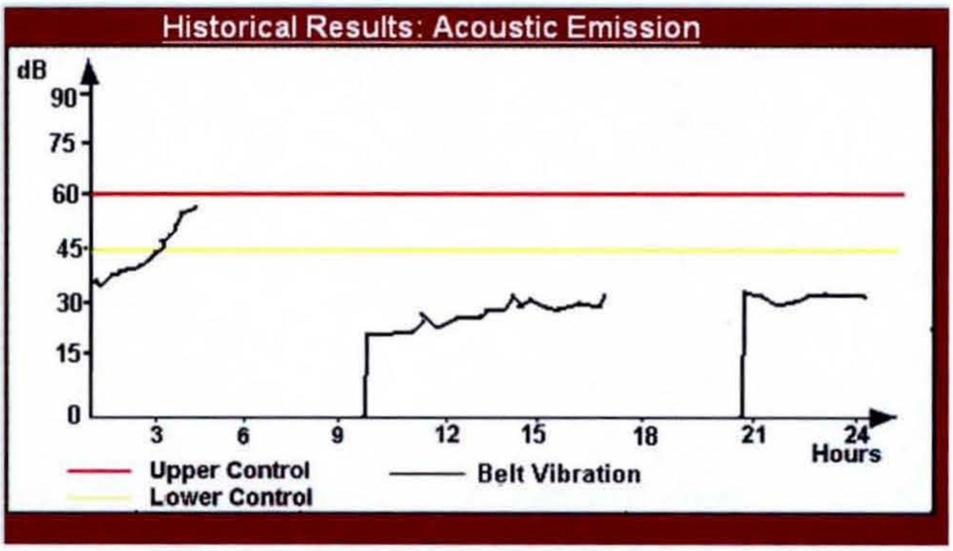


Figure 6.14. Graph showing acoustic emission condition movements.

Thirdly a set of x-y axis graphs, each a prediction based upon best straight-line calculations, for each individual distinguishable operational period, demonstrated in Figure 6.15.

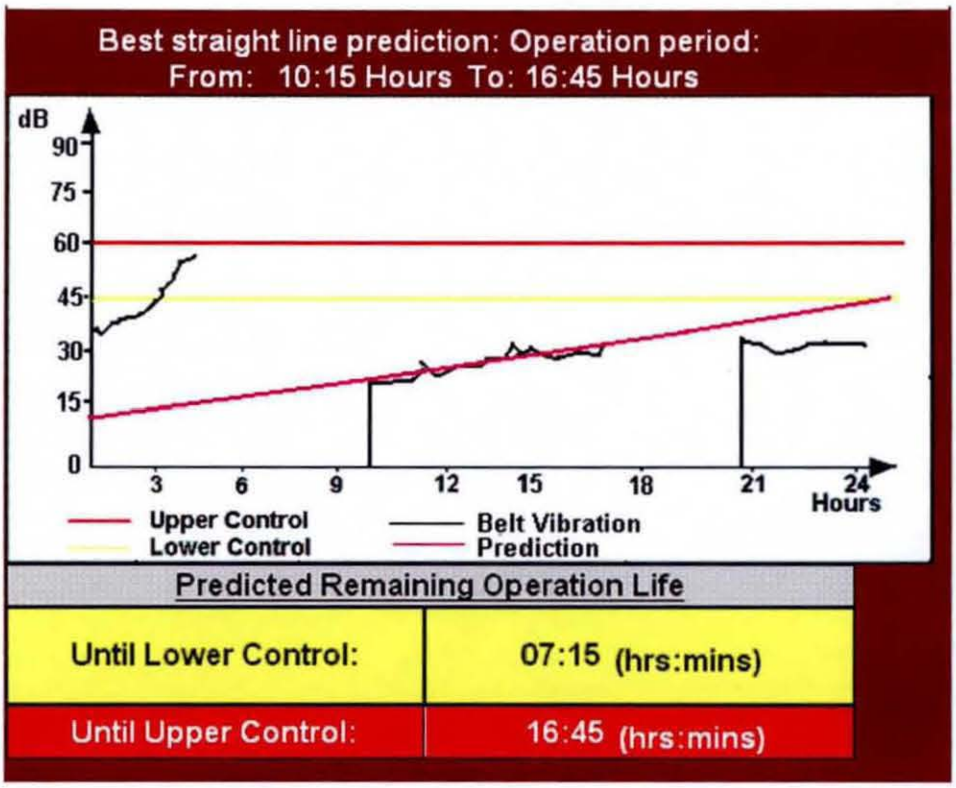


Figure 6.15. Best straight line prediction graph between: 10:15 to 16:45.

Fourthly a colour coded table, consisting of numerical and percentile values, displaying the amount of time a component has been in operation and within control limits, for the user selected time period, shown in Figure 6.16.

Status	Time (hrs: mins)
Total Operating Time:	14:15
Total Down Time:	9:45
Time Inside Limits:	13:00
Time Inside Lower Limits:	01: 15
Time Inside Upper Limits:	00:00

Machine Operation	% Time over 24 Hour Period
% Operating Time Inside Limits:	91.23%
% Operating Time Inside Lower Limits:	8.77%
% Operating Time Inside Upper Limits:	0.00%

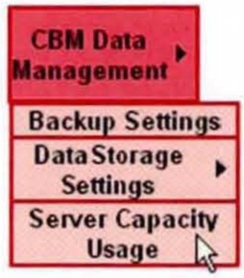
Figure 6.16. Component CM performance table.

The second CBM report example shown in Figure A.5.8, consists of two tables. The first table, located at the top of the page, contains the parameters that the CBM report is constructed from. The second table compares the amount of time a component has remained within or exceeded control limits, against similar components in other mail centres. Each mail centre is anticipated to set different control limits, which is why they are included in the report.

6.5.5. CBM data management

Incorporating data archiving features within a CBM GUI, was found to be very important, in the eyes of industrial maintenance personnel, refer to section 4.4.3.6, Table 4.4. Explanations summarising the purpose of CBM data management have been discussed in sections 2.4.3 and 3.3.5.

The conceptual design incorporates four data management functions, available through three selectable drop-down-menu buttons, shown in the adjacent image. Firstly data back up settings can be specified, e.g., backup server location and times back ups are performed. Secondly CM sensory data storage locations can be set, as can the frequency data items are stored. Thirdly data item filtering time intervals applicable to CM sensory data, stored on database can be set. And fourthly users can view the amount of server hard drive storage space consumed by CM data and still available. Access to all data management web pages will be restricted to users with recognised user name access rights. The data management functions are indexed as 3.1, 3.2, 3.2.1, and 3.3 in Figure 6.1.



6.5.5.1. Backup server settings

The backup server settings web page shown in Figure A.5.9, Appendix A.5, provides users with the functional capability to:

- View and alter server locations used for storing and backing up all CM data.
- View and alter times data is backed up to servers.

The contents of the web page are structured inside a table, for improved visual clarity. Labels located in the cells under the heading, 'Existing Settings', take on the values of the existing settings, during web page construction. Text boxes are provided to enable users to manually alter backup server settings.

6.5.5.2. CM sensor data storage settings

Two web pages have been designed for viewing and altering the storage locations for CM sensory data. Firstly users are provided with a screen designed for selecting a specific CM sensor, shown in Figure A.5.10, Appendix A.5. Design features incorporated in this web page include, a page header, a choice of hierarchical selectable options, contained within a table, for selecting a CM sensor, and drop down lists as illustrated in Figure 6.12, described earlier in section 6.5.4. Secondly users are presented with a screen displaying the storage location for the selected CM sensor data, along with capabilities for altering these settings, as shown in Figure A.5.11, Appendix A.5. This second web page contains two tables: 1) A table populated with the selected parameters entered in the previous web page. 2) A table designed to display the existing CM sensor storage location; the time intervals sensory data values are extracted for storage, and text boxes for manually altering either setting. Each table incorporates headers in greyed out boxes to improve visual clarity, as shown below in Figure 6.17.

	Enter New Settings
Primary server	
Time Intervals data transferred to primary server:	Hrs:Mins:Secs __:__:__

Figure 6.17. Table design demonstrating techniques to improve visual clarity.

6.5.5.3. CM sensory data filtering settings

Access to the CM sensory data filtering settings web page, are provided through the navigation bar or by clicking the 'Submit button', incorporated towards the bottom of the 'CM sensor's data storage settings web page', refer to Figure A.5.11, Appendix A.5. The web page is designed to provide authorised users with the ability to set data filtering options, for reducing the amount of data in storage on databases. Section 3.3.5.2 emphasises the importance of freeing up storage space using data filtering techniques to prevent server storage over capacity.

The web page comprises two tables, demonstrated in Figure A.5.12, Appendix A.5. Firstly, a table populated with values selected from the CM sensor selection web page, shown in Figure A.5.10, Appendix A.5, top of the page. Secondly, a table for viewing and manually altering the weekly, monthly and yearly time intervals CM sensory data is filtered; a section of which is shown in Figure 6.18. Methods incorporated in the design for specifying filter settings, from left to right, include: check boxes, drop down lists, and text boxes. Existing data filter settings are displayed through labels, which take on the value of the settings in question, when the web page is constructed. Clicking the submit button located towards the bottom of the web page, refer to Figure A.5.12, Appendix A.5, sets any altered data filter settings for all future machine operations, for the sensor in question.

Filter Frequency		Filter	Interval Filtering Performed	Time Filtering Performed (hrs:mins)	Intervals data will be stored (hrs:mins:secs)
Weekly	Existing	Yes	Saturdays	00:00	00:00:05
	New	Yes No	Select from below:		

Figure 6.18. Section from the sensory data filter settings table

6.5.5.4. Server storage capacity

The server storage capacity web page, shown in Figure A.5.13, Appendix A.5, is designed for communicating the amount of server capacity being used and free for use, on those servers storing CM data. Information contained on the web page, is communicated using pie charts and numerical values, located in a table, as demonstrated in Figure 6.19 below.

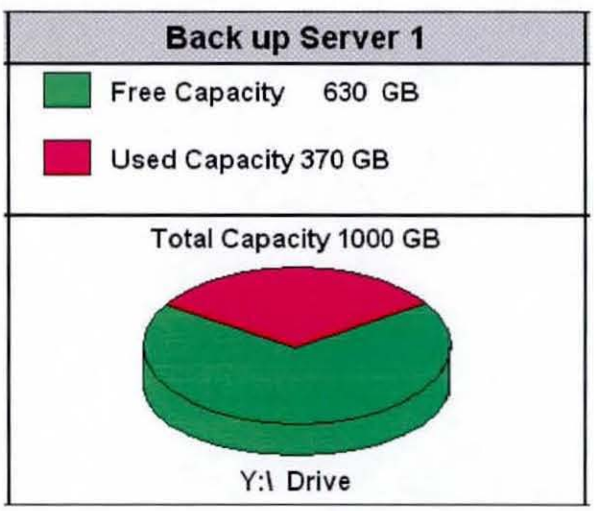


Figure 6.19. Communicating server storage consumption using pie charts.

Influencing factors driving the chosen design are linked to and derived from Microsoft Explorer. Numerical figures showing server capacity utilisation will take on the value of labels, and be converted into pie charts, constructed automatically. Active server page programming provides the behind the scenes dynamic web page construction capabilities.

6.5.6. Alarm settings

Findings from survey 2, section 4.3.2.3 and survey 3, section 4.4.3.6, Table 4.5, suggests CBM systems should be designed with an alarm system. An alarm system capable of gaining the attention of maintenance personnel, once machinery conditions deteriorate, above or below accepted control limits. Findings from user requirements investigations at Royal Mail, included in sections 5.5.1 and 5.5.8, also identify a need for designing alarms into a CBM system. The process of selecting alarms for CBM systems was discussed in section 3.3.7.6.

The conceptual design incorporates two web pages designed with the intension of providing users with the capability of selecting and setting up CM alarm controls, illustrated as 4 and 4.1 in Figure 6.1.

- Firstly a web page that enables users to select a desired CM sensor, for viewing or altering alarm settings, shown in Figure A.5.14, Appendix A.5. Design features incorporated in this web page copy the 'database storage settings CM sensor selector web page', described in section 6.5.5.
- Secondly a web page for viewing and altering the control limits, that define when a CM alarm is automatically activated, and the type of alarm activated or issued, shown in Figure A.5.15, Appendix A.5.

Access to both web pages is provided by moving the mouse over the 'Alarm Settings', drop down menu button and clicking, 'Select Alarm', illustrated in the adjacent image.

The CM alarm settings web page incorporates two tables. The first table identifies the CM sensor selected from the previous screen, under the headers: mail centre, Machine, Module, CM technique and Sensor Number. Each selected parameter takes on the value of labels, within cells below the header, during web page construction. The second table presents upper and lower control limits, along with the alarms activated when sensor values enter these limits. This information is populated into the web page template during its construction, using behind the scene ASP programming instructions. To the right of this table, users are provided with controls for altering and specifying new control limits, along with alarms, activated if the limits are breached. Controls incorporated in the design include, text boxes and check boxes, demonstrated in Figure 6.20 below. Clicking the submit button located towards the bottom of the web page, refer to Figure A.5.15, Appendix A.5, updates the CBM system with a users new (if altered), alarm settings.

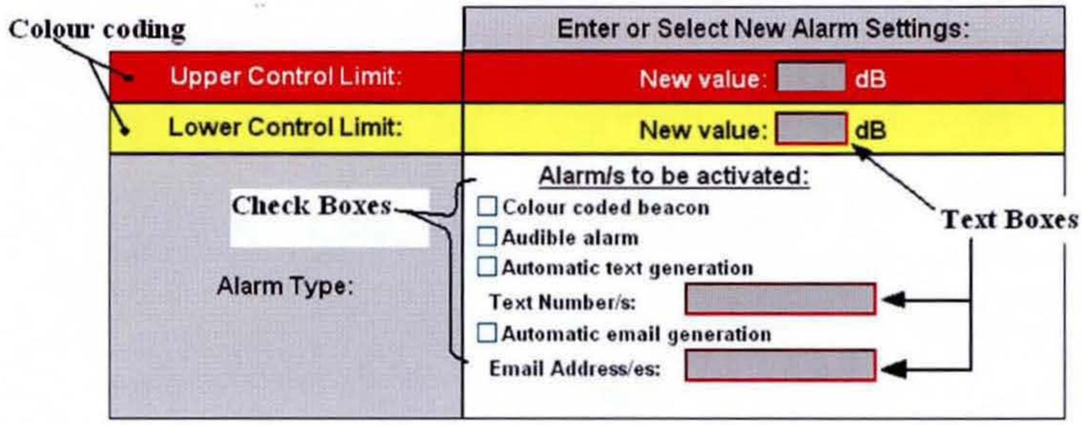


Figure 6.20. Section from the CM alarm settings web page.

6.5.7. Links to alternative maintenance software

Providing links to other maintenance software regularly used at Royal Mail, was included as a user requirement listed in section 5.5.5. Two methods of linking to alternative maintenance software applications are included in the conceptual design. Firstly through the menu drop down button titled, 'Alternative Maintenance Software', and secondly by clicking a hyperlink buttons located at the bottom of each web page. Images of the drop down menu and the hyperlinks are shown in Figure 6.21 below.

Figure 6.21. Links to alternative maintenance software.

6.6. Summary

Design ideas for a conceptual CBM web site and its individual web pages have been presented in this chapter. Individual images showing many of the web pages comprising the design are included in Appendix A.5. At this stage in the software development process, the web site represents a first attempt, an untested and untried set of design ideas. Many CBM GUI design requirements, and suggested design rules, recommended in earlier chapters, are missing, prompting further design work. Feedback from maintenance personnel at Royal Mail, the target user and an industrial collaborator for this research, is also missing. The next chapter discusses design improvements, instigated following feedback on the present design ideas, from Royal Mail maintenance personnel and maintenance professionals in general. The process represents a usability engineering stage, aimed at pushing concepts closer towards accepted design solutions, which meet and satisfy the intended users requirements.

Chapter 7

7. USABILITY EVALUATION AND DESIGN MODIFICATIONS

7.1. Introduction

Section 2.11 introduced the topics: 'User Interface Modelling', 'Usability Engineering', 'Iterative Design Techniques' and 'Usability Testing'. A central theme in each of these methodologies is to understand user requirements and build them into the design process prior to product release, thereby increasing the probability of user acceptance. Kim [2001] promotes the importance of using usability testing to identify error prone situations or potential human errors in advance. He suggests doing so provides opportunities for resolving human engineering deficiencies, which may exist in an interfaces' design. The intension of this chapter is to discuss feedback from potential users of the user interfaces, and discuss design alternatives aimed at resolving identified human engineering deficiencies. Identifying design deficiencies incorporated in the conceptual design, will be undertaken at two levels; firstly, from the perspective of feedback from Royal Mail and secondly, from the perspective of maintenance professionals in general. Feedback from Royal Mail personnel is directed towards bringing the conceptual design closer to meeting their own personal user requirements. Feedback from maintenance professionals in general, helps focus design ideas towards generating a generic CBM GUI solution, more likely to be accepted by multiple industries. Combining both sets of feedback, and considering previously identified generic CBM software design features, listed in section 4.4.3.10, offer sufficient material for identifying design solutions applicable to a generic CBM HMI design.

7.2. Design Feedback

Feedback has been gathered directly from Royal Mail maintenance personnel and maintenance professionals in general. Nine maintenance personnel at Royal Mail received presentations describing the conceptual design. Presentation recipients were encouraged to provide vocal or written feedback, on ideas presented or ideas missing, from the conceptual design. Feedback from maintenance professionals in general was obtained via an Internet feedback form, consisting of 22 questions, shown in Appendix A.6. Maintenance personnel were invited via email, to open and view the web address containing the conceptual design, before completing the online feedback form. Questions included in the feedback form are similar to those asked in survey 3. The intension being to determine whether factors identified as having value, in a generic CBM GUI design, are sufficiently catered for in the conceptual design. Respondents were asked to provide the level of agreement they associated with each question, between: strongly agree, agree, average, disagree and strongly disagree. A no comment or do not know check box, was also provided, as was a text box for receiving personalised comments.

7.2.1. Feedback from Royal Mail

Recommendation for improving the conceptual design and proposed design alterations, categorised into 14 CBM GUI design considerations, are presented and discussed below.

7.2.1.1. Suggestion for improving web site navigation

In addition to drop down selectable navigation menus, right click mouse activated command functions will increase navigational capabilities. For example, a user selects a mail centre, right clicks the mouse and is presented with additional selectable options, e.g., CBM Report or Alarm Settings.

Recommendations: Deciding what menu options to include is critical to this proposal. Incorporating a selection of menu options already included in the navigation menu bar is a good start, e.g., Machine condition overview, Module condition overview, Maintenance list, Module report, Performance report, Alarm settings, Alarm log, and Filter settings. Example programming code suitable for creating right click mouse-activated menus is freely available on the Internet, at web sites such as www.dynamicdrive.com. An example right click mouse activated menu is shown opposite.

7.2.1.2. Suggestion for improving system security

Host the nationwide CBM web site on Royal Mail's own Intranet as apposed to the Internet, in order to improve computer security.

Recommendations: Hosting the conceptual design on a company Intranet will not require any additional graphical design alterations, and would place the web site under Royal Mail's own internal security umbrella.

7.2.1.3. Suggestions for improving machinery image representations

1.) The images portraying and representing Integrated Mail Sorting Machines (IMPs) and Letter Sorting Machines (LSM), shown in Figure 6.7, could be further improved in appearance.

Recommendations: More suitable images that more accurately represent IMP machines and LSMs must be obtained from Royal Mail. Each image must then be converted into a format designed to represent machine and module condition, through colour coding, as is the present case.

2.) Names and recognised abbreviations should be used to differentiate the constituent modules, comprising sorting machinery, rather than module numbers as illustrated in Figure 6.7.

Recommendations: Correct and familiar abbreviations for each modular unit comprising both IMP machines and LSMs, should be sort from Royal Mail. Existing numbered module numbers, can then be replaced with identified modular names or abbreviations.

7.2.1.4. Suggestion for improving web page space utilisation

1.) Redesign the date selection calendars, shown in Figure A.5.3, Figure A.5.5, Figure A.5.6, Appendix A.5, so that they consume less screen space or minimise when not being used.

Recommendations: Replace the existing calendars with calendars that are displayed in a minimised form, and only maximise when the mouse cursor is rolled over them. The diagrams below illustrate this proposal.

Minimised calendar

Maximised Calendar

7.2.1.5. Suggestion for improving machinery/component condition interpretability

1.) Redesign the conceptual design so that users can drill down from the mail centre machine performance overview screen, shown in Figure A.5.1, down to individual machine module components. If maintenance personnel are to be expected to perform accurate machinery fault diagnosis, they need to be able to access component condition information.

Recommendations: Drilling down to component level can be achieved through image hyperlinks. For example, at the machine level each identifiable module comprising the machine may be selected with a left click of the mouse. Selecting a module as shown in Figure 7.1, opens a web page containing a diagrammatical representation of all the components within a selected module, as shown in Figure 7.2. Each component within a module can itself be selected, causing a further web page to open, shown in Figure 7.3. The set of images below demonstrate this drill down process.

1. User selects Module 1, in order to investigate why its condition is showing red.

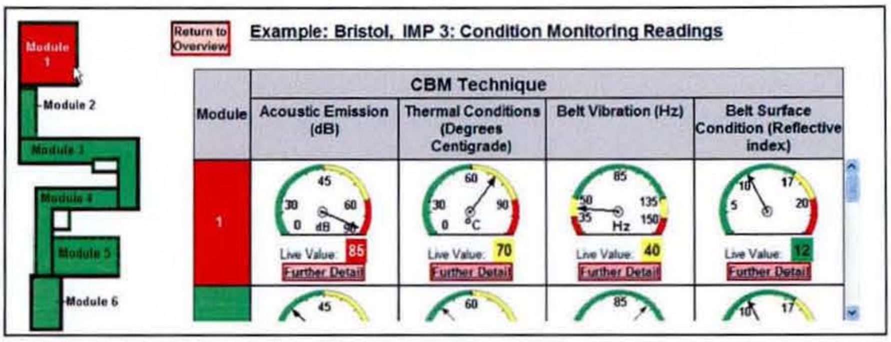


Figure 7.1. Machine module condition overview.

2. User selects bearing 12 because its red condition indicates maintenance is urgently required.

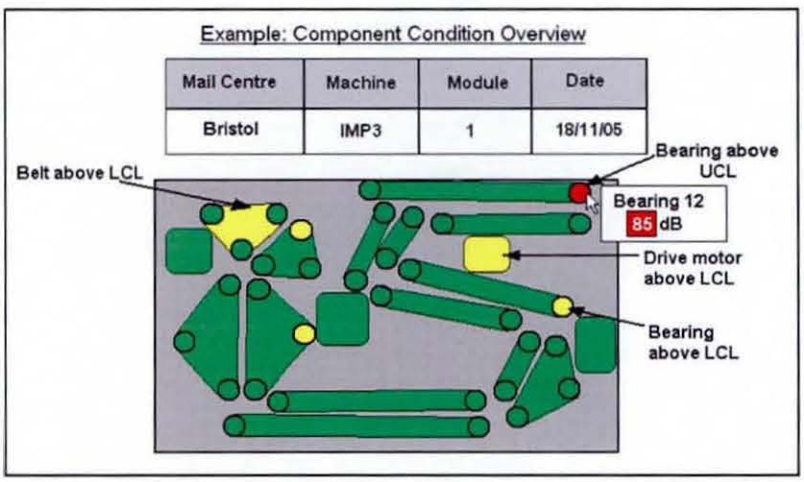


Figure 7.2. Module components condition overview.

3. User examines sensory condition data for bearing 12, in order to assess the components deteriorating condition, and decide how urgently maintenance is required, and of what sort.

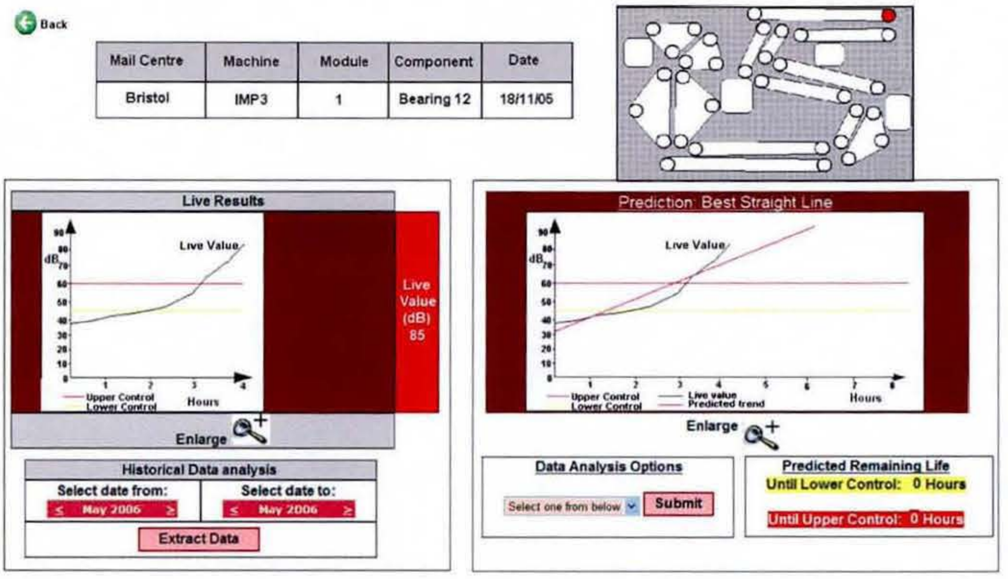


Figure 7.3. Component condition data analysis.

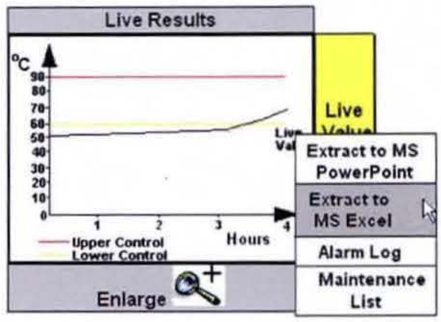
2.) Design the conceptual design to only record component conditions whilst sorting machines are processing mail.

Recommendations: Two alternatives are available as possible solutions, neither of which requires a graphical design alteration. Firstly, the sensors extracting component condition data could be controlled to only extract data when sorting machinery is in operation. Secondly, sensory data could only be recorded to database if sorting machinery is in operation.

7.2.1.6. Suggestion for adding a data extraction design feature

Incorporate the capability within the conceptual design, to allow historic and predicted machinery condition graphical and tabular information, to be extracted and converted into MS Power Point and MS Excel. In these formats, Managers familiar with MS Excel and MS PowerPoint will feel confident at converting the extracted information, into displayable performance league tables and used for management presentations.

Recommendations: A selectable hyperlink located to the left of all enlarged graphs, titled 'transfer data to MS Excel', shown in Figure A.5.4, has the design intension of enabling users to transfer the data comprising the graph in question, into an MS Excel compatible format. In addition and as an alternative design solution, a right click mouse activated menu containing the command functions, 'Extract to MS Excel', and 'Extract to PowerPoint', could be provided, shown in the diagram opposite. Right clicking any graph generated within the web site using the mouse, would generate a menu with the above-mentioned selectable command functions.



7.2.1.7. Suggestion for adding a data export design feature

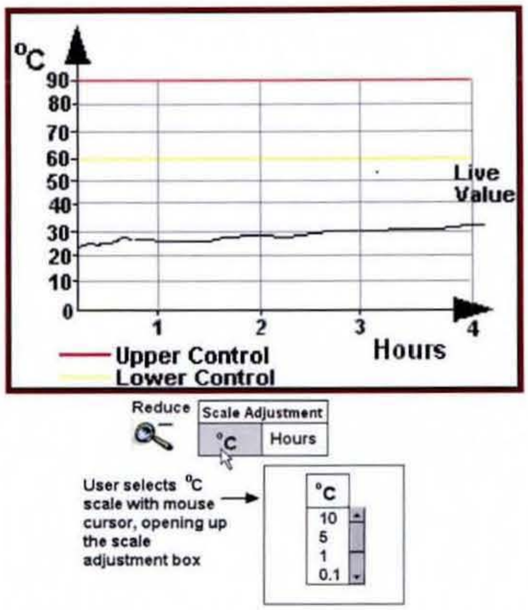
Provide the capability to export CM data from the CBM servers, into a format for analysis and comparison against information from the ADC or NEIDs computer applications.

Recommendations: Initially it is necessary to understand what benefits will be gained from comparing ADC and NEIDs machinery performance data, against CBM system data. If there are benefits, it is necessary to identify the most suitable data format these can be realised in. For example, data comparisons can be made at a database to database level, via data transfer using open database connectivity (ODBC); or by converting CBM data into MS Excel format; or by generating CBM reports for the required period, printing them off, and comparing these against data from ADC and NEIDs systems. Answers to these considerations must be investigated further, before deciding upon an appropriate data export design capability.

7.2.1.8. Suggestion for improving graphical displays

Incorporate customisation features for all machinery condition graphs, enabling users to manually adjust the x and y axis scales.

Recommendations: Provide two selectable scale adjustment controls for altering the x-axis and y-axis scales, below or to the right hand side of each graph, as shown in the diagram opposite. Each scale adjustment control will be represented as a selectable button, identifiable with the units of the scale in question. Clicking either button with the mouse opens up a smaller window on the web page, containing a scrollable scale adjustment selector. Scale selection is made once a user moves the mouse cursor over a chosen incremental scale value and clicks the left mouse button.



7.2.1.9. Suggestions for improving CBM reports

1. When generating CBM comparison reports, ensure the comparison considers the amount of time each machine has been utilised, for the operational period being compared against.

Recommendations: A simple solution is to add an additional column into the machinery comparison performance report table, that will to be populated with total machinery operational time values. Figure 7.4 below demonstrates this proposal.

Mail Centre	Lower Control Limits	Upper Control Limits	Total Operational Time (hrs:mins)	% Time inside Control Limits	% Time inside Lower Control Limits	% Time inside Upper Control Limits
Bristol	60 °C	90 °C	60:00	95 %	3 %	2 %
Beaston	60 °C	90 °C	45:00	87 %	6 %	7 %
Cardiff	60 °C	80 °C	56:34	85 %	10 %	5 %
Glasgow	70 °C	90 °C	37:00	95 %	3 %	2 %
HWDC	60 °C	90 °C	74:35	90 %	7 %	3 %
Leeds	80 °C	90 °C	43:00	97 %	1 %	2 %
Leicester	60 °C	100 °C	55:00	85 %	14 %	1 %
Manchester	60 °C	90 °C	84:30	92 %	5 %	3 %
Peterborough	60 °C	110 °C	65:25	94 %	6 %	0 %
Sheffield	65 °C	90 °C	54:55	95 %	3 %	2 %

Figure 7.4. Performance comparison table.

2.) Provide a CBM report generation feature, which identifies and displays all those components on a machine requiring maintenance, in rank order of maintenance priority. It would also be useful if the report generated a list of suggested maintenance actions as remedies to the anticipated cause.

Recommendations: Add an additional selectable menu below the drop down menu, 'CBM Reports', titled 'Maintenance List', as shown opposite. Selecting 'Maintenance List' opens a web page designed to allow users to select a desired mail centre, or specific machine, a maintenance list will be generated for. Figure 7.5 illustrates the appearance of the maintenance list selector.

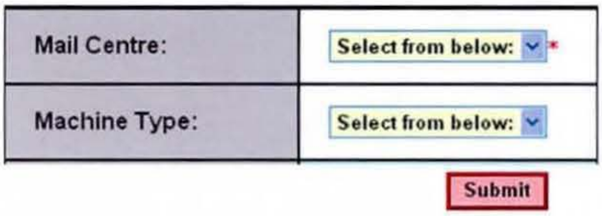


Figure 7.5. Maintenance list selector.

Once a user has made a selection from the drop down lists, shown in Figure 7.5, they click the submit button. Clicking the submit button instructs the webserver to open and construct a web page showing all the recommended maintenance work, for the users selection. Recommended maintenance actions will be populated into a table, as demonstrated in Figure 7.6.

Mail Centre	Bristol

Machine	Module	Component	CBM Technique	Live Result	Maintenance Priority	Recommended Maintenance Action
IMP 1	2	Bearing 4	Acoustic Emission	85 dB	Urgent	Replace pulley
IMP 1	4	Belt 3	Belt Vibration	148 Hz	Medium	Tighten belt
IMP 4	3	Belt 11	Surface Condition	18 RI	Medium	Replace belt
LSM 2	1	Drive Motor 4	Thermal	70 °C	Medium	Spot check + service
LSM 3	5	Bearing 14	Acoustic Emission	55 dB	Medium	Replace pully

Figure 7.6. Maintenance list for Bristol mail centre.

3.) Provide a CBM report that acts as a mail centre comparison league table. The report should present a list of best performing to poorest performing mail centres. In this case performance could be based upon the percentage amount of time machines linked to CM equipment, remained inside operational condition control limits. The report should be aimed and possibly restricted to maintenance management level.

Recommendations: Add an additional selectable menu button to the drop down menu 'CBM Reports', titled 'Performance Table', as illustrated to the right. Selecting 'Performance Table', with a left click of the mouse, opens a new web page containing a set of selectable options, for specifying the contents of the performance table. Figure 7.7 below illustrates the appearance of the performance table selector.

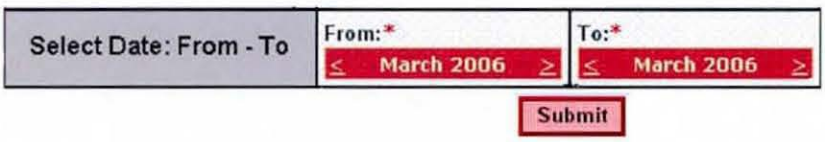


Figure 7.7. Performance table selector.

Users choose the date period they wish a performance table to be generated for and click the submit button. This action causes a new web page to be opened containing a performance table, illustrated in Figure 7.8. The best performing mail centre is positioned at the top of the table, and lesser performing mail centres, positioned in rank order below. Performance is based upon the percentage amount of time all machines at a particular mail centre, have remained inside control limits.

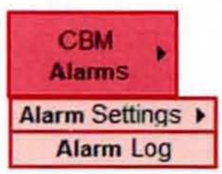
Date	
From	To
14/11/05	18/11/05

Mail Centre	% Time inside control limits	Total Operational Time (hrs:mins)
Bristol	95%	220:13
Beaston	94%	310:09
Cardiff	92%	150:45
Glasgow	92%	260:15
etc	etc	etc
Manchester	70%	300:14

Figure 7.8. Maintenance performance table.

7.2.1.10. Suggestion for providing access to all recorded alarms

Provide access to an alarm log within the conceptual design. The alarm log should identify every occasion an alarm has been activated due to CM control limits being exceeded. Logged details should include: the date and time an alarm was activated, the condition or cause resulting in the alarm, the date and time the alarm was attended to, and links to maintenance actions undertaken to resolve the alarm causing condition.



Recommendations: Alter the title 'Alarm Settings', to 'CBM Alarms', on the navigation bar. Add an additional menu to the drop down menu, titled 'Alarm Log', as shown opposite. Selecting the 'Alarm Log' button opens a web page containing a table with selectable options, for choosing a users desired maintenance log. Figure 7.9 shows an image of the intended table.

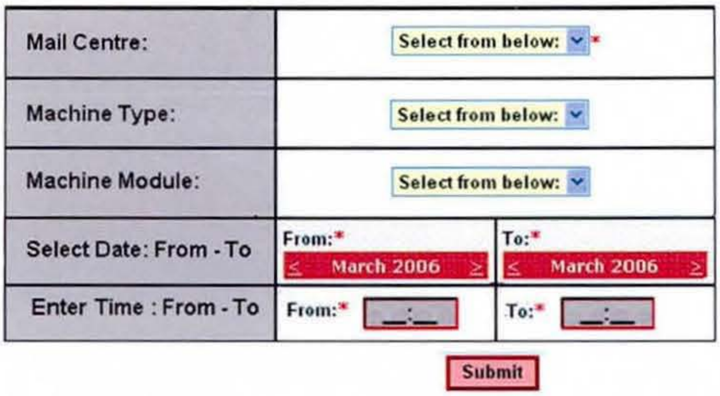


Figure 7.9. Alarm log selector.

Once a user has made their selection and clicked the submit button, refer to Figure 7.9, a further web page will be opened containing the users requested alarm log. The alarm log should provide all the information illustrated in Figure 7.10.

Mail Centre	Date		Time	
	From	To	From	To
Bristol	05/06/05	06/06/05	00:00	23.59

Machine	Module	Component	Alarm Cause	Alarm Activated		Alarm Deactivated		Maintenance Completed
				Date	Time	Date	Time	
IMP 1	2	Bearing 4	dB > UCL	05/06/05	05:30	05/06/05	05:45	SAP SDMM
IMP 1	4	Belt 3	Hz > UCL	05/06/05	12:30	05/06/05	12:35	SAP SDMM
IMP 4	3	Belt 11	Hz > UCL	06/06/05	06:25	06/06/05	06:30	SAP SDMM
LSM 2	1	Drive Motor 4	°C > UCL	06/06/05	08:35	06/06/05	09:10	SAP SDMM
LSM 3	5	Bearing 14	dB > UCL	06/06/05	16:53	06/06/05	17:10	SAP SDMM

Figure 7.10. Alarm log for Bristol mail centre.

7.2.1.11. Suggestion for communicating maintenance work completed

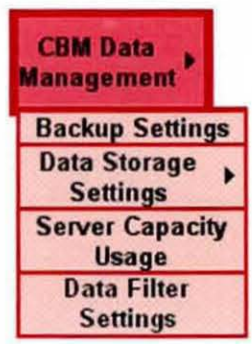
Incorporate a feature within the conceptual design to enable users to identify maintenance work undertaken during machine stoppage times. Such a feature will prove useful in understanding why step machinery condition changes shown graphically occur, e.g., refer to Figure A.5.7, Appendix A.5.

Recommendations: Incorporating a link that opens the SAP log in page from within the CBM web site, as presently provided, is still considered the best approach. The CBM system under investigation is not intended to replace the computer maintenance management system, but rather compliment it. Reviewing details of maintenance work that has led to a visible graphical change in a machines/components condition, is therefore best undertaken using the SAP system.

7.2.1.12. Suggestions for adding universal alarm and data filter control adjustment features

1.) Incorporate the feature within the conceptual design to alter CM sensory data, data filtering options, for all mail centres and on a mail centre by mail centre basis. Providing this design feature will reduce the time consuming nature of altering data archiving and filtering settings for each and every CM sensor.

Recommendations: Add an additional selectable menu button onto the drop down menu 'CBM Data Management', titled, 'Data Filter Settings', as illustrated to the right. Selecting the 'Data Filter Settings' button, opens a web page containing a table of selectable options, enabling users to specify the level they wish to apply data filter settings. Figure 7.11 shows an image of the table containing the choices of levels available for selection.



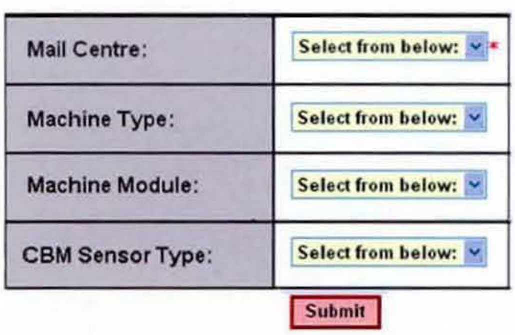


Figure 7.11. Selector for choosing the level data filtering will be applied.

The first selectable option contained in Figure 7.11, mail centre, is mandatory for selection; all other selectable choices are optional. Users can set universal data filter parameters for all sorting machinery within an entire mail centre, or for a specific machine within a mail centre, down to filter parameters for individual sensors. Having selected the level data filtering parameters will be set at, users click the submit button, and are presented with a web page designed for specifying CM data filter settings. The design for this web page has not changed from that shown in Figure A.5.12, Appendix A.5.

2.) Incorporate the design feature for altering alarm control limits for each CM sensor, globally for all mail centres and on a mail centre by mail centre basis. Providing this design feature will reduce the time consuming nature of setting up alarm control limits for each and every CM sensor.

Alter the design functionality of the present CM alarm selector table, described in section 6.5.6 and shown in Figure A.5.14, so that the only mandatory selectable option is mail centre. Making all other selectable options optional, enables users to alter or set alarm control limits universally, for an entire mail centre, or specifically down to individual CM sensors. For example, if a user wished to alter the alarm settings for all acoustic emission CM sensors at Bristol mail centre, they would select Bristol as their desired mail centre and Acoustic Emission as the CM technique, and then click the submit button as illustrated in Figure 7.12.

Figure 7.12. Example of an alarm control limit selection table.

Clicking the submit button opens a web page with the same design structure as that shown in Figure A.5.15, Appendix A.5, described in section 6.5.6.

7.2.1.13. Suggestions for improving language legibility

1.) Alter the wording 'Total down time', in the CBM report example, shown in Figure A.5.7, Appendix A.5, to 'Time Machine Stopped'.

The figure opposite illustrates the altered design proposal.

Status	Time (hrs: mins)
Total Operating Time:	18:47
Time Machine Stopped :	05:13

7.2.1.14. Further questions and design concerns

1.) How secure is the web site, do the security measures prevent unauthorised access?

Discussion: *Design measures to prevent unauthorised access to the web site include: hosting the web site on a fire wall protected Intranet as discussed in section 7.2.1.2, and incorporating Log In, user name and password access controls.*

2.) Does the conceptual design provide any method of notifying how long a maintenance task will take to perform?

Discussion: *No, this information, if available, will remain exclusive to the SAP SDMM system, described in section 5.4. Anticipating how long maintenance tasks/jobs will take is a best guess rather than an accurate prediction. Differences in Maintenance Engineer skill and experience levels, unforeseen maintenance tasks, and other unforeseen problems, complicate the process of predicting how long an anticipated component failure will take to repair.*

3.) Does the conceptual design consider and take account of different wear and abrasive qualities associated with different mail items, and the affect they have on predicted remaining useful equipment/machinery life?

Discussion: *No. Prediction calculations are presently based upon previous historical condition trends rather than anticipated future workloads.*

4.) Will it be possible to delete CM sensory data stored on database?

Discussion: *No. This feature is not incorporated. Such a feature could easily be added, but would have to be restricted to a very few authorised individuals. The design allows sensory data to be filtered at weekly, monthly and yearly intervals, a controlled form of data removal.*

5.) Including multiple CM data analysis capabilities into the CBM GUI may not be necessary. Maintenance Engineers should not be drawn into time-consuming data analysis situations while examining machinery condition. It is questionable whether components requiring routine regular maintenance on a daily or weekly basis should be monitored using CM equipment in the first place.

Discussion: *Section 7.2.1.9 suggests several CBM Report design improvements that assist maintenance decision-making, without the need for further data analysis.*

6.) Consider providing an automatic capability for setting upper and lower control limits for CM sensors, based upon the standard deviation of historical data.

Discussion: *This is a useful design idea, which theoretically can be incorporated into the conceptual design. Further investigation and thought are required in order to determine its feasibility. Suggested graphic design alterations include the addition of a toggle switch, designed to enable users to switch between, automatically specified or manual entry alarm control limits. Such a switch could be incorporated into the alarm control limits settings web page, shown in* Figure A.5.15.

7.) Issuing CBM reports automatically, every time machinery components rise above control limits, might prove impractical. This will especially be the case if up to ten separate emails are generated each day, because they might not all be opened. A more practical solution might be to group together automatically generated emails, and issue them as a prioritised list of maintenance actions at the start of each day or shift.

Discussion: *This design concern requires further thought and design alterations to the method by which automatically generated CBM reports, activated if CBM control limits are breached, will be issued. Providing access to a prioritised maintenance list, suggested as a design improvement in section 7.2.1.9, may replace the need for receiving alarm email notification following control limit breaches*

8.) Automatically control the contents of CBM reports according to the intended recipient. For example, Maintenance Managers and Regional Managers need only receive notification via email or text message, concerning the number of CBM alarm conditions detected within a mail centre per day. Additional detail would not be required for this user type.

Discussion: *This design concern requires further thought and investigation into the method by which, CBM reports and automatically generated alarm messages, are requested and issued. A method of differentiating between different user types and the contents of CBM reports, or automatic alarm notification messages, should be added to the conceptual design. For example, providing users with the ability to specify the type of CBM report* *they wish to receive from a selectable list, e.g., Management Report, Analyst Report, Maintenance Engineers Report, etc. In this case it might be necessary to prevent maintenance engineers from requesting a management report, but fine for a manager to request a maintenance engineers report*

9.) You have incorporated IMPs and LSMs in your conceptual design, but have not included Flat Sorting Machines.

Discussion: *Flat sorting machines were not considered or discussed at the commencement of this research. Adjusting the conceptual design to cater for flat sorting machines is not anticipated to require considerable design modifications.*

10.) Ideally, the CBM system should integrate with all other computerised maintenance software systems. The ideal system should monitor machinery condition, predict remaining useful component operational life, trigger maintenance schedules in advance, notify maintenance engineers what and when maintenance is required, prioritise maintenance work according to its level of urgency, provide component performance statistics aimed at identifying problematic machinery components, and aid and assist maintenance management maintenance improvement initiatives.

Discussion: *This statement acts as a benchmark on which all generic CBM software applications should ultimately aim at achieving.*

11.) What will prevent people from stopping using your CBM system and avoiding it becoming a white elephant?

Discussion: *This concern is applicable to all products, systems and procedures, rules and regulations. Following proven and accepted practices and principles in the following disciplines is recommended:*

- *Design and development.*
- *Testing.*
- *Implementation and championing.*
- *Maintenance.*
- *System and financial appraisal.*

7.2.2. Feedback from other maintenance professionals

Twenty-seven individuals provided feedback on the conceptual design, twenty-one via the feedback form, shown in Appendix A.6, and a further six in the form of email comments.

None of the returned feedback forms, on a percentage majority vote basis, resulted in a strongly agree reply, to any question. This suggests room for improvement in every aspect of the conceptual design is possible. Fifteen questioned design issues received a percentage majority agree vote, and a further seven received a 50:50 level of agreement. Table 7.1 presents the results in percentage voted majority hierarchical rank order, highest to lowest. Additional comments to each question have been provided solely by two individuals, a Mr T. Scott from Diagnostic Solutions Ltd. and a Mr E. Coetzer from BP Angola. Further comments concerning the design of the conceptual design as a whole, were provided by 18 individuals, presented in Table A.6.3, Appendix A.6.

Question	Level of Agreement (% of respondents)					
	Strongly disagree	**Disagree**	**An average amount**	**Agree**	**Strongly Agree**	**No Comment or Do Not Know**
The language used in the web site is fit for purpose and legible.	0.00	9.52	4.76	**61.09**	19.05	4.76
Data analysis features incorporated in the web site are essential for a CBM GUI.	0.00	14.29	19.05	**52.38**	4.76	9.52
The data archive and backup features incorporated in the web site are essential.	4.76	4.76	14.29	**47.62**	23.81	4.76
The web site demonstrates suitable use of password and user name authentication.	0.00	0.00	9.52	**47.62**	23.81	19.05
The web site makes good use of graphs and tables to represent machinery/component condition.	4.76	14.29	23.81	**47.62**	9.52	0.00
The navigation technique incorporated in the CBM web site is easy to follow and efficient.	0.00	0.00	33.33	**47.62**	9.52	9.52
The web site communicates machinery condition deviations from acceptable values to users clearly and rapidly.	9.52	14.29	19.05	**47.62**	4.76	4.76
The images and graphics used to represent and communicate a machines condition are acceptable.	0.00	9.52	38.10	**42.86**	9.52	0.00
The web site appears to follow acceptable Graphic User Interface design rules.	0.00	0.00	33.33	**42.86**	4.76	19.05
The web site demonstrates clearly the use of colour coding to reflect machinery condition.	0.00	0.00	28.57	**38.10**	33.33	0.00
Providing access to data from multiple CM techniques through one GUI, as demonstrated in this web site is a good design solution.	4.76	4.76	23.81	**38.10**	28.57	0.00
The web site demonstrates good use of text fonts and text size.	0.00	9.52	33.33	**38.10**	14.29	4.76
The web site makes adequate use of graphic icons.	4.76	14.29	28.57	**38.10**	9.52	4.76

Table 7.1 Results from conceptual design feedback form continued on next page.

Question	Level of Agreement (% of respondents)					
	Strongly disagree	Disagree	An average amount	Agree	Strongly Agree	No Comment or Do Not Know
The capability to make machinery condition predictions demonstrated in the web site are appropriate and adequate.	4.76	9.52	**38.10**	**38.10**	4.76	4.76
The web site appears to be user friendly, logical and easy to operate.	4.76	14.29	28.57	**33.33**	14.29	4.76
The 'CBM Report' examples contained in the web site are easy to interpret.	4.76	9.52	**42.86**	28.57	14.29	0.00
The web site is visually appealing making it desirable for use as a CBM GUI.	4.76	9.52	**38.10**	23.81	23.81	0.00
Information contained in the conceptual design is easy to interpret.	4.76	9.52	**38.10**	28.57	19.05	0.00
The design ideas incorporated in this CBM GUI web site could be easily tailored to meet other customer requirements.	4.76	0.00	**38.10**	28.57	14.29	14.29
The capability to integrate with other computer systems demonstrated in this web site is a useful design feature.	0.00	4.76	**33.33**	23.81	23.81	14.29
It would be useful if the web site incorporated manual controls to enable users to manually alter the web sites appearance and feel, to suite a users personal requirements.	9.52	23.81	**33.33**	23.81	9.52	0.00
The web site displays machinery condition information clearly with sufficient structure.	14.29	19.05	**28.57**	23.81	14.29	0.00

Table 7.1. Results from conceptual design feedback form.

7.2.2.1. Communicating machine condition and information interpretability

1.) The language used in the web site is fit for purpose and legible.

A majority of 61.09% percentage of replies agree and a further 19.05% strongly agree. No additional comments concerning this question were received. The result suggests language contained in the conceptual design, is the closest out of all the design items questioned, to satisfying design requirements expected within a generic CBM GUI solution.

Earlier in section 4.4.3.6, it was found that using legible language in the design of a generic CBM GUI is considered to be of high importance.

2.) The images and graphics used to represent and communicate a machines condition are acceptable.

A percentage majority of 42.86% of replies agree and a further 38.10% have a 50:50 level of agreement to this question. A positive reply, supporting the implication of the question. One additional comment was received from Mr E. Coetzer, who stated: "I am concerned about the prediction algorithms".

The comment is ambiguous and does not appear to relate to the question. It might however be interpreted to mean; the conceptual design does not demonstrate how the various data analysis options provided, will communicate machinery condition to users.

3.) The web site makes good use of graphs and tables to represent machinery/component condition.

A percentage majority of 47.62% of replies agree and a further 23.81% have a 50:50 level of agreement towards this question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott, who stated: "Reasonable but the layout could be improved".

Although ambiguous this might suggest, positioning of tables and graphs on individual screens should be reassessed, from a visual clarity perspective and from an ease of decision-making perspective.

Earlier in section 4.4.3.6, it was shown that using tables to structure information incorporated in a generic CBM GUI is of high importance.

4.) The web site communicates machinery condition deviations from acceptable values to users clearly and rapidly.

A majority of 47.62% of replies agree and a further 19.05% have a 50:50 level of agreement towards this question. A positive result, supporting the implications of the question. One additional comment was received from Mr T Scott, who stated: "Peer to Peer comparison is great for contrast visualisation".

The comment implies providing a method of comparing acceptable operating machinery condition signatures/data, with live machinery conditions at the same time. This could be achieved through a GUI by superimposing both sets of data onto a graph at the same time. Figure 3.2, section 3.3.7.1, shows an example of two superimposed graphs.

Earlier in section 4.4.3.8, it was shown that correct interpretability leading to accurate maintenance decisions does improve the saleability and success of CBM software.

5.) The web site displays machinery condition information clearly with sufficient structure.

A small majority of 28.57% of replies place a 50:50 level of agreement and a further 23.81% agree with this question. 33.33% of responses disagreed with the question. An overall average response towards the implications of the question. Two additional responses were received. Mr T. Scott commented: "No this could be much better".

Mr E. Coetzer commented: "From a Condition Monitoring practitioners point of view the information is not very useful at all. I first published a CBM implication model at COMADEM 91 and have since refined it considerably".

Both comments are very negative, suggesting considerable room for improving the conceptual designs ability at communicating machinery condition information to users. Design improvement suggestions discussed in section 7.2.1.3, 7.2.1.5, and 7.2.1.9 are each targeted at improving the communication of machinery condition to users.

Earlier in section 4.4.3.6, it was shown that screen structure and information classification are considered to have a high level of importance, whilst designing a generic CBM GUI.

6.) The web site demonstrates clearly the use of colour coding to reflect machinery condition.

A percentage majority of 38.10% of replies agree and a further 33.33% strongly agree with this question. A positive result, supporting the implications of the question. No additional comments were received.

Earlier in section 4.4.3.6, it was shown that the level of importance associated with the use of colour coding to reflect machinery condition, when designing a generic CBM GUI, is high.

7.) The capability to make machinery condition predictions demonstrated in the web site are appropriate and adequate.

A joint majority of 38.10% of replies place a 50:50 level of agreement and agree with this question. A positive result, supporting the implications of the question. One further comment was received from Mr T. Scott who stated: "They don't seem to work and the data basis is unknown".

Further examples other than the best straight-line prediction demonstrated in Figure A.5.3, Appendix A.5, would prove useful in order to communicate the conceptual designs intensions. Section 6.5.3.3 described the intended design functionality of the data analysis features, incorporated within the conceptual design.

8.) The 'CBM Report' examples contained in the web site are easy to interpret.

A percentage majority of 42.86 % of replies place a 50:50 level of agreement and a further 28.57% agree with the question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott who stated: "There is more data than information and metrics".

The comment suggests too much numerical and graphical data is included in the CBM reports, and not enough clear informative explanations. Explanations that clearly state failure cause/s and suggest maintenance remedies. Figure 7.6 and Figure 7.10 illustrate alternative design ideas, which communicate machine condition, maintenance requirements and maintenance priority.

Earlier in section 4.4.3.6, it was shown that a high level of importance is associated with designing CBM reports to be interpretable.

9.) Information contained in the conceptual design is easy to interpret.

A percentage majority of 38.10% of replies place a 50: 50 level of agreement and a further 23.57% agree with this question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott who stated: "There is more data than information".

Mr T. Scott made a similar comment in the above question.

Earlier in section 4.4.3.6, it was shown that a CBM software application's saleability is strongly influenced, if accurate maintenance decisions can be achieved through correct interpretability of information.

10.) Additional Comments

Design improvements suggested in Table A.6.3, Appendix A.6, relevant to communicating machine condition and information interpretability include:

i.) Provide CBM reports and or automatically issued alarm messages that clearly state: component failures, suggested reasons for failure, and the urgency of the maintenance actions.

ii.) Incorporate an ability to compare component condition against acceptable condition using a peer-to-peer comparison indicator.

iii.) Use more vivid colours in graphs because yellow lines against a white background are difficult to see. Either change the background colours or line colours or incorporate hashed regions for the control limits. Use bigger bolder lines.

iv.) Increase the size of graphs.

v.) There appears to be too much information especially for management decision-making. Management require information, not data.

vi.) Clearly label all graphs with date markings and line marking references. Avoid showing graphs with lines starting and ending in the middle of the charts.

7.2.2.2. Data management

1.) The data archive and backup features incorporated in the web site are essential.

A majority of 47.62% of replies agree and a further 23.81% of replies strongly agree, to the design question. A positive result supporting the data archiving and backup design features incorporated within the conceptual design. Two additional comments were received. Mr T. Scott stated, "You could provide an event tagging and intelligent seed rage feature"
Mr E. Coetzer stated: "This feature should be automated".

The present data archiving and backup capabilities are designed to function automatically. Once users have manually set-up archiving and backup parameters, the system performs the task according to these parameters automatically. Section 6.5.5 describes the intended functionality of the CBM data management design features.

Earlier in section 4.4.3.6, it was shown that providing a design feature for selecting and setting data archiving capabilities in a generic CBM GUI is of high importance.

2.) Additional Comments

Design improvements suggested in Table A.6.3, Appendix A.6, relevant to improving data management design features incorporated in the conceptual design include:

i.) Incorporate some form of intelligent agent to support the CBM decision process.

7.2.2.3. Issues concerning data analysis

1.) Data analysis features incorporated in the web site are essential for a CBM GUI.

A majority of 52.38% of replies agree and a further 19.05% place a 50:50 level of agreement on this design issue. One additional comment was received from Mr E. Coetzer. He stated: "There is a need for more choice, e.g., waterfall plots etc."

This comment suggests Mr. E. Coetzer would like to see more methods for data analysis incorporated in the conceptual design. Presently six data analysis methods are provided, shown in Figure 6.11. Waterfall data plots are not one of these methods. Section 3.3.6.1 discussed the process of selecting suitable and appropriate data analysis techniques for inclusion in a CBM GUI.

Earlier in section 4.4.3.6, it was shown that providing a selection of data analysis techniques in a generic CBM GUI is very important.

7.2.2.4. Web site security

1.) The web site demonstrates suitable use of password and user name authentication.

A percentage majority of 47.62% of replies agree and a further 23.81% strongly agree. A positive result, supporting the implications of the question. No additional comments were provided.

Earlier in section 4.4.3.6, it was shown that incorporating password and user name authentication features into the design of a generic CBM GUI is very important.

7.2.2.5. Web site navigation

1.) The navigation technique incorporated in the CBM web site is easy to follow and efficient.

A percentage majority of 47.62% of replies agree and a further 33.33% have a 50:50 level of agreement towards this question. A positive result supporting the implications of the question, especially since no individuals disagreed. No additional comments were received.

Earlier in section 4.4.3.6, it was shown that navigation techniques employed within generic CBM GUIs should be considered to have a high level of importance.

2.) Additional Comments

Design improvements suggested in Table A.6.3, Appendix A.6, relevant to improving GUI navigation capabilities include:

i.) Provide a method of immediately zooming in on component condition data, if an alarm message identifies a specific component as exceeding control limits.

7.2.2.6. Meeting GUI design standards

1.) The web site appears to follow acceptable Graphic User Interface design rules.

A percentage majority of 42.86% of replies agree, and a further 33.33% have a 50:50 level of agreement to this question. A notable 19.05% did not know or had no comment. A positive result, supporting the implications of the question. One additional comment was received from Mr E. Coetzer, who stated: "Ask Human Factors experts this question".

The comment follows in tune with the 19.05% of respondents who do not know or have no comment towards the implications of the question.

Earlier in section 4.4.3.7, it was shown that the level of influence GUI design rules are considered to have whilst designing a CBM GUI is an average amount.

2.) The web site demonstrates good use of text fonts and text size.

A percentage majority of 38.10% of replies agree and a further 33.33% of replies place a 50:50 level of agreement on this question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott, who stated: "They appear to be a bit large and in your face".

Web pages comprising the conceptual design are intentionally bold and striking, with the deliberate intension of projecting information directly into the viewers site. Large and in your face GUIs are ideal for quick interpretation and quick decision-making. Ideal for the hands on maintenance engineer. GUIs designed with smaller text and greater quantities of information, are better suited to drawn out decision-making, where larger quantities of information will be interpreted before a decision is taken. Ideal for the methodical analyst or manager. Since most CBM systems will be used by a selection of different user groups, there exists a requirement for both large and in your face GUIs, as well as more detailed GUIs containing greater quantities of information.

Earlier in section 4.4.3.6, it was shown that the level of importance concerning text size and font type, when designing a generic CBM GUI is an average amount.

3.) <u>The web site makes adequate use of graphic icons.</u>

A percentage majority of 38.10% of replies agree and a further 28.57% place a 50:50 level of agreement on the question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott who stated: "Hardly at all, could be so much more".

Very few icons are incorporated in the conceptual design, because descriptive wording was conceived to convey the intended interpretation more clearly than available and recognised icons, in the majority of cases. This may prove acceptable for satisfying Royal Mail's user requirements, but can be expected to be unacceptable for a generic CBM GUI solution.

Earlier in section 4.4.3.6, it was shown that an average amount of importance is associated with incorporating icons and icon designs, during the design of a generic CBM GUI.

7.2.2.7. System Integration

1.) <u>Providing access to data from multiple CM techniques through one GUI, as demonstrated in this web site is a good design solution.</u>

A percentage majority of 38.10% of replies agree and a further 28.57% strongly agree with this question. A positive result, supporting the implications of the question. One additional comment was received from Mr E. Coetzer, who stated: "You need to be able to see different techniques and views on one page".

The machine modules condition overview web page shown in Figure A.5.2, Appendix A.5, does show machinery condition for several different CM techniques on one screen. An improvement to the conceptual design will be to present information from multiple different CM techniques graphically, on one screen, as demonstrated in Figure 3.1 and Figure 4.3.

2.) The capability to integrate with other computer systems demonstrated in this web site is a useful design feature.

A percentage majority of 33.33% of replies place a 50:50 level of agreement and a further 23.81% agree with the question. 23.81% of replies also strongly agree to the question. A positive result, supporting the implications of the question. No additional comments were received.

Earlier in section 4.4.3.7, it was shown that networking and integration have quite a lot of influence on design decisions for a CBM GUI.

7.2.2.8. Transferability of design ideas

1.) The design ideas incorporated in this CBM GUI web site could be easily tailored to meet other customer requirements.

A percentage majority of 38.10% of replies place a 50:50 level of agreement and a further 28.57% agree with this question. A positive result, supporting the implications of the question. Two additional comments were received.

Mr T. Scott commented: "It is hard to know, it depends on the flexibility of the design ideas themselves".

Mr E. Coetzer commented: "There is no visibility of the business/diagnostic process".

The conceptual design is targeted at satisfying Royal Mail's user requirements. Considerable design alterations will therefore be required, if the conceptual design is to be tailored to another customer's user requirements. Design alterations such as, language, images and graphics, units of measure, and algorithms provided for a specific type of CM technique. The design structure chosen for the conceptual design, illustrated in Figure 6.1, is however anticipated to be transferable. The design structure represents a common foundation containing functional design features common to all CBM software applications, identified in section 4.3.2.3.

Earlier in section 4.4.3.7, it was shown that being able to tailor a CBM software application's GUIs, has quite a lot of influence over design decisions.

7.2.2.9. GUI appearance and design layout

1.) It would be useful if the web site incorporated manual controls to enable users to manually alter the web sites appearance and feel, to suite a users personal requirements.

A percentage majority of 33.33% of replies place a 50:50 level of agreement and an equal 23.81% of replies, disagree as well as agree with this question. A 50:50 or average response to the implications of the question. Two additional comments were received. Mr T. Scott commented: " Within limits, good front end design is essential for visualisation".

Mr E. Coetzer commented: "Adds complexity".

Neither of these comments is particularly positive or negative, which agrees with the average overall feeling towards this question.

Earlier in section 4.4.3.6, it was shown that enabling users to control and manipulate the look and feel of a CBM GUI is of high importance. Section 4.4.3.8 also suggested that incorporating this feature in a CBM GUI has an average effect on the saleability of a CBM software application.

2.) The web site appears to be user friendly, logical and easy to operate.

A percentage majority of 33.33% of replies agree and a further 28.57% of replies place a 50:50 level of agreement on this question. A positive result, supporting the implications of the question. One additional comment was received from Mr E. Coetzer who stated: "The layout is logical, but the logic does not align with the business process, therefore the design is of limited value".

Mr E. Coetzer's reference to 'aligning to the business process', is explained in a paper published by Coetzer and Bentham [1998]. The CBM business implementation plan in question appears most relevant to a localised CBM architecture. The conceptual design has been designed for an Internet CBM architecture, involving automatic data collection and processing.

3.) The web site is visually appealing making it desirable for use as a CBM GUI.

A percentage majority of 38.10% of replies place a 50:50 level of agreement and a further 23.81% agree with this question. A positive result, supporting the implications of the question. One additional comment was received from Mr T. Scott who stated: "The design could utilise login type matching, linking the GUI page construction with respect to page design and content, according to the type of user logging on".

Earlier in section 4.4.3.6, it was shown that designing a generic CBM software application, with the ability for users to manually alter the look and feel of its GUIs, has a high level of importance.

4.) Additional Comments

Design improvements suggested in Table A.6.3, Appendix A.6, relevant to GUI appearance and design layout include:

i.) It would be useful if a picture showing the physical part of the machine to which data/graphs pertain, was provided to the side of the web pages. Figure 7.3 demonstrates this suggestion, for an individual pulley on an integrated mail-sorting machine.

7.2.2.10. Help assistance, tutorials and design explanations

1.) Additional Comments

Design improvements suggested in Table A.6.3, Appendix A.6, relevant to help assistance, tutorials and explanations include:

i.) Provide access to explanations, which explain the purpose and intended operation of design features, incorporated in the conceptual design.

7.3. Discussion

Feedback from Royal Mail has focussed on altering the conceptual design, to meet their user requirements. In this respect it is more usable than the feedback provided by the maintenance community in general. Both sets of feedback indicate considerable improvements can be made to the conceptual design. Feedback provided by the maintenance community proved less descriptive and detailed, than that provided by personnel at Royal Mail. Explanations for this anomaly are due to different usability testing methods being conducted on each group. Personnel from Royal Mail received a demonstration and explanation, describing the intended purpose and functional capabilities of the conceptual design, via presentation and demonstration. Individuals providing feedback over the Internet via feedback forms received no demonstration or explanation. Instead they were asked to view the conceptual design over the Internet and make their own interpretations of its intended purpose and functionality. This one off result would suggest usability evaluations are more useful and effective when those providing feedback receive demonstrations and explanations of the design being tested. Demonstrating and explaining a design's intended purpose is more likely to result in similar interpretations of its intended use, than self-exploratory testing. A person's ability to interpret is greatly influenced by their previous personal experiences, which is why individuals with previous maintenance experience were asked to provide feedback.

Improvements to the conceptual design have been proposed in the following areas:

- Web site security.
- Web site navigation.
- Machinery image representation.
- Web page space utilisation.
- Communication and interpretability of machinery/component condition.
- Data extraction design features.
- Data export design features.
- Clarity of charts and graphs.
- Variety of CBM reports.
- Accessing alarm history information.
- Accessing maintenance work completed history.
- Universal alarm and data filtering control adjustments.
- Language legibility.
- Demonstrating predictive data analysis capabilities.
- Use of Icons.
- Design possibilities made available by user type access right control options.
- GUI help assistance.

Once the proposed design improvements have been implemented, further usability evaluations should take place, and the whole process repeated several times, until Royal Mail, the intended user, accepts the design as usable. It is not the intension of this research to continue until design acceptance, because many unfinished and unresolved issues, which will affect the final CBM GUI design solution, still remain. Issues including:

- Identifying every piece of critical machinery, CM is suited to within Royal Mail mail centres.

- Selecting suitable Condition Monitoring techniques and equipment, to monitor them with.

Other than using design feedback as a directional tool to improving the conceptual design, reassessing identified user requirements will also prove valuable. New user requirements can also be anticipated to surface as a consequence of design feedback following usability evaluations. Table A.6.2, included in Appendix A.6, identifies which user requirements are included in the conceptual design before and after suggested design improvements. From the forty-seven user requirements identified and presented in section 5.5, only twenty-one have been considered or included in the conceptual design. However, with suggested improvements, this figure rises to thirty-four. This leaves a further twelve user requirements to be considered for inclusion in the conceptual design.

Discussion in section 7.2.2.8 states that the conceptual design would require considerable design alterations, if it were to be tailored to another businesses user requirements. In order to determine which design ideas are transferable from the conceptual design to a generic CBM GUI, they are compared against proposed design and development rules identified in section 4.4.3.10, in Table A.6.1, Appendix A.6.

Design items either already included or presented as an improvement for inclusion in the conceptual design, matching a rule or guideline in Table A.6.1, Appendix A.6, would appear suitable for inclusion in a generic CBM GUI solution. Under this assumption, before suggested design improvements, 67.5%, and after proposed design improvements, 85%, of the design ideas included or to be included, in the conceptual design are transferable to a generic CBM software GUI solution. Design idea transferability is not however the same as design transferability, because although the intension of a design idea may prove transferable, the final design solution chosen may not prove so acceptable by the majority. Besides, there may be one recommended design rule or guideline but many ways of creating solutions that satisfy or meet them. This point emphasises the difficulty between identifying CBM software design rules and guidelines, and expecting to design a generic CBM software GUI solution.

7.4. Summary

Findings resulting from usability evaluations conducted on the conceptual design introduced in chapter six have been presented in this chapter. Design concerns and considered inadequacies with the conceptual design are identified, and subsequent suggestions for design improvements proposed. Two usability evaluation approaches were selected in order to obtain design feedback. The first approach consisted of group demonstrations and presentations, leading to design idea discussion and open criticism, from the receiving audience. The second approach involved voluntary design review and feedback over the Internet, without explanations. Feedback in this case was provided via an Internet survey feedback form, consisting of twenty-two design appraisal questions. Design comments and feedback proved more understandable and appropriate to Royal Mail's user requirements using the first approach.

Findings from both usability evaluation approaches indicates the conceptual design neither satisfies, all the proposed CBM software design and development rules and guidelines, identified in section 4.4.3.10, nor does it meet all the user requirements identified in section 5.5. In total, design concerns and discrepancies are identified for almost every aspect of the conceptual design. Consequential suggestions for design improvements are targeted at adding further detail to the conceptual design, and communicating information obtainable from a CBM system more effectively with respect to aiding and assisting maintenance decisions. Repeated usability evaluations following the implementation of any or all of the suggested design improvements, will lead to the emergence of an iterative-engineered design solution.

It is unlikely the final CBM software GUI solution will convert easily into a generic solution, because it has been tailored from the out set, towards meeting Royal Mail's own user requirements. Design ideas incorporated within the conceptual design, identified as proposals for CBM software design and development rules and guidelines, can however be expected to transfer to a generic CBM solution.

Results to the usability evaluation provide further material for consideration and inclusion, as proposals for design and development rules and guidelines, applicable to a CBM software's GUI. For example, the design structure for the conceptual design, illustrated in Figure 6.1, would be expected to transfer to a generic CBM software application.

Chapter 8

8. DISCUSSION

8.1. Introduction

Research presented in this thesis follows two paths of investigation.

1. Assisting Royal Mail, one of the case study industrial sponsoring organisations for this research project, develop suitable methods of Human Computer Interaction (HCI), for a future nationwide Condition Based Maintenance (CBM) system.
2. Identify rules and guidelines for designing and developing generic CBM software applications.

Research direction and findings for each chapter are discussed and contributions resulting from this research project identified.

8.1.1. Chapters 1 and 2

Literature has been reviewed in two key areas. Literature identifying what CBM represents as a maintenance approach and how it has been implemented in different organisations, and literature identifying what constitutes accepted Human Computer Interaction and methodologies to achieve it.

Early literature investigations discussed Maintenance Strategy, Predictive Maintenance and introduced Condition Based Maintenance. Explanations behind Royal Mail's interest and reasons for investing in CBM research are provided. Resistance towards the introduction of CBM at Royal Mail Plc. is anticipated, because previous experiences at using CM equipment on a small-scale basis have proven unsatisfactory.

Literature describing CBM presents an appreciation of the information a CBM system can be expected to communicate, to users through a chosen method of human computer interaction. For example, CBM systems should provide users with a true indication of a machines operating condition, notify users if a machine's condition falls or rises above acceptable operating levels, and predict when machinery should be made available for maintenance and repairs. Technologies constituting CBM systems are discussed, and their individual impact upon the accuracy of information generated from CM equipment realised. For example, sensors, artificial intelligent data noise reduction algorithms, data transmission technologies, data post processing and data analysis algorithms, all influence the accuracy of information generated from a CBM system. Continuous machinery monitoring creates large quantities of sensory data. Data storage and data management therefore represents a major concern for continuous CM on a large scale, as is being proposed at Royal Mail. Over coming this concern represents a major challenge, which requires an understanding and appreciation of database design, database mining, and data presentation. Graphic User Interfaces (GUI) are presently the most popular media for presenting CM data to users. Other than presenting data and information to users, GUIs should act as an interactive tool, providing a selection of interactive controls, for activities including:

- Manually manipulating and controlling the actions of the CM equipment.
- Manipulating and managing CBM data stored on databases.
- Altering the method and appearance by which CM information is communicated to users.
- Controlling the actions and activation triggers of alarms.
- Recognising and differentiating between different user and their preferences.
- Setting security options for accessing the CBM system.

Presenting CM information through an Internet Browser on web pages, was the preferred choice chosen and described by Kennedy et al. [2000], for their CBM system. Their paper explains how active server pages, using Visual Basic Script and Java Script, construct the contents of each web page. Kennedy and company's solution for communicating CBM information to users, is similar to the idea being proposed for Royal Mail's development CBM system. Advantages with this method of presentation include:

- Browser web pages are multi platform (operating system) independent.
- Active server pages provide the flexibility to generate interactive web page content.
- Active server pages provide an efficient method for controlling the look, feel and contents of web pages.

- Presenting information through Browsers, represents a move from a thick client to a thin client networking solution.

Presenting CM data through Browser web pages is typical of an Internet CBM design architecture. Literature discussions differentiate between localised CBM design architectures, remote CBM design architectures, and Internet CBM design architectures. Differentiating between different design architectures provides the researcher with an understanding of the advantages and disadvantages each approach brings, helping select the most desirable choice. An Internet CBM design architecture suites Royal Mail's user requirements most completely, because their requirements necessitate a networked CBM system, accessible from multiple widely spread locations, throughout Great Britain.

At this stage in the literature review the focus moves away from Condition Based Maintenance per se and turns towards Human Computer Interaction and methodologies for selecting and designing them. The first design methodologies discussed are Human Centred Design (HCD), Human Factors (HF) and User Profiling. Each methodology acts as a set of design procedures for improving the actual and perceived design quality, for new products or improvements to existing products/designs, intended for use by and with humans. Each methodology should be considered during the selection and development of suitable methods of Human Computer Interaction for a CBM system. Actively involving the intended users or existing users, whilst developing new or improving existing designs, is common to all three methodologies. Involvement from maintenance staff at Royal Mail, and maintenance professionals from the general community was requested and obtained whilst conducting this research. A select group of personnel from Royal Mail were asked to identify their user requirements, for a method of Human Computer Interaction with a CBM system, describe their user profile, and comment on existing maintenance practices. Examples of questions asked can be found in Appendix A.4. Maintenance professionals from the general community took part in three surveys, aimed at establishing generic CBM software GUI design rules and guidelines. Chapter 4 documents the results from these surveys.

Literature describing two further design methodologies: Cognitive Engineering and Schema Theory, have also been presented. Applying both methodologies to a HCI problem correctly, ideally should result in an intuitive design solution. A design solution, which fits alongside or with, existing working practices and is at a level of complexity suited to the intended audience. Decision support systems, e.g., CBM software applications, designed according to Cognitive Engineering and Schema Theory principles, would be expected to present easily interpretable information, in a format conducive to rapid and accurate decision-making. For example, a CBM GUI, which descriptively identifies the deteriorating condition of a machine's component/s, and recommends corrective maintenance and repair actions, is unlikely to cause cognitive overload to the intended user.

Ideally the chosen method of HCI for a CBM system should exhibit learn-ability, efficiency, memorability, low error rates, and user satisfaction, Nielsen [1993]. Each of these usability attributes represents an intentional goal when applying Human Factors, Human Centred Design, User Profiling, Cognitive Engineering and Schema Theory. Several different examples of HCI techniques are identified in the literature, each a worth while consideration for inclusion in a CBM system, e.g., Graphic User Interfaces (GUIs), Mouse and Keyboard, Audible alarms, various overhead light configurations, display screens, mobile devices, selectable buttons and joysticks. GUIs have already been identified as the most popular form of HCI chosen for CBM systems. Authors of notable authority in the field of GUI design and Human Machine Interface (HMI) design include: Professor B. A. Shneiderman, Dr C. Plaisant, Dr. N. A. Donald, Professor B. A. Myers, Dr. P. A. Chalmers, and Professor G. Johnnsen. Hobart [2004], foresees the next generation of Browser web sites, to be capable of performing all the functionality expected from off the shelf software applications. This represents the same level of interactivity expected from the proposed CBM software GUIs being developed for Royal Mail's CBM system. Other than communicating CM information through standard PCs networked together, there also exists the desirable need for communicating CBM information through mobile devices. Literature describing design requirements for mobile devices, emphasises the importance of restricting information intended for presentation via GUI, to a few lines of text and minimising every design feature to its minimum, due to the size of mobile device GUIs.

Once the design content and intended functional capabilities for inclusion in a GUI have been established, programmers can be expected to convert the design into a working solution. Software applications tools designed to simplify this task are discussed in the literature. Myers [1995] and Myers [2000] provide a full explanation for user interface design tools. Since 40-90% of the code making up a typical software application drives the user interface, Sheppard and Rouff [1994], simplifying its construction is welcomed. Microsoft Visual Web Developer 2005 Express Edition, a user interface design tool, for creating active server page web sites, was selected to develop a prototype simulation, for the research project. Selecting this software development tool was under taken on the basis that it allows ASP web sites to be constructed, is relatively easy to learn with the assistance of freely available animated tutorials, it requires little previous programming knowledge, and the researcher possessed previous experience with Microsoft FrontPage 2000, an earlier version of this software application.

Documenting and modelling the decision processes whilst developing a software's GUIs is supported by Puerta et al. [1999] and John and Kieras [1996]. Both authors explain how modelling is useful for predicting how people will use a proposed GUI; predicting anticipated learning time, execution time, anticipated errors, and identifying those parts of an interface that can be improved before the GUI has been tested. None of these pre-testing modelling techniques were applied during the development of the conceptual design described in chapter 6. Insufficient information was immediately available to construct such models and time limitations led the development process directly towards creating and testing a simulation. Usability testing was conducted via inquiry and simulation. Usability testing via simulation is supported by Nielsen [1993], Archer and Tuan [1995], Ivory and Hearst [2001] and Shneiderman and Plaisant [2004]. Usability testing via inquiry involved asking maintenance professional from various industries, to complete a survey feedback form, whose results commented on the quality and contents of the simulation, viewable over the Internet. Usability testing via simulation was conducted at two of Royal Mail's mail centres. Presentations and demonstrations were given and subsequent criticism and feedback noted. Chapter 7 documents the findings from both usability tests. Findings from both sets of usability tests identify areas for improving the initial concept. Suggestions for improvements are extensive, affecting almost every aspect of the conceptual design. Having identified areas for design improvement, the obvious next step is to make the necessary suggested design alterations. Repeating this process several times is referred to as iterative design, described by Sullivan [1996]. An iterative-engineered product will more closely satisfy user requirements and is therefore more likely to be accepted. Although experimental work conducted for this research project does not progress beyond the conceptual design stage, the literature review finishes on the topic of system implementation guidelines. Guidelines for implementing a final CBM system solution into an existing organisation, with well-established practices already in place, have been suggested.

8.1.2. Chapter 3

The methodology sets out the intended research direction necessary for selecting and developing methods of Human Computer Interaction, for a CBM system. It represents a design specification, based upon knowledge acquired during the literature review, following discussions with maintenance personnel at Royal Mail, discussions with members of the Mechatronics Research Group, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, and the researchers own knowledge and understanding. Eight titled sections comprise the CBM HMI design specification, presented in section 3.4. Subsequent research activities documented in chapters 4, 5, 6, and 7 consider recommendations made in the design specification.

A certain amount of overlap occurs between the contents of information in the methodology and chapter 4. Survey results presented in chapter 4 comment on what industrialists consider good practice, for selecting and developing methods of Human Computer Interaction, for a CBM system. These findings represent up to date views from CBM practitioners, for selecting, designing and developing suitable methods of HCI for a CBM system.

8.1.3. Chapter 4

Chapter 4 documents and discusses findings from three industrial surveys, aimed at establishing how CBM systems have been introduced, how they are applied, how they communicate information to users through various forms of HCI, and the importance and values associated with graphical design and functional design capabilities, provided for in a CBM HMI.

Results obtained from survey 1, 'Condition Based Maintenance application indicators for 2004-2005', provides influential information relevant to the selection, design and development of CBM systems, results which have been published in Higgs et al. [2004]. Findings identified that a majority of industries represented in the survey have implemented CBM systems to adopt predictive maintenance techniques and reduce the number of unscheduled machine breakdowns. Generic CBM systems should therefore be designed to identify and notify CBM practitioners of remaining useful machinery life, before maintenance and repair. It also suggests a CBM system should provide some form of urgent mechanism for attracting the attention of CBM practitioners, to identified deteriorating equipment. Survey findings suggest that the chosen method of HCI for a CBM system, is not as important as the method of system implementation. Budget costs should therefore take account of the resources used and costs incurred as a result of training and system implementation. Survey findings suggest continued successful operation of predictive maintenance practices using CBM systems, requires an appreciation from CBM practitioner of all the benefits they provide. Survey findings recommend several different media be used for communicating CM information to CBM practitioners, notably: graphs, discrete values, printable reports, alarms, and images designed to portray a machine live operating condition through colour coding. Survey finding show that only a third of all CBM systems form part of a larger networked maintenance system. The majority of CM equipment sold, is therefore used as an independent maintenance decision tool. Such knowledge is useful for commercial CBM system designers, because it indicates that the market place for independent localised CBM systems, is larger than that for networked CBM systems. Independent CM equipment requires fewer functional design capabilities be included in its software's GUIs, than networked CBM systems. For example, networking and integration controls need not be developed to the same extent, as they are for networked or remote CBM system software.

Despite a limited response to survey 2, a journal paper, documenting its findings, Higgs et al. [2006], was produced and published. Results to the survey have been compiled into a set of six design drivers, each influencing design and development decisions for a CBM system's HMI, listed in section 4.3.2. Findings overlap to a certain extent with proposals for a CBM HMI design specification, presented in chapter 3. Combining the proposed design specification with the identified design drivers, provides sufficient material to begin establishing a set of industrially approved proposals for generic CBM software GUI design rules and guidelines, applicable to CBM software HMIs.

Survey 3, 'Guidelines and rules for Condition Based Maintenance software GUI design', assesses values and levels of importance placed upon design features and GUI design rules, identified following survey 2, and as a result of the literature review. Results to the survey have been presented for journal publication, and are awaiting printing at the time of writing. Understanding CBM practitioners and CBM solution providers opinions on this matter, enables the researcher to establish a rank ordered list of proposed CBM software design and development rules and guidelines. Rules and guidelines, which can be recommended to the CBM solution provider community, to assist them improve the quality and potential saleability of their software. Equally so, these rules and guidelines will influence design decisions whilst developing a CBM software's GUI, targeted at satisfying Royal Mail's user requirements.

8.1.4. Chapter 5

User requirements investigations conducted amongst maintenance personnel at Royal Mail's mail centres, is documented in chapter 5. Recommendations supporting this research approach are documented in sections 2.6, 3.3.1, and 4.3.2.2. A select group of maintenance personnel from Royal Mail were interviewed with the objective of:

- Understanding Royal Mail's existing maintenance practices.
- Enquiring about the user profiles of their maintenance personnel.
- Identifying existing computerised systems and applications used by maintenance personnel.
- Asking what is expected from a CBM system, and what specific design features individuals would like to see incorporated within its GUIs.

A large quantity of information was obtained as a result of these enquires, providing plenty of food for thought. Royal Mail predominately use preventative maintenance practices. User profiling investigations identify a hierarchical maintenance personnel structure consisting of six levels, shown in Figure 5.2. Job responsibilities for each level are identified in Table 5.1 through to Table 5.8. Differentiating between different maintenance personnel levels and their associated job responsibilities, encourages the Human Machine Interface designer, to create a design suited to different user profiles and their grouped user requirements. Further user profiling and user requirements investigations is recommended, as the present level of detail could be improved.

Computerised systems and applications used for maintenance decision-making are identified in section 5.4, Table 5.9. A modular extension to the business computer application SAP, referred to as Service Delivery Materials Management (SDMM), is used in every mail centre apart from Heathrow World Wide Distribution Centre (HWDC), for Computerised Maintenance Management System (CMMS) activities. Integrating a CBM system with the CMMS, offers benefits for aiding maintenance decisions, which rely upon a comparison between machinery operation condition and machinery operational performance. Critical to the benefits and success of integrating both systems is secure and accurate data transfer between databases belonging to both systems, and providing adequate and intuitive design features for controlling data transfer and presentation within each systems GUIs.

User requirements describing the desired design capabilities for a CBM system and the preferred method of Human Computer Interaction, for Royal Mail are presented in section 5.5. Each user requirement is presented in tables, categorised according to requirement type. Associated job title acronym categories are positioned in cells to the right of each user requirement. Presenting user requirements in this manner provides the reader with a quick overview of the design expectations for a CBM system. Further investigations aimed at associating a level of priority for each user requirement will prove useful, in helping the HMI designer determine the level of effort, which should be put into meeting higher priority user requirements, as opposed to lower priority ones.

8.1.5. Chapter 6

A conceptual design for a set of CBM GUIs, designed to Royal Mail's user requirements is presented in chapter 6. The conceptual design simulates and provides examples showing the full functional capabilities for the proposed design ideas. The conceptual design is designed around a five-category structure, shown in Figure 6.1. Each of the five categories represents top-level functional capabilities for a CBM system. Navigating down through each category provides users with all the functional design requirements expected from CBM software applications, identified in survey 2, section 4.3.2.3. Designing the concept around five categorises should promote the use of modular programming techniques, for the final design solution. Software designed using modularised programming techniques, can be tailored, at a later stage, to satisfy other users requirements more easily than other programming techniques.

In order to simplify and standardise the method by which web pages are constructed and information presented through an Internet Browser, templates are extensively used within the conceptual design. Each template is intended to self populate with information, graphs and data, according to a users personalised selection. Active server page instructions (code), control the movement and content of information loaded up onto each web page. Constructing the code to perform all the intended actions intended for the final solution, requires advanced programming and database skills, as well as a good understanding of web design. At this stage in the development process it has only been necessary to use a web development tool.

8.1.6. Chapter 7

Work continued on the conceptual design until the researcher reached a point where further progress was considered most productively achievable, with external feedback on the design ideas already generated. Maintenance personnel from Royal Mail and maintenance professionals within the general community, provided feedback following usability evaluation testing on the conceptual design. Suggestions for improving the conceptual design are documented for both sets of providers in section 7.2.1 and 7.2.2. Table A.6.1, located in Appendix A.7, assesses whether proposed software design and development rules and guidelines presented in section 4.4.3.10, are included in the conceptual design or suggested as recommendations for design improvements. From the forty-three proposals for design rules and guidelines, thirty-eight would be included in the conceptual design, if all the design improvement recommendations were accepted and incorporated. Three of the seven proposals for rules and guidelines represent a functional design recommendation; the other three are concerned with recommendations not directly associated with software functional capabilities.

Table A.6.2, located in Appendix A.7, assesses whether user requirements presented by Royal Mail maintenance personnel for a CBM system, are included in the conceptual design or suggested as recommendations for design improvements, or associated with a proposed CBM software GUI design rule and guideline. Suggested improvements which match initial user requirements, considered unsatisfactorily provided for in the conceptual design, should be given priority during future design alterations and improvement work. User requirements, which are unique to the proposed CBM software HMI design rules and guidelines, represent potentially new proposals for design rules and guidelines. This assumption is only true for user requirements which remain true for the majority of other companies, intending to or who already use CBM software. Following similar procedures to those documented in section 4.4, is one way of determining the acceptability for proposed new rules and guidelines.

Table A.7.1, Appendix A.7, presents an alternative set of proposals for CBM software GUI design rules and guidelines. The list is considered more comprehensive than the existing set included in section 4.4.3.10. Realistic suggestions for rules and guidelines identified at different stages during this research project are collated under eleven categories. Contributions to the revised set of proposed rules and guidelines are taken from:

- Proposals for a Human Machine Interface design specification presented in section 3.3.
- Identified factors driving CBM GUI design presented in section 4.3.2.
- Proposed CBM software design and development rules and guidelines, included in section 4.4.3.10.
- User requirements for a CBM system identified in section 5.5.
- Design features suggested for inclusion in CBM software GUIs presented in section 5.9.
- Suggestions for design improvements to the conceptual design, presented in section 7.2.1 and 7.2.2.

Further investigations aimed at determining the acceptability of the revised list of proposed rules and guidelines is recommended.

8.2. Contributions

Tangible research contributions presented in this thesis include:

- Survey results documenting the industrial application of CBM systems for 2004-2005.
- A set of guidelines identified as influencing the design of generic CBM GUIs.
- Survey results documenting the level of importance and value associated with multiple Human Machine Interface design considerations, applicable to generic CBM software applications.
- Design ideas and development suggestions for a CBM Human Machine Interface, designed to meet Royal Mail's user requirements.
- A proposed set of CBM software design and development rules and guidelines.

Chapter 9

9. CONCLUSIONS AND FURTHER WORK

9.1. Introduction

Two research objectives have been investigated and discussed in this thesis. Firstly, to research and develop methods of Human Computer Interaction (HCI), for a Condition Based Maintenance (CBM) system, under development for Royal Mail Plc. Secondly, to establish a set of justifiable CBM system Graphic User Interface (GUI) rules and guidelines. Each research objective is discussed in section 1.1.

9.2. Developing a CBM system's GUI, which meets Royal Mail's user requirements

Design ideas for a CBM system's GUI have been converted into a simulation and evaluated, using usability evaluation tests. Research activities constituting towards the formulation of the design ideas, construction of the simulation, and usability evaluation, are documented in chapters 2 to 7. Ideas incorporated in the design proposal have been influenced by five areas of investigation, notably: 1) Findings from literature review investigations, documented in chapter 2; 2) Results from three surveys, conducted amongst CBM practitioners and CBM solution providers, documented in chapter 4; 3) User requirements investigations conducted amongst maintenance personnel at Royal Mail, documented in chapter 5; 4) Results following a comparison of existing GUIs developed for earlier CM techniques, by members of the Royal Mail University Technology Centre, documented in chapter 5; 5) Feed back following usability evaluations, documented in chapter 7.

A web site to be hosted on Royal Mail's company Intranet, represents the proposed CBM GUI. The proposal is designed on the assumption that machinery condition data will be gathered from four types of Condition Monitoring (CM) techniques, identified in earlier research projects, conducted by previous members of the Royal Mail University Technology Centre, Mechatronics Research Group, Loughborough University. The CM techniques in question are: Acoustic Emission CM, designed to measure pulley bearing noise emission levels; Belt Vibration CM and Belt Surface Condition CM, designed to monitor individual belts conveying mail through mail sorting machinery; And Thermography CM, designed to monitor electric motors driving pulleys.

Graphic User Interfaces (GUIs) controlled using a mouse and keyboard; provide the main method of HCI for the proposed design. Additional methods of HCI include audible alarms, overhead colour coded lighting, hand held mobile devices and printable reports.

The proposed CBM GUI incorporates a design structure, offering all the functional design capabilities expected from generic CBM software, identified in section 4.3.2.3. Functional design features offered include: 1) A selection of data analysis options; 2) A selection of CM reporting options; 3) Controls for choosing and adjusting alarm settings; 4) Controls for data archiving and other data management capabilities; 5) A selection of options for communicating machinery condition including: graphs, numerical values and colour coding; 6) Images designed to portray the plant, machinery, sub assemblies and components; 7) User type recognition access rights.

The design proposal assumes an Internet CBM system design architecture will be chosen, and that the CBM HMI will reside on Royal Mail's Intranet. The design proposal assumes data will be stored on a dedicated CBM system database, and a dedicated web server will perform data extraction, data manipulation, user request action commands, and web page construction. Behind the scenes programming code, constituting each active server page, will provide control over all the interactive capabilities offered through the GUI, perform database query requests and construct each web page.

9.2.1. Further Work

In its present state, the proposed CBM GUI represents a collection of design ideas, incorporated in a web site, designed to simulate and provide examples of its intended operational capabilities. Further usability tests are recommended once all the design improvements proposed in chapter 7, have been fully incorporated in the simulation. The processes of: implement design improvements, conduct usability tests, identify areas for design improvement, should be iterated until no further economically or technologically viable design improvements are identified. Once the design ideas have been settled on, the next phase will be to construct a fully functional web site, capable of performing all the functional capabilities proposed in the design ideas. A team of web development programmers with experience in ASP web design, and database design and construction are suggested for this phase. Opportunities for further research may become evident during the conversion of the design ideas into a fully functional product. For example, research aimed at developing an intelligent design aid, capable of suggesting causes for machinery deterioration and suggestions for corrective maintenance action. Designing an efficient database management system capable of organising the vast quantities of CM sensory data, anticipated from a networked nationwide CBM system, such as that under development for Royal Mail. Developing efficient methods for converting CM data, extracted from database and post processed, into animated dials, graphical representations, and colour coded images portraying the machinery being monitored. The objective in this case would be to reduce web page construction time to a minimum.

In order to test the fully functional web site, once complete, it is recommended that a data generator be developed. The data generator should be designed to produce phantom data, simulating data extraction for each anticipated CM technique, included in the final CBM system solution. Further usability tests should aim to determine the efficiency and accuracy of maintenance decision-making, for different user types, on a selection of different simulated failure condition scenarios.

9.3. Generic CBM software GUI design rules and guidelines

Eleven design rules and guidelines have been proposed, with the intension of improving the quality of future CBM software GUIs, leading to greater user satisfaction, presented in Table A.7.1, Appendix A.7. Each of the eleven proposed rules and guidelines and their associated sub categories and examples, have been derived following surveys conducted amongst the CBM practitioner and CBM solution provider community. Other constituting sources include: results from user requirements investigations, conducted at Royal Mail; Comparisons of existing GUIs developed for experimental CM equipment, by members of the Royal Mail Technology Centre; and feedback following usability evaluation tests on the conceptual design. Findings from survey results discussed in section 4.3, established a list of six CBM GUI design drivers. Each design driver represents a justifiable proposal for a CBM software GUI design rule and guideline. Design drivers incorporated in the list of eleven category header proposed design rules and guidelines, shown in Table A.7.1, Appendix A.7, include: 1) Design CBM software GUIs to follow accepted Graphic User

Interface design rules; 2) Design CBM software with due consideration towards the systems functionality; 3) Design CBM software with due consideration for networking and integration requirements and expectations; 4) Design CBM software with due consideration for the environmental conditions the GUI will reside in; 5) Design CBM software so that it can be easily tailored to users requirements. The sixth design driver, 'design CBM software to satisfy the intended audience', falls into the category of designing CBM software that follows acceptable Graphic User Interface design rules. Designing CBM software GUIs with due consideration towards a systems functionality, is subdivided into identified functional capabilities, expected from CBM systems. Each functional capability is associated with a design rule or guideline included amongst the eleven proposals, as follows: 6) Design CBM software GUIs with a selection of data analysis capabilities, selected to suite the type of CM technique/s included in the CBM system; 7) Design CBM GUIs to communicate the condition of machinery using techniques and methods, which offer easy interpretability; 8) Design CBM GUIs with features for controlling and monitoring alarms. Alarms designed to attract a user's attention, in the event of identified deteriorating machinery conditions, exceeding control limits; 9) Design CBM software GUIs with a selection of data management control features. The remaining two proposed rules and guidelines from the list of eleven, are derived from findings following the survey discussed in section 4.4. Findings from this survey placed a level of importance and value on twenty-six design recommendations, with respect to their influence over CBM software GUI design decisions, and the final saleability of CBM software. The design recommendations in question were derived from information gathered during the literature review and following feedback from the surveys discussed in section 4.2 and 4.3. Identifying perceived levels of importance is useful knowledge for CBM solution providers, as it can influence the amount of design effort or focus directed during the design, development, marketing and sales procedures. A further thirteen design and development recommendations were suggested in addition to the twenty-six questioned in the survey. From these thirteen, a further two categories, making up eleven proposed design rules and guidelines were created. The additional proposed CBM software GUI rules and guidelines are: 11) Design CBM software with adequate security measures aimed at preventing unauthorised access to the software and data corruption. 11) Design CBM software with due consideration for marketing and after sales design considerations. Each of the forty-three design and development recommendations identified in section 4.4, have been associated with and placed under one of the eleven categories, forming the proposed CBM software GUI rules and guidelines, creating sub headers and examples.

Identified levels of importance for each of the eleven proposed rules and guidelines, and their associated sub categories and examples, are shown in the right hand column of Table A.7.1, Appendix A.7. Levels of importance have been derived from the results to the survey discussed in section 4.4. Further research investigations are recommended in order to determine the levels of importance or value, for those proposed rules and guidelines with no known level of importance or value, shown in Table A.7.1, Appendix A.7.

9.3.1. Further Work

The proposed set of generic CBM software GUI rules and guidelines is not completely validated. Further research is recommended in order to justify every proposed rule and guideline, and their associated sub categories and examples. It is suggested this be undertaken using a survey, as has already been the case, and through direct contact with a number of CBM solution providers. Several CBM solution providers should be approached on a one to one basis, and questioned in person on their views towards the list. CBM solution providers should be asked to describe the procedures previously followed, whilst designing and developing the HMIs for their own products. CBM solution providers should be asked whether the procedures they followed in the past, while designing and developing CBM HMIs, resulted in satisfactory final products, and whether they could improve these procedures. Ultimately a set of internationally recognised standards outlining rules and guidelines for generic CBM system GUIs, should be produced.

9.4. Contributions to Knowledge

Both research objectives have been satisfactorily met. Further research and development activities have been proposed, aimed at taking this area of research beyond the point at which this thesis draws to a close. Contributions to knowledge resulting from this thesis include:

1. Eleven proposed rules and guidelines for designing and developing a CBM software's GUIs, presented in Table A.7.1, Appendix A.7. The proposed rules and guidelines are intended for CBM designers and solution providers, in order to reduce the development time and improve the quality of generic CBM software GUIs.

2. The level of importance and value linked to twenty-six CBM HMI design and development recommendations, presented in section 4.4.3.10.
3. Knowledge and understanding towards the applications of CBM systems within industry for 2004 to 2005.
4. Design ideas for a CBM software's GUI, designed to Royal Mail's user requirements. A design based upon identified novel functional design expectations for inclusion in a CBM systems HMI, presented in section 4.3.2.3.

9.5. Papers

Papers to which this thesis has contributed

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Appendices

A.1. SURVEY 1: CONDITION BASED MAINTENANCE APPLICATION INDICATOR FOR 2004-2005

A.1.1. Percentage Utilisation of CBM systems According to Industry

Industrial and Business Groups	Number of Replies (Percentage of replies)
Manufacturing-Petroleum refining, chemicals and associated products	59 (21.61%)
Other	27 (9.89%)
Manufacturing-Metal products	21 (7.69%)
Oil and Gas-Oil and gas extraction	21 (7.69%)
Utilities-Electrical Generation	21 (7.69%)
Manufacturing-other	17 (6.23%)
Choice-Manufacturing-Wood and paper products	16 (5.86%)
Services-Contact Maintenance/Repairs	14 (5.13%)
Services-Other	13 (4.76%)
Manufacturing-Food, beverages, tobacco	13 (4.76%)
Mining-Metal ore	11 (4.03%)
Services-Business Services/Consulting	11 (4.03%)
Services-Education/Academia	6 (2.2%)
Manufacturing-Machinery and equipment	5 (1.83%)
Utilities-Water, sewerage, drainage	5 (1.83%)
Services-Transport	4 (1.47%)
Services-Healthcare	4 (1.47%)
Utilities-Electricity Transmission and Distribution	3 (1.10%)
Services-Property services/Building Maintenance	1 (0.37%)
Manufacturing-Textiles, clothing, footwear, leather	1 (0.37%)

Table A.1.1. Survey 1 results: Industrial distribution of CBM systems.

A.1.2. Company Details for Respondents to Survey 1

Company Names and Addresses		
Abbott Lbs,	Fauji Fertilizer Company Ltd. Pakistan	Philippine Resins Industries Inc. PPDC Complex, Batangas Dos, Mariveles, Bataan Philippines, 2105
AF Condition Monitoring (M), Sdn Bhd	FENOC, PO Box 4, Shippingport, Pa.15077	PME AB.
AIRBUS, New Filton House, Bristol, BS99 7AR, UK	Freeport Indonesia	Pratt & Whitney Jet Engines USA
Alcoa	GABRIEL India Limited Dewas	Private Bag X1033, Pullenshope, 1096 South Africa
Alexander Stuber & Partner Consulting for Operational Excellence	Golden Bay Cement	PT PUPUK ISKANDAR MUDA, JL MEDAN BANDA ACEH PO BOX 21 LHOKSEUMAWE ACEH UTARA N A D INDONESIA
Allison Transmission, 4700 W 10 Indianapolis, 46222, USA	Hadeed, Saudi Arabia	PT. Inco, Soroako, Sulawesi Indonesian
Amana Refrigeration Products	Hamersley Iron Pty Ltd Dampier, 6713, Western Australia	Pulp & Paper – Specialty

Table A.1.2 continued on next page:-

Company Names and Addresses		
Ashanti Goldfields Company Ltd	Indian Institution of Plant Engineers, 3-100/1 Snehapuri Road No.14, Hyderabad 500 035 A.P. India	PZ Industries PLC, Ikorodu, Lagos State, Nigeria
Birla Copper, Dahej, INDIA	INDUSTRIAL DIAGNOSTIC SYSTEMS & SERVICES LLC	Qatar Fuel Additives Company, PO Box 22700, Doha Qatar
BMW, MC LLC 1400 Hwy, 101 S Greer, S.C. 29651	Interactive Facilities Corp. San Diego, CA. USA.	Qatar Petroluem Offshore Fields P.O.Box 47 Doha QATAR
BOC No2 Hosseyni Alley, Saba Blv. Shariati Ave, 19338-Tehran-Iran	IPR Pharmaceuticals Inc.	REK "Bitola"-Termoelektrani, 7000 Bitola, MACEDONIA
BOC Edwards	ISKI Omerli Dam	Reliability Systems Technologies, USA
Boise Paper Solutions	Jacobs Sverdrup Kennedy Space Centre, Florida USA	Rolls-Royce plc UK
Bombardier Transportation, Switzerland	Jacobs Engineering India H&G House CBD Belapur Navi Mumbai 400614 India	ROMPETROL SA, ROMANIA
BP FFBU 1501 Colquitt Highway, Bainbridge, GA. 39817	Jarvis Rail (Fastline Ltd)	ROTEC, 16550 189th AVE NE, Woodinville, WA, 98072

Table A.1.2 continued on next page:-

Company Names and Addresses		
Brown & Williamson Tobacco Corporation, 2600 Weaver Road Macon, GA 31217, USA	JM Huber Oudenburgsesteenweg, B8400 Oostende, Belgium	ROTOMECH CONDITION MONITORING 510 DIMPLE ARCADE, OFF. WESTERN EXPRESS HIGH WAY, KANDIVALI (EAST) , BOMBAY –400101 INDIA
BSRIA	Johnson Controls, Inc. 2400 Kilgust Road Madison, WI 53713 USA	Royal Mail Engineering Services UK
Burford Electric Service, Inc.	K.C.M. Services Ltd	Samsung Corning Deutschland GmbH, Tschernitz, Deutschland
Cadbury Adams, 40 Bertrand Avenue Scarborough, Ontario, M1L 2P6	Kaiser Aluminium and Chemical Corp.	Santos Ltd, 91 King William Street, Adelaide, SA 5000 Australia
CAIDMARK SDN BHD 53, JALAN SS21/56B, DAMANSARA UTAMA, 47400 PETALING JAYA, MALAYSIA	Kaltim Methanol Industri (PT.KMI), Kaltim Industrial Estate, Bontang, East Kalimantan, Indonesia.	Saudi Aramco Rabigh Refinery, PO Box 177, Rabigh 21911, K.S.A.
Canadian Nexen International, Yemen Operations, Yemen	Kuwait oil co.	Saudi Electricit Co. Qatif 3191 P.O.Box#60290 K.S.A.
Caribbean Ispat Ltd.	L.V.M-Mantenimiento Predictivo, Italy	Saudi Iron & Steel Co. Saudi Arabia
Chesapeake Reliability Services, LLC	Lockheed Martin, 1111 Lockheed Martin Way, Sunnyvale , Ca. 94088 USA	SC Rompetrol SA

Table A.1.2 continued on next page:-

Company Names and Addresses		
CHINO MINES COMPANY, PHELPS DODGE CORPORATION	Luxus Ltd, Belvoir Way, Fairfield Ind. Estate, Louth Lincs, LN11 OLQ	SCE – SONGS, PO Box 128, M/S D2B, San Clemente, CA 92674-0128
CPM Engineering Ltd, BARTONDOCK ROAD, TRAFFORD PARK, MANCHESTER	Lyondell Chemical	SCM SA Costa Rica
Crane & Co. Inc. Dalton, MA 01226, USA	MACSEA Ltd, 163 Water St, Stonington, CT 06378, USA	Schenck Pegasus, 2890 John R Road Troy, MI 48083
Data Systems & Solutions, 430 The Avenue, Bristol Business Park, BS16 1EJ, UK		Serba Dinamik Sdn Bhd
Delta Co. for Electronics, 31 El Shahid Abdel Moneim Hafaz, Cairo, Egypt Tel: +2024189605; Mobile: +20122361990	MAHINDRA & MAHINDRA LTD, 89 MIDC, SATPUR, NASHIK	Shanghhai Jiao Tong University China
Delta Electricity Off Main St, Wallerawang	MARAFIQ, Power & Water Utility company for Jubail & Yanbu	SigPoint Pty Ltd
Dept of Sport and Recreation Western Australia State Library WA	Marposs S.P.A.	SIMTECH Singapore
Development Engineering International, Wellheads Road, Farburn Industrial Estate, Dyce Aberdeen, AB21 7HG, UK	Mass Transit Railway Corporation Limited, Hong Kong Republic of China	Smith Services Of Alabam, 701 Bill Myles, Dr. West Saraland, AL 36571

Table A.1.2 continued on next page:-

Company Names and Addresses		
DG SERVIS STUPAVA, s.r.o. Cementarska 15, 900 31 Stupava, Slovakia	Mitsubishi Heavy Industries Ltd. Nagasaki R&D Centre, Japan	Staatsolie Refinery State oil Company of Suriname
Diagnostic Technologies India Pvt. Ltd	MOD/RAF UK	Stanwell Corporation Limited, PO Box 5895, CQ Mail Centre, Q 4702, Australia
DLI Engineering Corporation, 253 Winslow Way, West Bainbridge Island, WA 98110 USA	Mopani Copper Mines Plc, PO Box 40499, Mufulira, ZAMBIA	STEEL AUTHORITY OF INDIA, DURGAPUR STEEL PLANT, DURGAPUR-713204, WEST BENGAL, INDIA
Dofasco 1330 Burlington St E Hamilton, Ontario L8N 3J5 CANADA	Morton Salt Rittman, OH USA	Steve Moyle Engineering Maintenance Mgr, Tyco Water, smoyle@tycowater.com
Dow Corning LTD Barry Plant	Namteknoloyg 2256 Davison Ave Richland, WA 9352, USA	T-Solutions, Inc. US Coast Guard MR&E Consultant USA
Dubai Aluminium, PO Box 3627, Dubai, UAE	National Oilwell, 10000 Richmond Avenue, Houston Texas 77042 USA	Tanzania Portland cement Company Ltd.
East Carolina University Greenville, NC 27858 USA	Naval Sea Logistics Center, Carlisle Pike P.O. Box 2060, Mechanicsburg, PA 17055-0795 USA Attn: Bill Lumnitzer – Code 05312 5450	Thai Copper Rod Co. Ltd. 22/2 M.5, Theparak Rd, Bangpleeyai , Bangplee, Samutprakarm 10540 Thailand

Table A.1.2 continued on next page:-

Company Names and Addresses		
EASTERN PETROCHEMICAL COMPANY	Nestle South Africa	The Shell Company of Australia Clyde Refinery, NSW, Australia
Egyptian Glass Company	Nexfor Ltd, Cowie, FK77BQ Stirling, Scotland UK	Thermal Vision, 8 Old Fair Green, Dunboyne Co Meath
Engelhard Corp. 9800 Kellner Rd, Huntsville, Ala 35824 USA	Norampac Inc. Red Rock, Ontario, Canada	Total E&P UK plc, Crawpeel Road, Altens, Aberdeen, AB12 FG, UK
ENIP METHANOL PLANT ARZEW CHEMICAL INDUSTRY	Novartis Ringaskiddy Ltd, Ringaskiddy, Cork, Ireland	United Water 200 Old Hook Road, Harrington Park, NJ 07640
Entergy James A. FitzPatrick NPP P.O. Box 110 Lycoming, NY 13093 USA	OIL & NATURAL GAS CORP. LTD, 606 VASUDHARA BHAVAN MRBC, BANDRA EAST, MUMBAI-400051, INDIA	US Navy, PSNS & IMF C/210
Entergy Nuclear South, 1340 Echelon Pkwy, (M-ECH-36) Jackson, MS 39213	OneSteel Manufacturing Australia	Vibration & Sound Services & sales Singapore
Equipo de Servicios Petroleros Ltd, Atn:Edwin Rios – CBM Engineer, Cra 11A No 93-67 OF 501 Bogota, Colombia (South America), Tel +57-1-6212425 Fax: +57-1-6212264 e-mail: _dwin_rios@hotmail.com	Perse Sanco, No.26 Shahid Shavari Alley, Shariati Street, Tehran 19487	We Energies 231 W. Michigan Milwaukee, WI 53203 USA

Table A.1.2 continued on next page:-

Company Names and Addresses		
ESSAR POWER LTD 27th KM.SURAT, HAZIRA RD, SURAT-394270, INDIA	Petroleum refining and marketing	Western Mining
European PdM Partners	PetroSa South Africa	Weyerhaeuser Hwy 480, Campti La 71141
FAG Industrial Services	PETRONAS CARIGALI SDN BHD POS ANGSI, GRD FLOOR, KOMPLEKS OPERASI PETRONAS, 24300 KERTEH	WMC Fertilisers

Table A.1.2. Company addresses for respondents completing Survey 1.

A.1.3. Percentage Industrial Utilisation of CM and NDT Techniques

Condition Based Monitoring and NDT Technique	Number of Replies (Percentage of replies)
Vibration Analysis	254 (17.27%)
Oil Analysis	199 (13.53%)
Infra-red Thermography	176 (11.96%)
Human Senses	159 (10.81%)
Motor Current Analysis	128 (8.70%)
Ultrasonic Thickness Testing	122 (8.29%)
Dye Penetrant Examination	119 (8.09%)
Ultrasonic Crack Detection	106 (7.21%)
Magnetic Particle Inspection	90 (6.12%)
Acoustic Emission Analysis	70 (4.76%)
Other	48 (3.26%)

Table A.1.3. Survey 1 results: Percentage utilisation of CM and NDT techniques in industry.

A.1.4. Industrial CM and NDT Techniques

CM and NDT Techniques
Alloy analyser x ray.
Airborne ultrasound detection.
Boroscope.
Dial indicator and laser alignment.
Dissolved Gas Analysis.
Eddy Current analysis.
Eddy current non-contact probe.

Table A.1.4 continued on next page:-

CM and NDT Techniques
Eddy Current Testing Vacuum Leak test Holliday Test Coating Test.
Endoscopy.
Flooded member detection Long-range ultrasonic Iris/centre tube bundle inspection.
Gamma Scanning of pressure vessel internals.
Information fusion. Every thing together with analyses like Neural Network and so on.
Infra Red (IR) Spot meter. Alignment with laser, foundations and couplings. Balancing, shop and on site. Modifying operation as well as designs to be correct.
Laser alignment checks, motor controller insulation resistance checks, ultrasonic flow testing.
Laser guided precision alignment.
Metallurgical examination hardness measurement risk based maintenance optimisation.
Model Based Fault detection technology and products called Motor Condition Monitor MCM.
Monitoring of system performance by built-in software that keeps record of system operating parameters, e.g., rolling stock traction system, telecomm. Systems, etc.
Mostly on smps electronic.
Motor Circuit analysis Ball Bar analysis Laser analysis.
Motor Operated Valve Diagnostic Testing, Air Operated Valve Diagnostics, Check Valve Non-Intrusive Testing.
Offline motor insulation testing.
On-line equipment monitoring.
Passive ultrasonic inspection, (airborne and contact).
Partial Discharge for large electric motors.
Performance model (physical or Neural network).
Pipeline leak detection.
POSMON, Ford's System.
Power Quality Electromagnetic fields.
Preventive Maintenance based on cycles or product run.
Process data analysis Performance Monitoring Rechip-Trap Analysis on reciprocating machinery.

Table A.1.4 continued on next page:-

CM and NDT Techniques
Process information such as number of blocks through or strokes on a cylinder.
Radiographic testing.
Reciprocating machines Analyser.
Reciprocating performance system - Rechip BETA and Windrock Analyser.
Rotor Position Analysis, Coast down Analysis.
Routine preventative maintenance inspections.
Sensors appropriate to specific parameters, P,T,T,F.
Shaft magnetism.
Shock Pulse.
Shock Pulse Method.
Software diagnostics.
Sound Analysis Air Testing.
SPM, Smart methods per IDCON's CMS. Wear Particle analysis, laser deviation alignment, Ultrasonic leak detection.
Strobe light.
Structural analysis, FEA.
TOFD (Time of Flight Diffraction). RVI (Remote visual inspection).
Ultrasonic air leak detection Machine Vision NDT.
Ultrasonic vibration.
Ultrasonics for bearings and lubrication.
Ultrasound leak detection for boiler leaks. Ultrasound lubrication system.
We need to develop history card of individual equipments.
Wear debris Analysis.
Wear Debris, Extensive on line monitoring of motor management relays (1200 online).
Welding control; hydraulic test pressure test radiography control.

Table A.1.4. Survey 1 results: Alternative CM and NDT techniques in use within industry.

A.1.5. Additional media used for presenting CM information

Additional Media Types
Printable reports identifying: • Faults and their frequencies of interest. • Recommendations. • Machines in exception condition and recommendations for repair. • Inspection list (check sheet). • Conclusions and suggested remedy. • Exact nature of actions need to be taken in case of abnormalities detection. • Necessary corrective actions. • Severity of faults, and trends of individual fault severity. • Specific repair recommendation and priority. • Diagnostics with various calculations showing parameters for machinery conditions. • Detailed maintenance method descriptions/instructions. • Work order requests. • Notification that control limits have been breached.
Browser web pages which show the condition of an entire organisations equipment graphically.
Alerts, delivered to ANY computing or telephone device, 24/7 anywhere.
Alarms by exception.
Our contractors only supply appropriate reports – our own people only supply tabulated data.
CM is carried out by contractors who produce monthly reports on machine condition and 24-hour exception reports.
Spectrum Analysis.
Live presentation.
Reports and documentation with results.

Table A.1.5 *continued on next page:-*

Additional Media Types
About 20 signals, 16 vibration and 4 process signals are acquired on line at a 5000 samples second sampling rate; Using 4072 samples out of these, all the signals are analysed in real time in frequency domain and the signals in real time are displayed in chart form with discrete values at any instant of time, the orbits are also plotted in time. Whenever the pk to pk value or frequency domain values exceed the set limits, an expert system is automatically called and top 5 faults out of 23 analysed are displayed with percentile marks. The entire data is managed on a current day, yesterday, last week, last month and last year basis and the trends of rms values and frequency components are displayed. Coast up and coast down test data can also be recorded and analysed in frequency domain. Visual flashing and audio alarms are available whenever the signals exceed set values. The signals are also analysed for its properties like correlation, auto correlation, to make a decision whether the signal is correct or faulty from a sensor or circuits. Details on the expert system are also available on line. This code is also available to work with from a remote site; this has been demonstrated but not put in practice as yet.
An automatically generated audio voice, informing users when a machine is predicted to brake.

Table A.1.5. Survey 1 results: Alternative media used for presenting CM information to users.

A.2. SURVEY 2: IDENTIFYING CBM GUI DESIGN DRIVERS, A SURVEY

A.2.1. Company Details for Respondents Participating in Survey 2

Company Name	Company Address
SCHENCK PEGASUS, Corp.	2890 John R Troy, Michigan 48083, USA
STANWELL Corporation Limited	PO Box 5895, Central Qld. Mail Centre Q4702, Australia
TOTAL E&P UK plc	Crawpeel Road, Altens Industrial Estate, Aberdeen, AB12 3FG, UK
Siemens AG	Wittelsbacherplatz 2, D-80333 Munich, Germany
Mighty River Power	Level 19, 1 Queen St, P O Box 90399, Auckland, NEW Zealand
Eskom Enterprises	P.O. Box 40712, Cleveland, 2022, South Africa
BIRLA COPPER	HINDALCO Industries Ltd, Dahej, Gujarat, India
Sundyne Corporation	14845 West 64th Avenue, Arvada, Colorado 80007, USA
Industrial Machinery Diagnostics, LLC	Rotating Equipment Field Services, Houston, Texas 77584 USA
BOC EDWARDS	HEADQUARTERS, Manor Royal, Crawley, West Sussex, RH10 9LW, United Kingdom
Halliburton Corp	5 Houston Center, 1401 McKinney, Suite 2400, Houston, TX 77010, USA
PT Kaltim Prima Coal (KPC) Indonesian State Coal Company	
DLI Engineering Corporation	Corporate Office, 253 Winslow Way West, Bainbridge Island, WA 98110, USA
Nestlé Australia Ltd,	1, Homebush Bay Drive, Rhodes NSW 2138, Australia

Table A.2.1. Survey 2 results: Company details.

A.3. SURVEY 3: PLACING A VALUE ON CBM SOFTWARE DESIGN FACTORS AND FEATURES

A.3.1. Company Details for Participating Respondents to Survey 3

Company Name	Company Address	Name of CBM software being used
ABB Limited	BS Devshi Marg Off Sion-Panvel Road, Deonar, Mumbai - 400088, India	Oil Analysis
ABB Ltd	21 - 25 Commerce Street, Aberdeen, AB11 5FE, UK	ABB ArmadaCMS
ABB South Africa	ABB Aldore, Alberton, South Africa	RBM Suite
Airbus UK	Building 09H C1, New Filton House, Filton, Bristol BS99 7AR, UK	In development phase and not currently externally for sale
AIMIL Limited	201/202/203, "Arundeep" complex, Race course circle, Gotri road, Vadodara- 390007, Gujarat, India	OMNITREND
Baumgartner AG	Käsereiacker 7, 3317 Limpach, Switzerland	CSI
Belotti Sistemi S.A.S.	Italy	?
BOC Edwards	1810 West Drake Drive Tempe, AZ 85283, USA	Fabworks 32
BP America		
BP Angola		BN System 1
BP Polyethylene NA		Emonitor Oddessy
BSRIA Ltd	Old Bracknell Lane, West Bracknell, RG12 7AH, UK	Various
Caidmark Sdn. Bhd.	53, Jalan ss21/56B, Damansara Utama, 47400, Petaling Jaya, Selangor, Malaysia	Gastops ECMS
Crane & Co, Inc.	30 South Street Dalton, Massachusetts 01226-1799, USA	Entek Oddessy Ver. 2.2
CubeRoot Ltd.	18 Melton St, Leicester, LE1 3NB, UK	VID
De Jong & Partners	Valkenveld 15, 9302GT, Roden, The Netherlands	Taqc
Diagnostic Solutions Ltd	Chester	MAINTelligence
DLI Engineering	253 Winslow Way West, Bainbridge Island, WA 98110, USA	ExpertALERT
Dmsi	Halifax, Nova Scotia, Canada	MAINTelligence

Table A.3.1 continued on next page:-

Company Name	Company Address	Name of CBM software being used
EMG Energy Management Group Inc.	Halifax, Nova Scotia, Canada	?
ENTEK POWER PLANT	DEMIRTAS OSB OSMANGAZI/BURSA, TURKEY	?
FAG France	Germany	Trendline
FAG Industrial Services	Kaiserstrasse 100, 52134, Herzogenrath, Germany	
FENOC	PO BOX 4, Shippingport, Pas. 15043	RBM Ware
Georgia Pacific	Muskogee, OK, USA	?
Grayson Armature	1204 witter, Pasadena tx, 77506, Belize	CSI
Hyatt Industries Ltd	Canada	Pruftechnik OmniTrend
Institut supérieur de Technologie	Rue de la concorde, Camp Levieux, Rose-Hill, Republic of Mauritius	Divadiag from 01 db stell diagnostic
Machinery Management Solutions, Inc.	7724E 1100N, Clarks Hill, In 47930, USA	Several - Omnitrend, ultratrend, ..
MCM Ltd	Unit 6, Lon Parcwr Ruthin, Denbigshire, LL15 1NJ, UK	DDS 2000
Mighty River Power	PO Box 445, Hamilton, New Zealand	OSISoft PI, RCM Toolkit, Bently Nevada DM2000
Mobius	280 Myers Road, Merricks North, Victoria, 3926, Australia	I have developed iLearnVibration, and previously I developed ExpertALERT software, sold by DLI
Morton Salt	151 S. Industrial Street Rittman, OH 44270, USA	RIS 2K (In-House Developed)
National Oilwell	10000 Richmond Avenue, Houston Texas, 77042, USA	Hawk Optimum
National Reliability Systems	251 Forrester Drive, Greenville, SC 29607,	DDS2000
Nestle Australia	Australia	RBMware
Optimal Maintenance Decisions (OMDEC) Inc.	560 Burns Road, r.r. #2 Godfrey, Ontario, K0H 1T0, Canada	EXAKT
Phelps Dodge, New Mexico Operations	PO Drawer 571, Tyrone, NM 88065, Mexico	RBMware, CSI
PME AB (Predictive Maintenance Engineering AB)	Ostkindsvagen 11, S-610 24 Vikbolandet, Sweden	CSI MTWIN and RBMware

Table A.3.1 continued on next page:-

Company Name	Company Address	Name of CBM software being used
Predictive Maintenance Technologies Division Mountain View, LLC.	5600 N, 58th Court Suite 1, Lincoln, NE 68507	Machinery Health Management by CSI
Queensland alumina Ltd	Parson point, Gladstone, 4680 QLD, Australia	RBMware from CSI
SigPoint Pty Ltd	22 Stanbury Way, Booragoon, WA 6154, Australia	SigPoint NDT
Sixteen-Eleven, Inc.	512 Webb Street, St. Marys, OH 45885, USA	Ascent, Prism4, EFW, & RBMWare
So. Calif. Edison	P.O. Box 128, San Clemente, CA 92674-0128, USA	Entek Enshare
sonatrach		?
Spintelligent Labs		?
Stanwell Corporation Limited	PO Box 5895, CQ Mail Centre, Q 4702, Australia	AMS Suite: Machinery Health Monitor
Syclo, LLC	1721 Moon Lake Blvd, #300 Hoffman Estates, IL 60194, USA	SMART
Tensor Systems Pty Ltd	10 Pigeon Bank Lane, Warrandyte, Vic 3113, Australia	Tensor Systems
Total E&P Indonesia	Jl. Yos Sudarso, PO BOX 606, Balikpapan, 76100, Indonesia	?
Tram Electric Inc.	1556 E 100 S Price, Utah 84501, USA	SKF - Prism 4
V.C. monitoring Limited	24 Coneyford Road, Shard End, Birmingham, B34 7AX, UK	CALM
Vibration & Balancing Solutions	1470 Langhorne Road, Lynchburg, VA 24503, USA	?
Vibrationsteknik AB	Taborsbergsv, 20 SE-602 13, Norrkoping, Sweden	?
Vibro Technology SRL	CALLE OLMOS 117, URB. EL REMANSO DE LA MOLINA, LIMA12, PERU	Master Trend of CSI

Table A.3.1. Survey 3 results: Reference section 4.4.3.1. Some of the companies who completed the survey and the name of the CBM software/s they use.

A.4. ROYAL MAIL'S MAINTENANCE SYSTEM

A.4.1. User and System Requirements Investigation: Interview Questions

A.4.1.1. Identifying and understand RM's maintenance practices

1. What mechanisms and systems are presently available for storing sharing and communicating maintenance information, amongst members of staff at Royal Mail, e.g., word of mouth and electronically?
2. What maintenance approaches are presently undertaken by maintenance staff, e.g., preventative, corrective, and predictive?
3. Are maintenance staff appreciative of different maintenance approaches, and do you think it matters?
4. Do you differentiate between maintenance tasks, and therefore schedule maintenance according to whether maintenance is preventative, corrective or predictive?
5. How is maintenance information recorded presently?
6. Do different members of staff involved with maintenance activities record maintenance information in different locations, using different techniques, e.g., maintenance engineers, operations managers, operators, and technologist?
7. In what situations and environments do individuals find themselves in, where they might want to record or have access to maintenance information?
8. Do all Royal Mail staff likely to require access to a CMMS, either for storing or accessing digitised information, possess the necessary computer literacy to easily familiarise themselves and use a typical software (Microsoft application) user interface or web site user interface?
9. How much internal computer system familiarisation training is provided to maintenance engineers, operators and operation managers and other staff likely to require access to the companies maintenance computer systems?

10. What specific user options would you expect to see incorporated within a CMMS user interface?

A.4.1.2. Integration design and development questions associated with SAP and CBM

1. Can information from the automatic data capture (ADC) system be accessed and displayed through the SAP system?

2. Would it be possible to take a copy (screen dump) of some of the modified SAP SDMM screens, e.g., Asset Care, malfunction reporting, and maintenance reporting?

3. Are you aware of future initiatives associated with the use of mobile devices, e.g., products from Blackberry or other PDAs, being introduced into Royal Mail in the near future?

4. Is the SAP system integrated with any other computer system within Royal Mail?

5. How do SAP SDMM request modifications filter down to your department, and how quickly are modification requests verified, accepted and completed?

6. How do you differentiate between modification requests suitable and applicable to the majority of Royal Mail's users, and those applicable to a single or a small group of individuals?

7. In the future will it be possible to link information stored as a malfunction report on the SAP system with information stored on a CBM computer system. This might be achievable by incorporating a link from one computer application to another, or involve the extraction and export of data from one computer system into another?

8. How do you envisage question 7 being made possible?

9. Do you have any views as to whether a link between SAP SDMM and a CBM system is necessary?

10. Why is the response time of the SAP SDMM system so slow?

11. Are any data records resulting directly or indirectly from remote diagnostics of IMP machines entered or automatically generated and stored in the SAP system?

12. If accuracy and relevance of the information entered into the ES-SDMM is improved, maintenance performance analysis routines can be performed more effectively. What would be your reply to this comment?

A.4.1.3. Understanding RM's maintenance practices, and identifying user requirements for a CBM systems method of HCI

1. Am I right in saying the only individuals who request access to maintenance information include:
    - Maintenance Engineers
    - Automation Performance Engineers (Maintenance Team Leaders)
    - Maintenance Managers
    - Regional Maintenance Managers
    - Operational Managers
2. Am I correct with my identification of the types of information each maintenance staff member requires access to, as listed below:

    i. Maintenance information that could prove useful in assisting a Maintenance Engineer complete his/her job:·

    - An indication of a machines present condition in comparison to an accepted normal state of operation.
    - An indication of a machines present condition in comparison to historical performance records.
    - An indication as to the likely hood of a machines breakdown, or an indication of the level of urgency before a machine requires maintenance.
    - A predicted time period before machinery should be stopped for maintenance or repair work.
    - A prediction of the maintenance work (corrective action) that would be required if a machine fell outside accepted operating conditions, along with a prediction of the identified (likely) failed or failing substance, equipment, or machinery.

- Anticipated consequential effects to other components or machinery or plant or the business, resulting from the identified failing substance, equipment, or machinery. For example, if the bearings seize up inside a generator, it would not only stop the generator but could also cause multiple other component failures.

ii. Maintenance information that could prove useful in assisting a Maintenance Team Leader complete his/her job:

- Information that depicts a machines changing condition with time, e.g., a graphical display of a machines live moving condition plotted between predetermined acceptable control limits.
- Historical CBM data presented as a comparison against operational performance figures for mail sorting lines; operational performance figures extracted using the IMP automatic data capture system, and LSM NEIDS performance measurement systems.
- The number of CBM system alerts generated between predefined periods of time.

iii. Maintenance information that could prove useful in assisting Maintenance Managers complete his/her job:·

- Information that provides the opportunity to compare machinery condition based upon historical CM data, against mail sorting line performance figures, as mentioned above in information of use for APEs.
- Knowing what type of maintenance work and what resources will be required to repair a predicted diagnostic cause, once CBM systems indicate machinery needs to be stopped for maintenance.
- A measure of a machines useful operating time between maintenance intervals as indicated or deduced from CM equipment.

iv. Maintenance information that could prove useful in assisting Operational Mangers complete his/her job:

iv. Notification of equipment breakdowns and an explanation as to why machinery has stopped or is not available for operation.

v. Information that provides an indication of the condition of equipment and machinery being monitored

3. Are password and username authentication used by Royal Mail staff to gain entry to any of the different computer systems used for maintenance?

4. Do different users have different access rights to the same system, but at a higher level?

5. Do maintenance staff have experience at analysing and assessing machinery performance based on statistical data?

6. Is the use of SAP still an issue of contention, as far as administrative time is concerned?

7. Are maintenance staff in general speeding up with their SAP SDMM entries, as they become familiar with its use?

8. Have all the ACS maintenance tasks been entered onto the SAP system?

9. Would you anticipate a CBM system integrating with the SAP computer system?

10. Is SAP used for managing inventory control, including stock reordering, and do maintenance staff perform this function at any time?

11. Other than HWDC are any other mail centres likely to adopt a wireless system for automatically updating the SAP or HolisTech systems, as maintenance work is completed?

12. Do you think the mechanical components being investigated for CBM system use are all valid and sensible?

13. Other than those areas up for consideration for CBM, can you suggest any other situations where CBM might prove effective in the maintenance and up keep of mail sorting machinery?

14. Do you believe it would be acceptable for an ACS works order to be automatically generated on the command of a CBM systems request?

15. What locations could you envisage maintenance staff being in who might want to gain access to CM information?

16. What type of information would you expect incorporated in a CBM report?

17. What type of alarms would you consider acceptable within the mail centre environment, for use by CBM systems. Alarms would be triggered on the detection of out of limit machinery conditions, or variations from accepted normal operating conditions?

18. In what format/medium would you expect CBM reports to be communicated to users?

A.5. CBM GUI CONCEPTUAL DESIGN

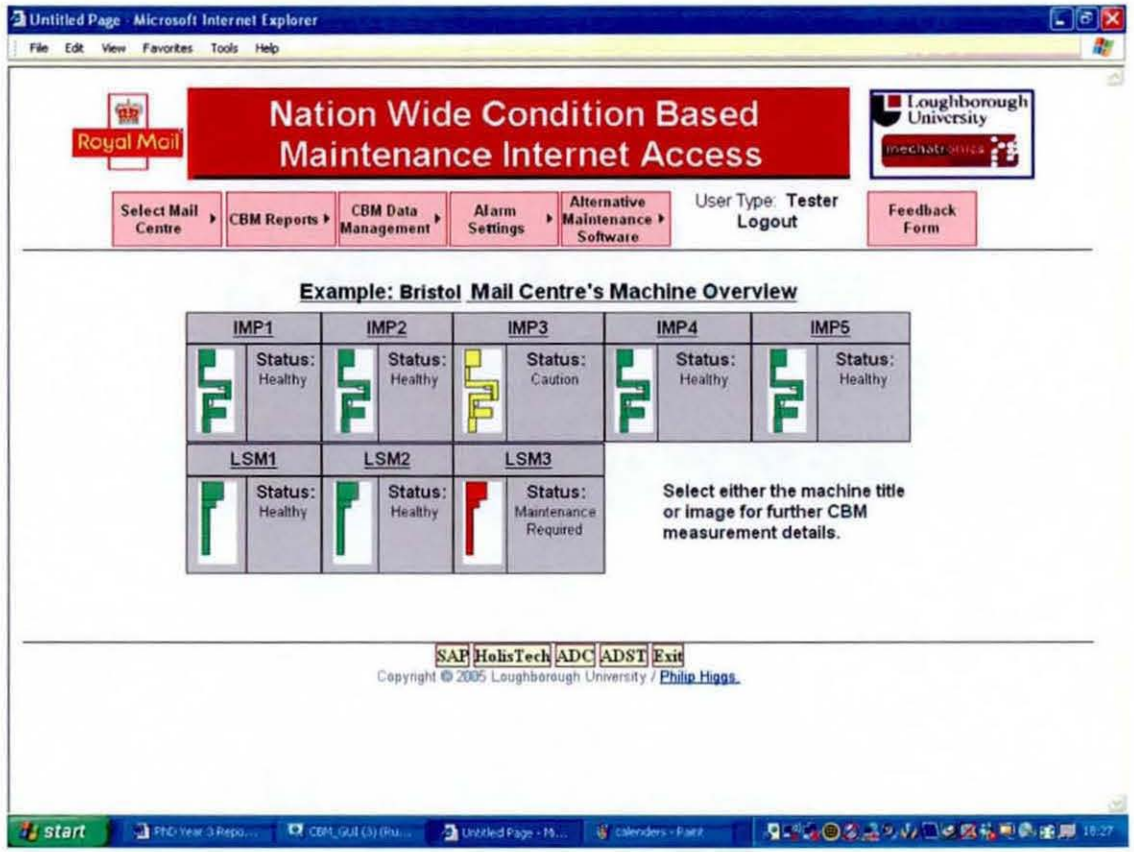


Figure A.5.1. Mail centre machine condition overview web page.

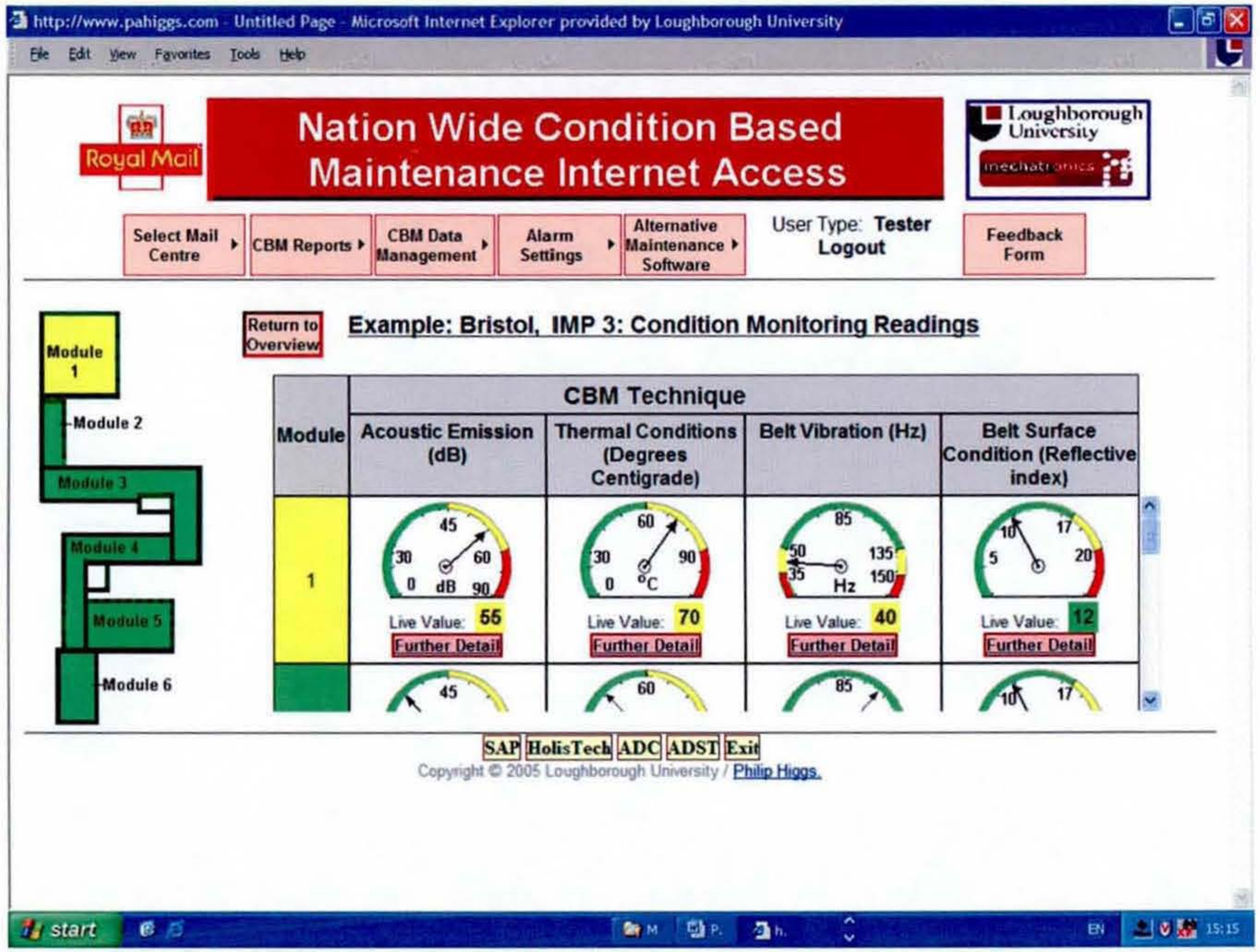


Figure A.5.2. Machine module condition overview web page.

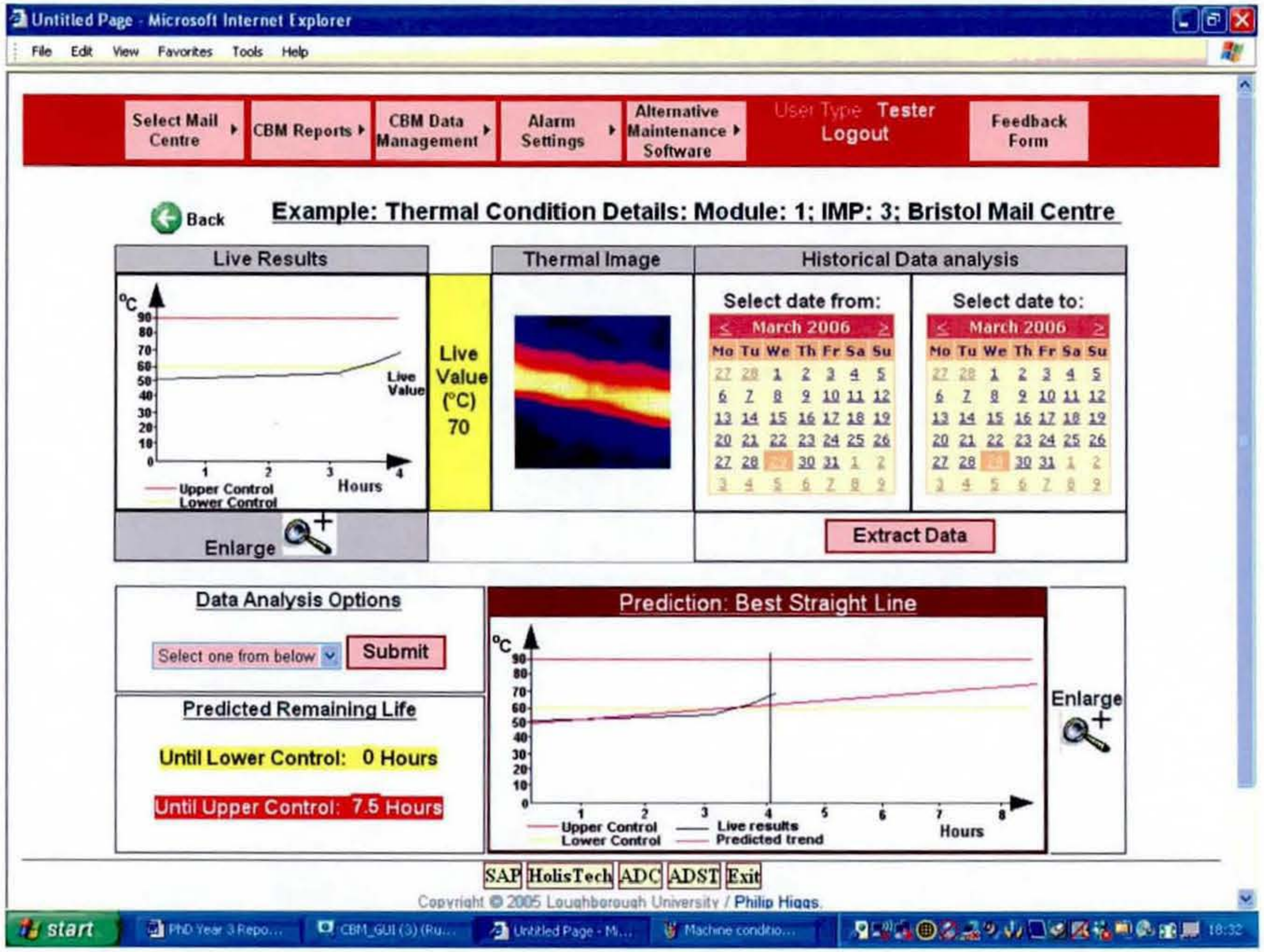


Figure A.5.3. Component condition health status web page.

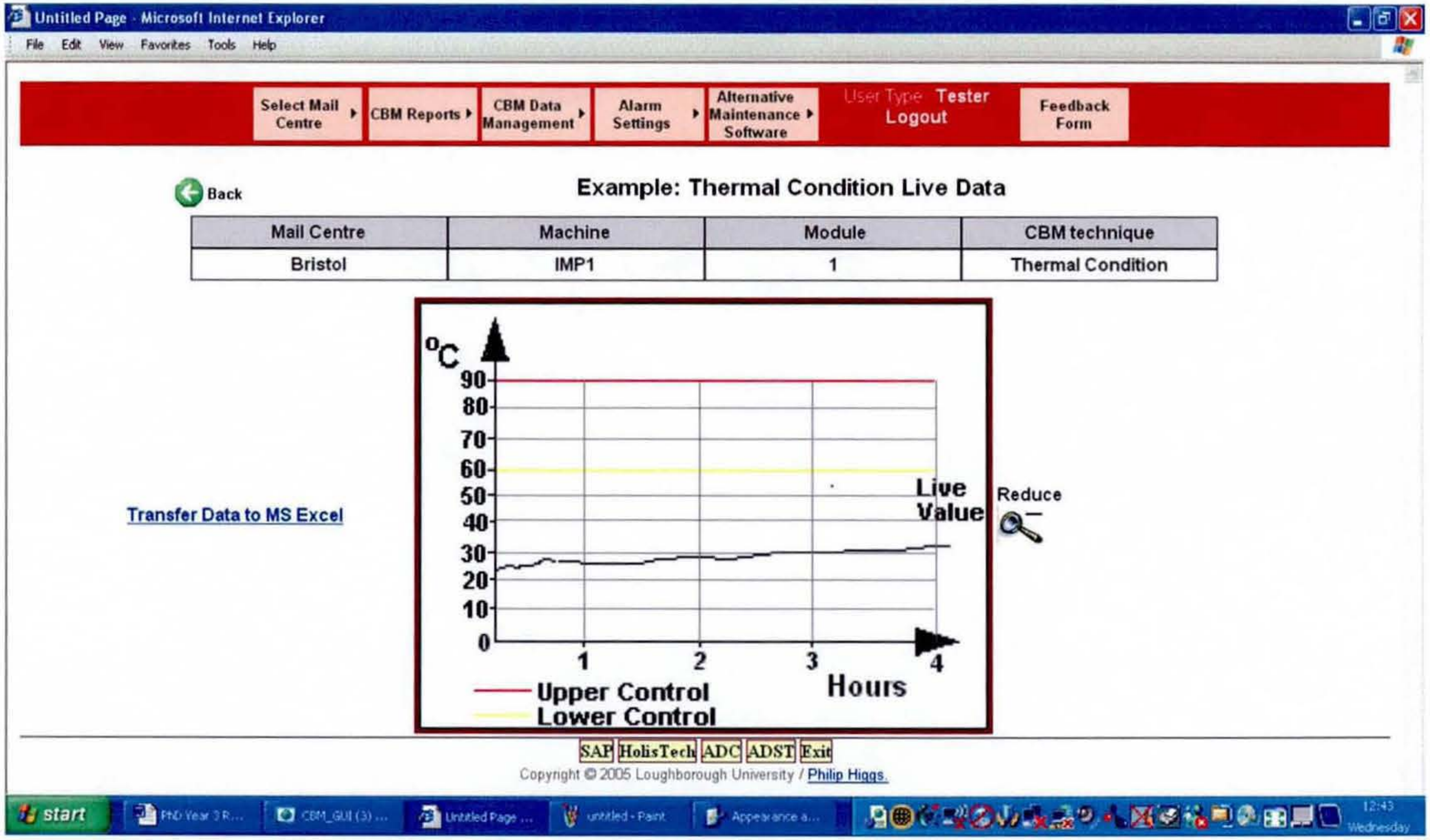


Figure A.5.4. Enlarged live results graph.

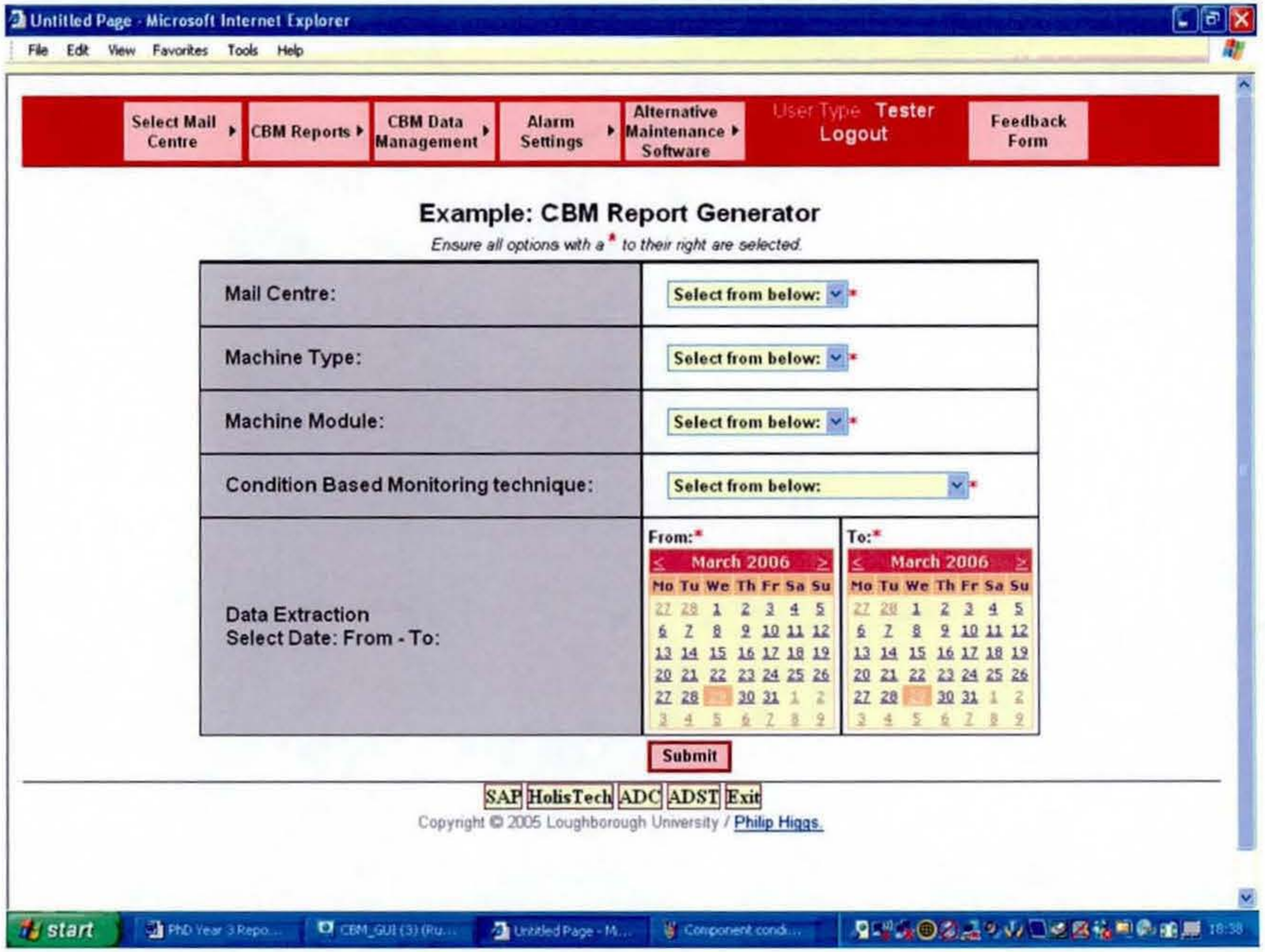


Figure A.5.5. CBM report generator web page.

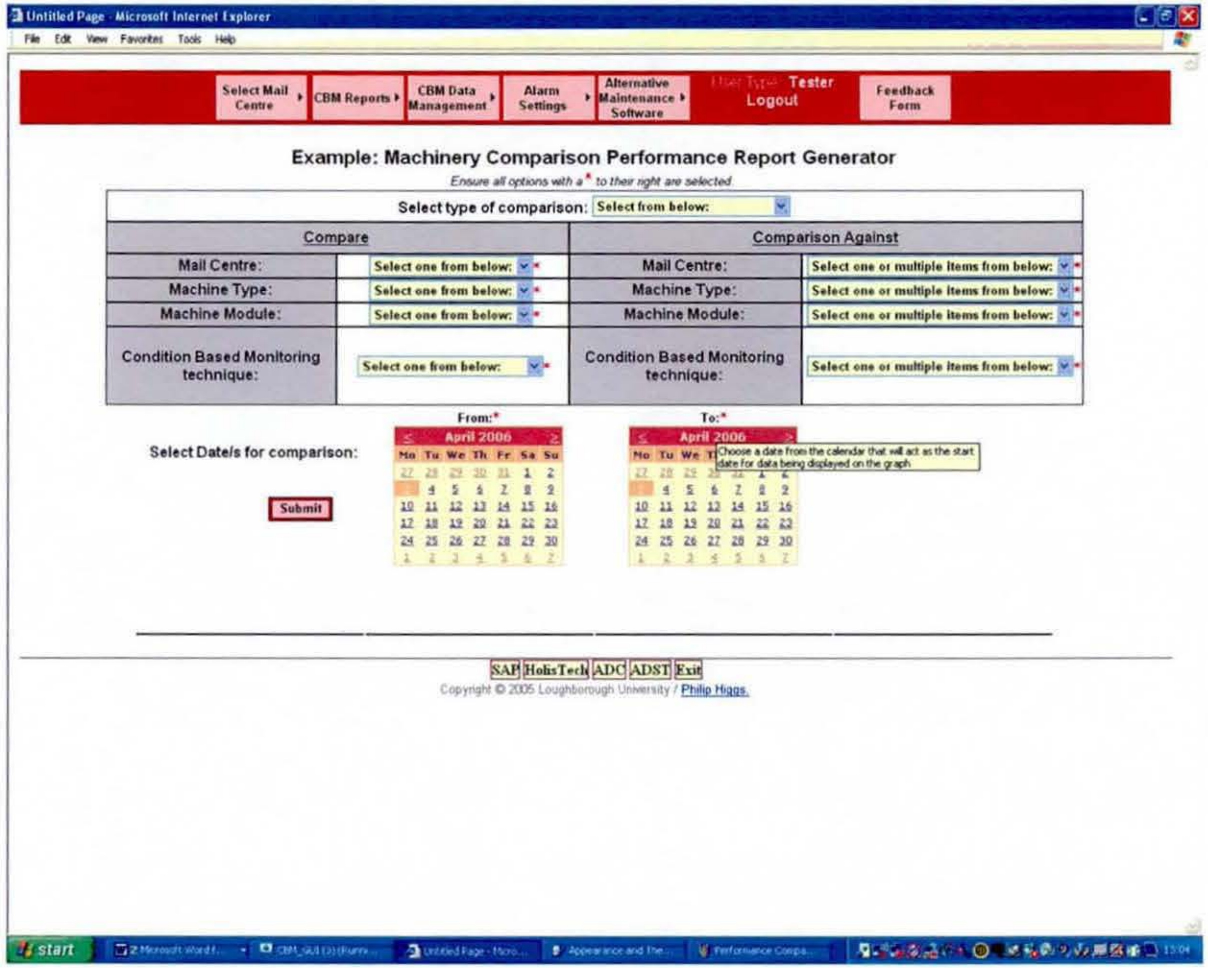


Figure A.5.6. Machinery comparison performance report generator web page.

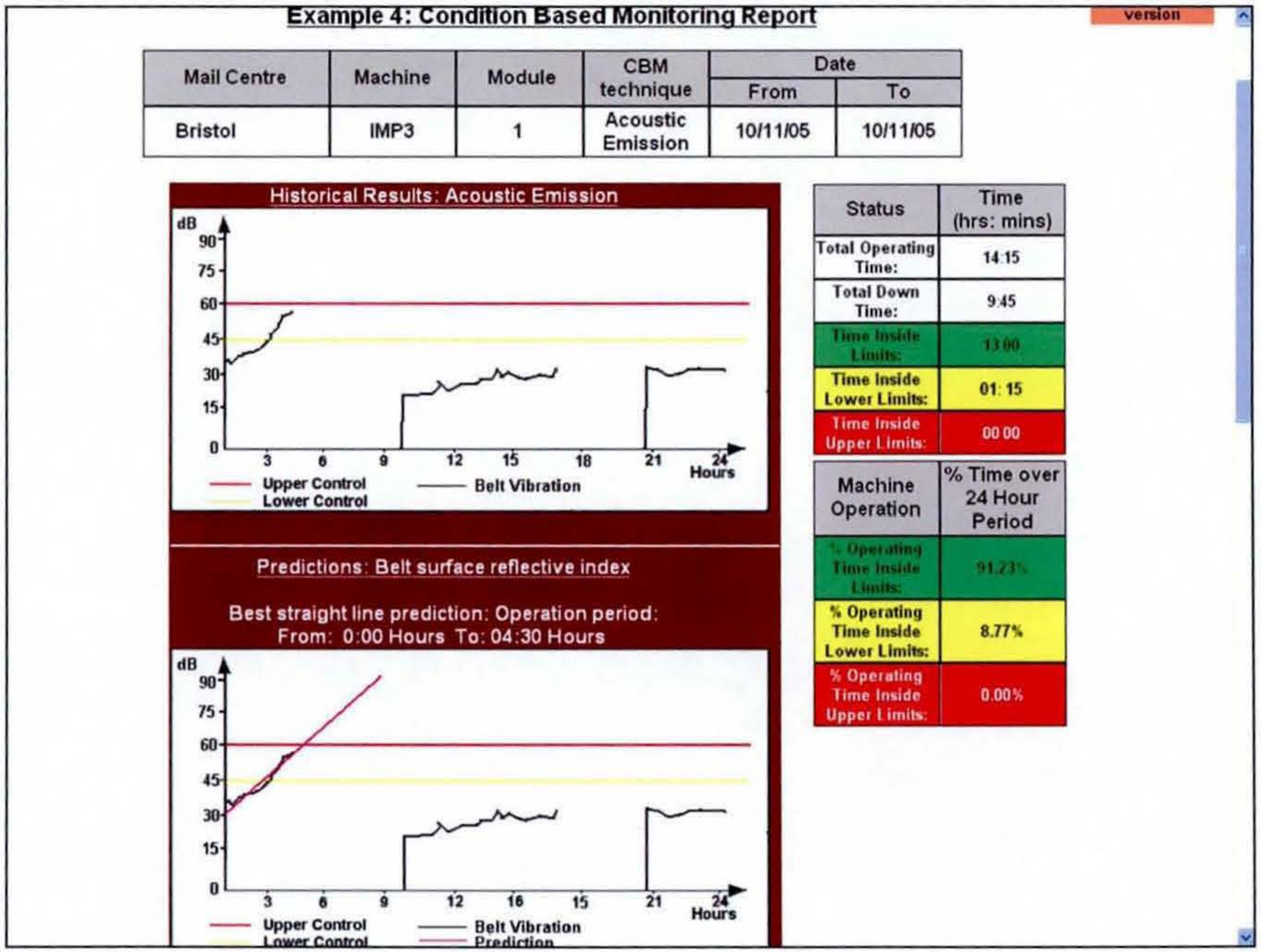
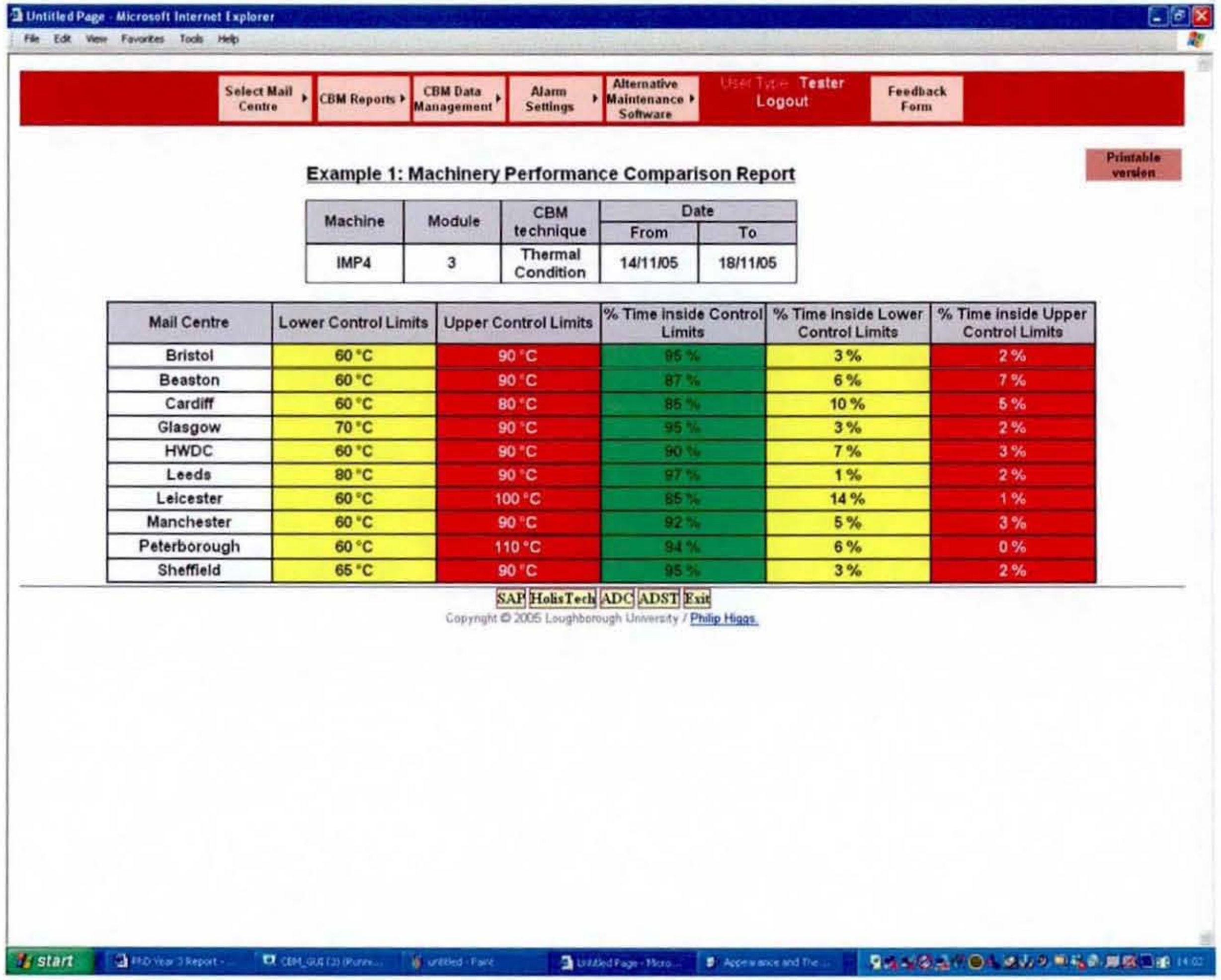


Figure A.5.7. CBM report example.



Machine	Module	CBM technique	Date	
			From	To
IMP4	3	Thermal Condition	14/11/05	18/11/05

Mail Centre	Lower Control Limits	Upper Control Limits	% Time inside Control Limits	% Time inside Lower Control Limits	% Time inside Upper Control Limits
Bristol	60 °C	90 °C	95 %	3 %	2 %
Beaston	60 °C	90 °C	87 %	6 %	7 %
Cardiff	60 °C	80 °C	85 %	10 %	5 %
Glasgow	70 °C	90 °C	95 %	3 %	2 %
HWDC	60 °C	90 °C	90 %	7 %	3 %
Leeds	80 °C	90 °C	97 %	1 %	2 %
Leicester	60 °C	100 °C	85 %	14 %	1 %
Manchester	60 °C	90 °C	92 %	5 %	3 %
Peterborough	60 °C	110 °C	94 %	6 %	0 %
Sheffield	65 °C	90 °C	95 %	3 %	2 %

Figure A.5.8. Machinery comparison performance report.

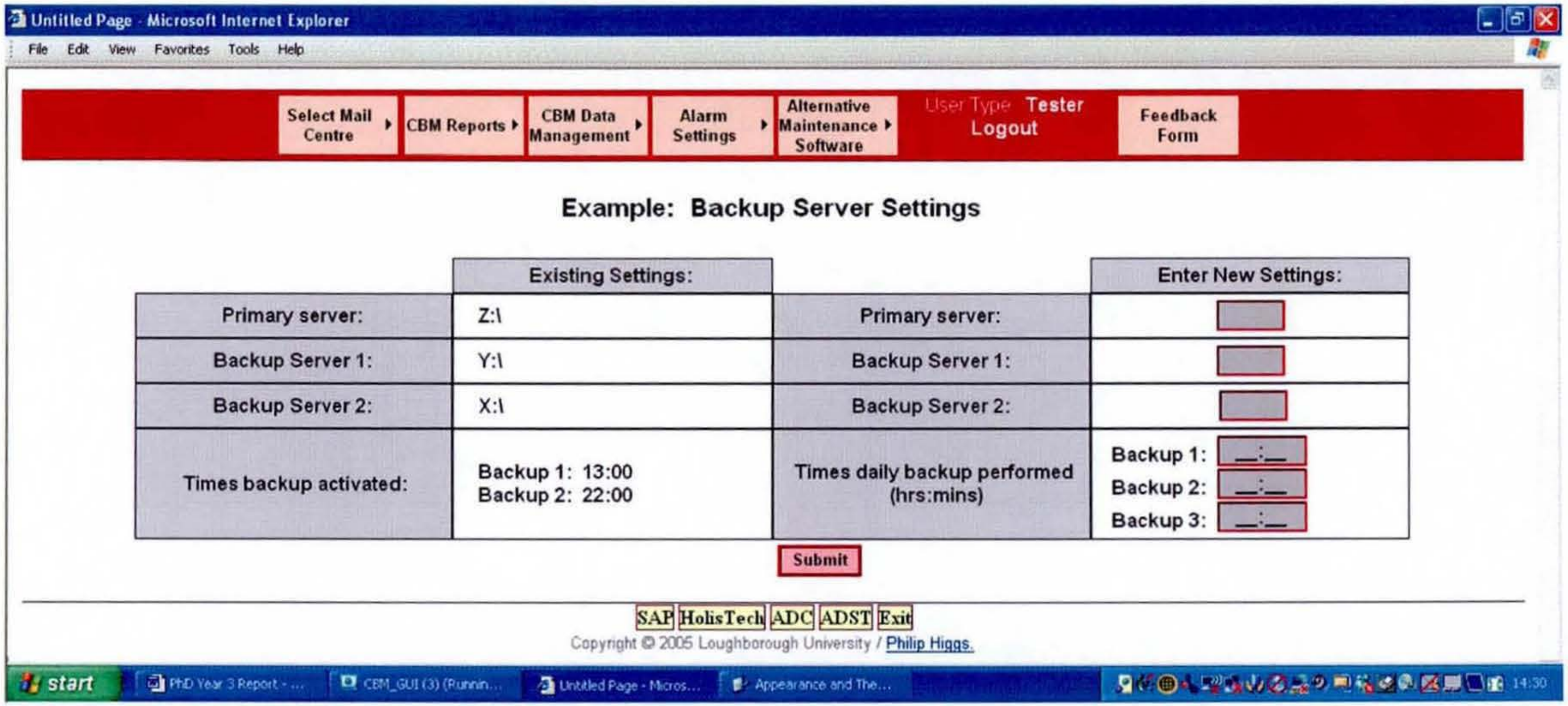


Figure A.5.9 Backup server settings web page.

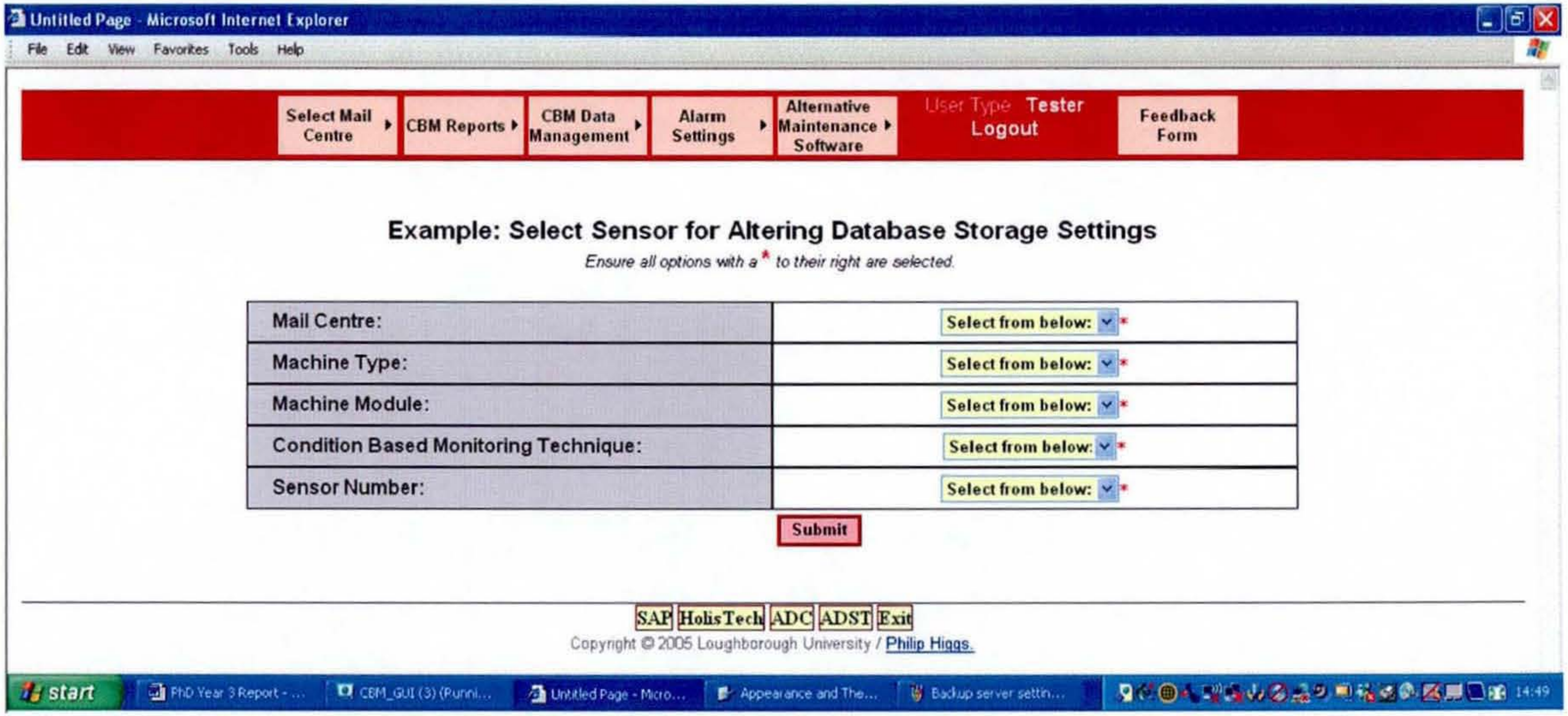


Figure A.5.10 Database storage settings CM sensor selector web page.

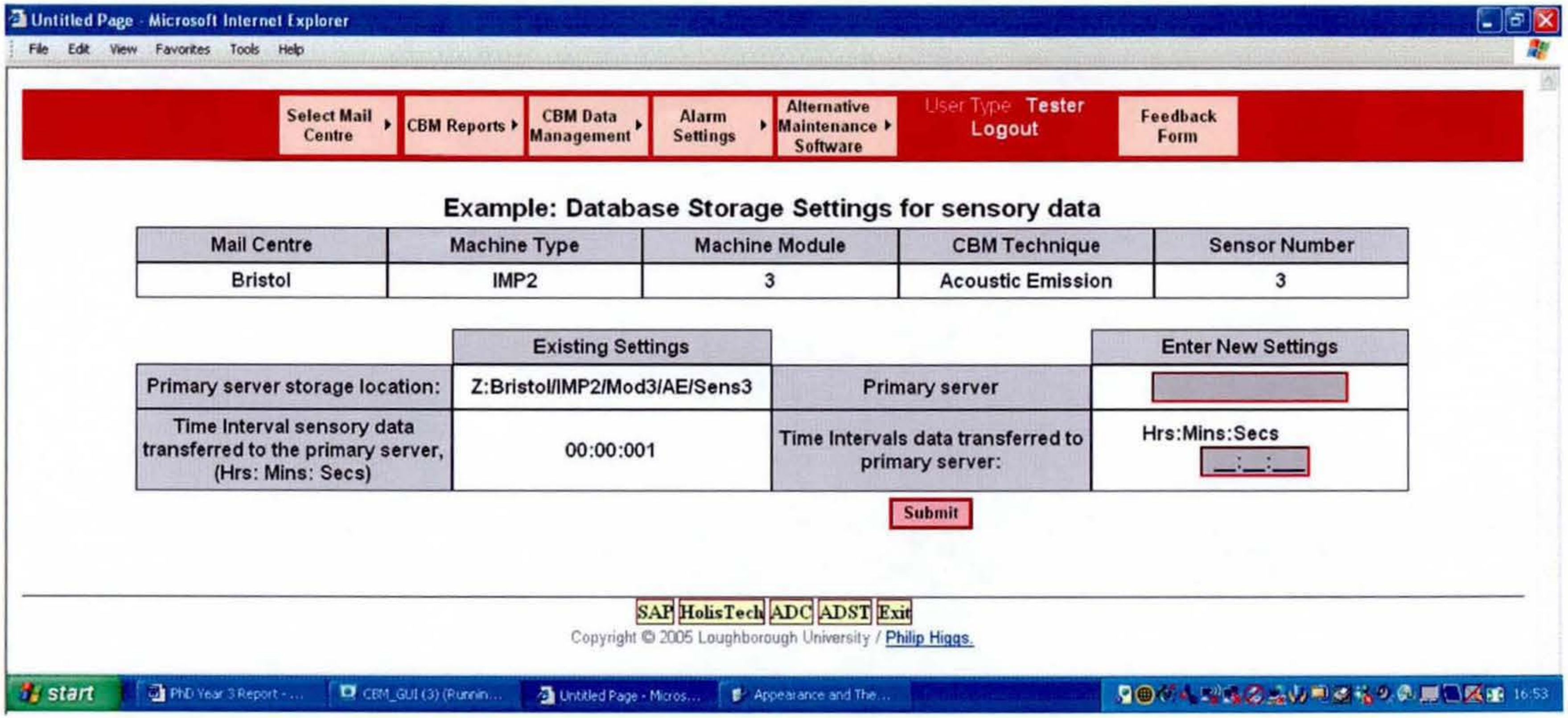


Figure A.5.11 CM sensory database storage settings web page.

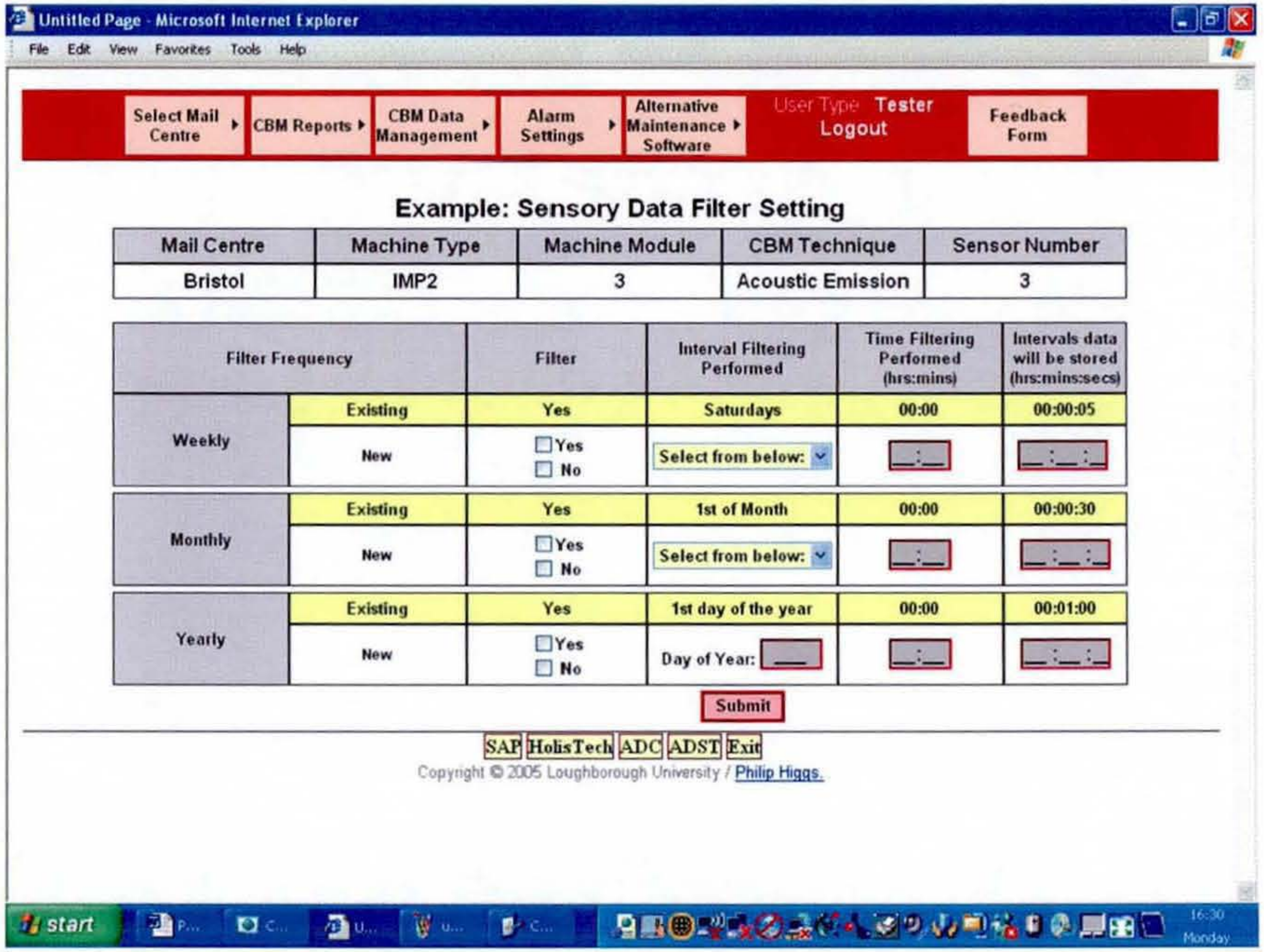


Figure A.5.12 CM sensor data filter settings web page.

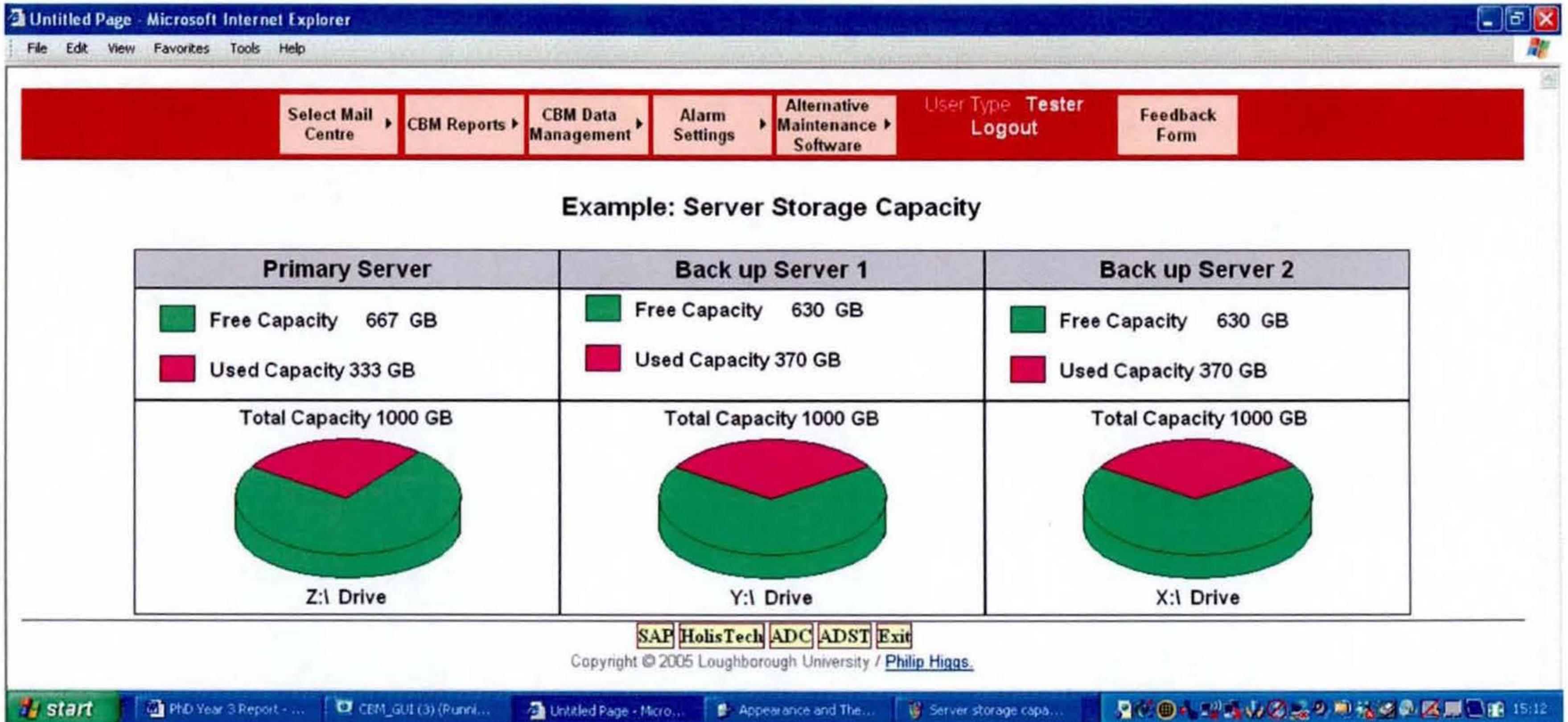


Figure A.5.13 Server storage capacity web page.

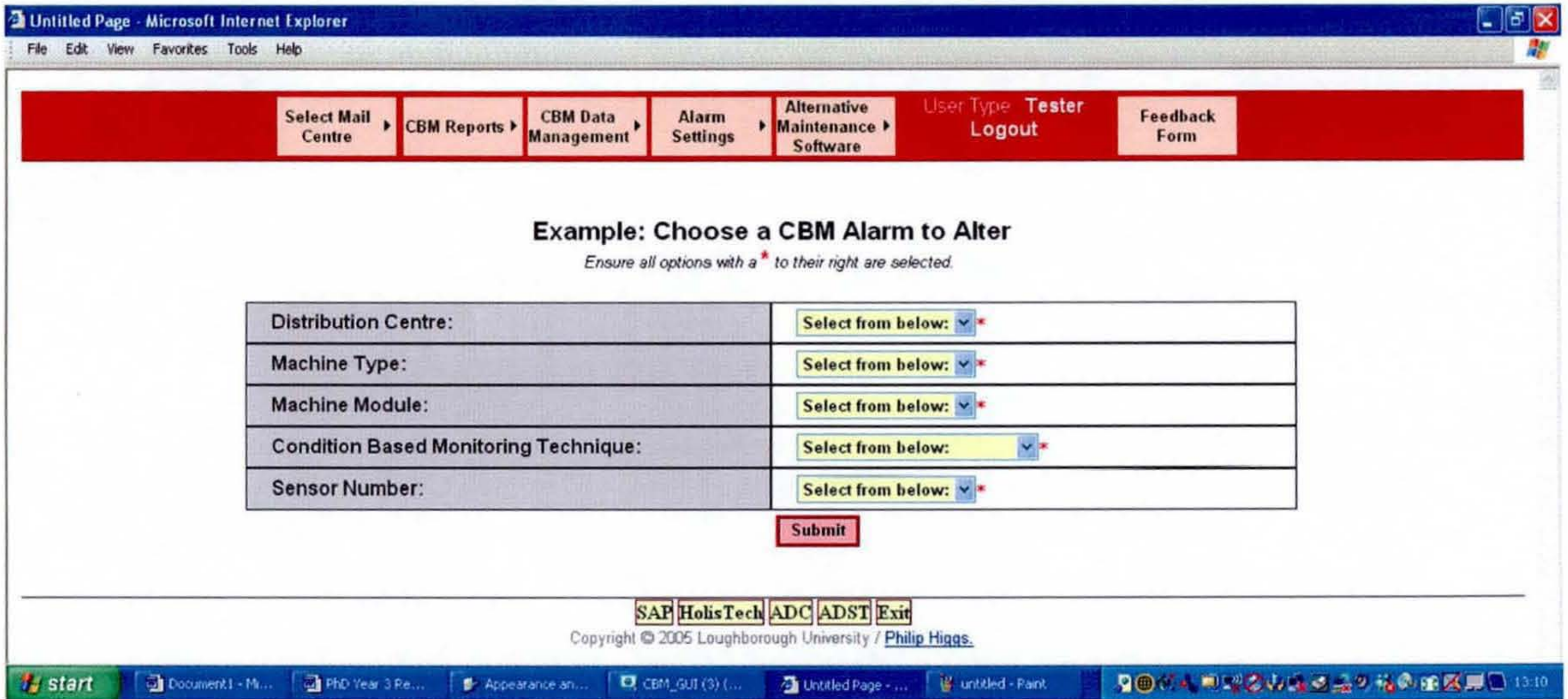


Figure A.5.14. CM alarm selector web page.

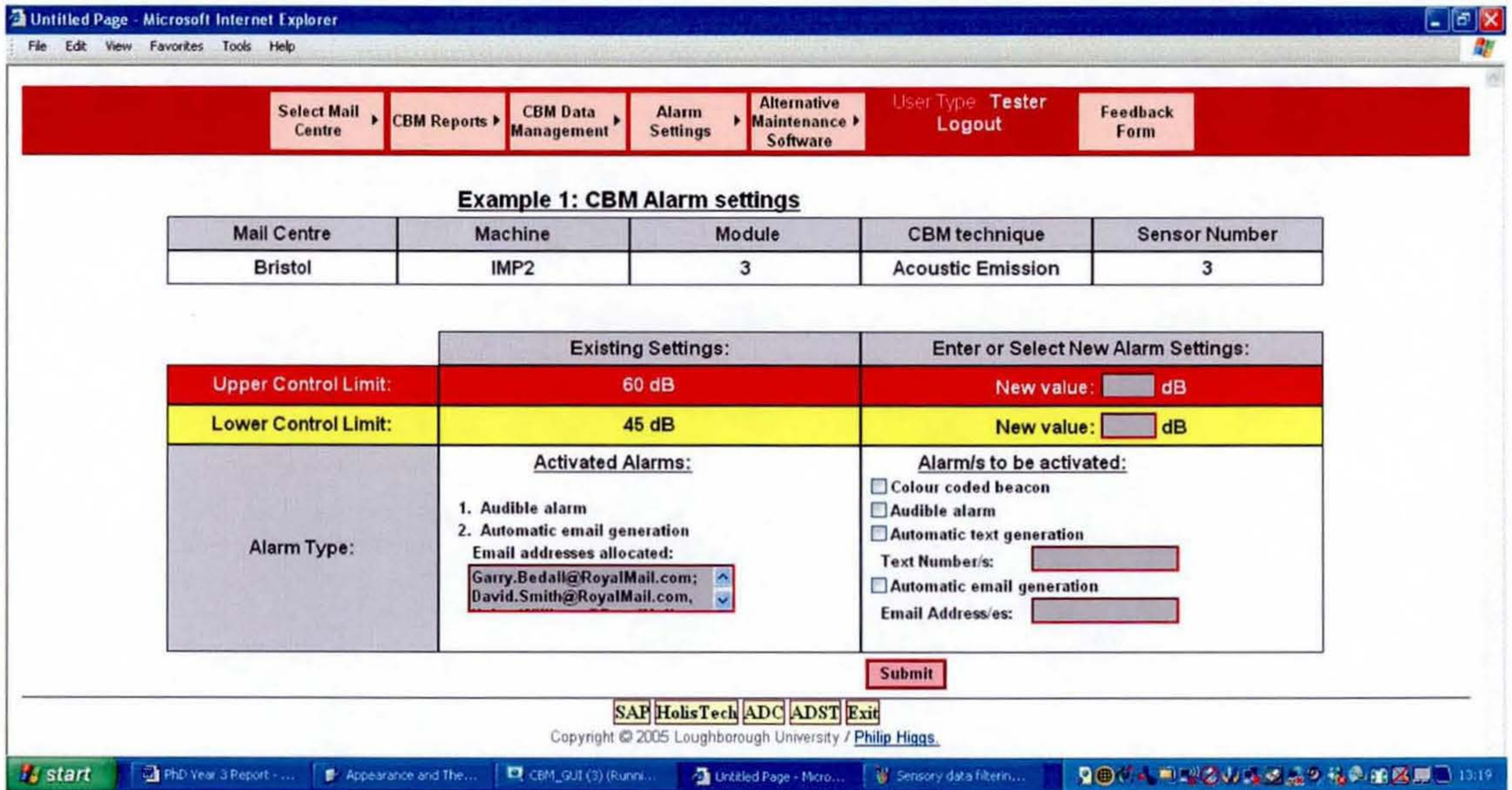


Figure A.5.15. CM alarm settings web page.

A.6. USABILITY EVALUATION

A.6.1. Conceptual Design feedback form

1. Information contained in the web site is easy to interpret?
   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

2. The data archive and backup features incorporated in the web site are essential?
   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

3. The 'CBM Report' examples contained in the web site are easy to interpret?
   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

4. The web site makes good use of graphs and tables to represent machinery/component condition?

   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

5. The web site demonstrates suitable use of password and user name authentication?

   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

6. The web site displays machinery condition information clearly with sufficient structure?

   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%
   - ☐ Disagree: 25-50%
   - ☐ Strongly disagree: 0-25%
   - ☐ No Comment or Do Not Know

   Any Other Comment

7. The web site is visually appealing making it desirable for use as a CBM GUI?

   - ☐ Strongly Agree: 75-100%
   - ☐ Agree: 50-75%
   - ☐ An average amount: 50%

☐ Disagree: 25-50%

☐ Strongly disagree: 0-25%

☐ No Comment or Do Not Know

Any Other Comment

8. The language used in the web site is fit for purpose and legible?

☐ Strongly Agree: 75-100%

☐ Agree: 50-75%

☐ An average amount: 50%

☐ Disagree: 25-50%

☐ Strongly disagree: 0-25%

☐ No Comment or Do Not Know

Any Other Comment

9. The navigation technique incorporated in the CBM web site is easy to follow and efficient?

☐ Strongly Agree: 75-100%

☐ Agree: 50-75%

☐ An average amount: 50%

☐ Disagree: 25-50%

☐ Strongly disagree: 0-25%

☐ No Comment or Do Not Know

Any Other Comment

10. Providing access to data from multiple CM techniques through one GUI, as demonstrated in this web site is a good design solution?

☐ Strongly Agree: 75-100%

☐ Agree: 50-75%

☐ An average amount: 50%

☐ Disagree: 25-50%

☐ Strongly disagree: 0-25%

☐ No Comment or Do Not Know

Any Other Comment

11. The design ideas incorporated in this CBM GUI web site could be easily tailored to meet other customer requirements?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

12. The capability to integrate with other computer systems demonstrated in this web site is a useful design feature?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

13. The web site demonstrates clearly the use of colour coding to reflect machinery condition?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

14. It would be useful if the web site incorporated manual controls to enable users to manually alter the web sites appearance and feel, to suite a users personal requirements?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

15. The web site appears to follow acceptable Graphic User Interface design rules?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

16. The web site demonstrates good use of text fonts and text size?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

17. The web site makes adequate use of graphic icons?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%

- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

18. The web site appears to be user friendly, logical and easy to operate?
    - ☐ Strongly Agree: 75-100%
    - ☐ Agree: 50-75%
    - ☐ An average amount: 50%
    - ☐ Disagree: 25-50%
    - ☐ Strongly disagree: 0-25%
    - ☐ No Comment or Do Not Know

    Any Other Comment

19. The web site communicates machinery condition deviations from acceptable values to users clearly and rapidly?
    - ☐ Strongly Agree: 75-100%
    - ☐ Agree: 50-75%
    - ☐ An average amount: 50%
    - ☐ Disagree: 25-50%
    - ☐ Strongly disagree: 0-25%
    - ☐ No Comment or Do Not Know

    Any Other Comment

20. The images and graphics used to represent and communicate a machines condition are acceptable?
    - ☐ Strongly Agree: 75-100%
    - ☐ Agree: 50-75%
    - ☐ An average amount: 50%
    - ☐ Disagree: 25-50%
    - ☐ Strongly disagree: 0-25%
    - ☐ No Comment or Do Not Know

Any Other Comment

21. Data analysis features incorporated in the web site are essential for a CBM GUI?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

22. The capability to make machinery condition predictions demonstrated in the web site are appropriate and adequate?

- ☐ Strongly Agree: 75-100%
- ☐ Agree: 50-75%
- ☐ An average amount: 50%
- ☐ Disagree: 25-50%
- ☐ Strongly disagree: 0-25%
- ☐ No Comment or Do Not Know

Any Other Comment

23. Any other comments. Optional request.

24. Company Name. Optional request.

25. Contact Email Address. Optional request.

A.6.2. Comparing proposals for CBM Software Design and Development Rules/Guidelines Against Conceptual Design Ideas.

Proposals for CBM software design and development rules/guidelines	Included in the conceptual design	Recommendation for design improvement
Design CBM software GUIs with correct interpretability of CM information leading to accurate maintenance decisions in mind.	Yes	Yes
Design CBM software with a selection of data analysis capabilities, suited to the CM technique being employed.	Yes	Yes
Incorporate a data archiving feature as an option in CBM software.	Yes	Yes
Design CBM reports with look, feel and interpretability in mind.	Yes	Yea
Design CBM software to present condition parameters graphically, i.e., using charts and graphs.	Yes	Yes
Design CBM software to incorporate maintenance and malfunction report generation capabilities, so CM information can be presented using performance reports.	No	Yes
Design CBM software to incorporate password and user name authentication.	Yes	No
Design CBM software using reliable, quality programming techniques and standards.	NA	N
Consider screen structure and information classification whilst designing CBM software GUIs.	Yes	Yes
Design CBM software to incorporate visually appealing GUI screens.	Yes	Yes
Use appropriate language that is legible to the intended audience in the CBM software GUI.	Yes	Yes
Design the structure of CBM software to incorporate windows.	No	Yes
Take into account the CM technique being employed when designing the CBM software.	Yes	No
Provide easy to use navigation techniques in the CBM software's GUIs.	Yes	Yes
Design CBM software GUIs to incorporate drop down menus.	Yes	No
Take into account networking and integration opportunities and requirements whilst designing the CBM software.	Yes	No
Anticipate having to tailor CBM software to users/customers requirements.	Yes	Yes
Design the CBM software with the intended functionality of the CBM system in mind.	Yes	Yes

Table A.6.1 Continued on next page:-

CBM software design and development rule/guideline	Included in the conceptual design	Recommendation for design improvement
Design the CBM software to satisfy the intended audiences requirements.	Yes	Yes
Design CBM software GUIs to incorporate colour coding to reflect machinery condition.	Yes	No
Design CBM software GUIs to make use of tables where appropriate.	Yes	No
Provide users with the ability to control the appearance and functionality of CBM GUI control features.	No	Yes
Use text size and font type appropriately in CBM software GUIs.	Yes	Yes
Take into account environmental issues, e.g., location of displays / monitors.	Yes	No
Whilst designing CBM software follow recognised GUI design rules.	Yes	No
Use icons and icon design appropriately in CBM software GUIs.	Yes	Yes
Provide software design features enabling data to be exported or imported between a CBM software application and other software applications.	No	Yes
Design CBM software GUIs to be user friendly logical and easy to operate, e.g., out of box user friendly, easy to use navigation techniques.	Yes	Yes
Design an urgent method of communicating machinery defects and deviations from acceptable trends into CBM software GUIs and other media.	Yes	Yes
Design CBM software to enable users to access CM information through Internet web pages.	Yes	No
Consider the after sales support, including maintenance, and software upgrades, at the design and development stages of a CBM software application.	No	No
Design CBM software to automatically distinguish and represent machinery condition according to the criticality before anticipated failure. Take into account the level of importance the machine being monitored represents if it fails and is unable to function.	Yes partly	Yes
Design the CBM software to receive and process data from multiple different types of CM techniques, and multiple machines.	Yes	No
Provide automated data screening and automated fault diagnostics into CBM software.	No	Yes
Consider the marketing and sales strategies anticipated at the design and development stages of a CBM software application.	No	No
Design CBM software to align with the major ICS software applications.	No	No
Incorporate an error protection feature for back stepping through user actions within the CBM software's GUIs.	No	No
Use 3D representation of machinery and machinery condition in CBM software GUIs.	No (Used 2D)	Yes for 2D
Provide users with an ability to make a selection from a group of GUIs. This selection might include user interfaces designed specifically for a particular operation or designed for a specific user group.	No	Yes

Table A.6.1 Continued on next page:-

CBM software design and development rule/guideline	Included in the conceptual design	Recommendation for design improvement
Incorporate a feature within the CBM software for automatic machinery identification verification.	Yes	No
Design the CBM system to operate through a single central database.	Yes	No
Design CBM software GUIs to present machine condition information in a self-explanatory format and media.	Yes	Yes
Providing statistical analysis tools within the software, i.e., for defining frequency bands for analysis purposes and standard control charts for each frequency band.	Yes partly	No

Table A.6.1. Comparison of proposals for CBM software design and development rules and guidelines against design features incorporated in the conceptual design.

A.6.3. Comparing User Requirements Against Conceptual Design Ideas

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
Accurately judge the amount of time sorting machinery can be reliably operated, before it needs to be stopped for maintenance.	Yes	No (Yes indirectly)	None
Automatically recognise anticipated component/assembly failure signatures, and generate an alarm system designed to notify ASMEs or MSTL.	Yes	No	29
Knowing or anticipating how sorting machinery will perform during known periods of high mail volume.	No	Yes	None
ASME, MSTL, and MTL ideally want a maintenance scheduling system that prioritises maintenance tasks and provides an indication of the time available to complete the task.	No	Yes	6
If a CBM system is to be accepted, it must enable maintenance engineers to identify deteriorating equipment and machinery conditions as they arise; and assist them determine what corrective action should be taken to resolve the problem. Having completed maintenance actions suggested by CBM systems, maintenance personnel must witness the machinery move back into acceptable operating conditions, if their confidence is to be gained.	Yes partly	Yes	1 and 29
Compare the condition of sorting machinery against machinery performance. Such comparisons open the way forwards to improving maintenance scheduling, identifying substandard components, and optimising operational conditions to maximise component life expectancy.	No	Yes	None
Suggest possible causes for deterioration in component/assembly condition.	No	Yes	1
Provide help assistance on predictive maintenance practices and CBM systems on the ADST Royal Mail web site.	No	No	None
Integrate CBM systems with other maintenance systems other than SAP SDMM, e.g., HolisTech and ADC.	Yes partly	Yes	16 and 27
Enable CBM systems to transfer or export data into SAP SDMM. Doing so will enable ACS to be automatically generated as a consequence of a CBM system detecting out of tolerance conditions, or erratic operating condition movements.	No	No	16 and 27

Table A.6.2 continued on next page:-

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
Provide the functional capability to export data generated by CBM systems, for analysis against IMP and LSM performance data. Such a capability presents the opportunities to compare equipment condition against overall machinery performance.	No	Yes	16 and 27
The capability to export CM data into MS Excel spreadsheets for personal data analysis calculations.	Yes	Yes	16 and 27
CBM system implementation on an organisational level should be networked (integrated) country wide, enabling like for like machinery Condition Monitoring comparison.	Yes	Yes	16
Associate causes of failure with existing known and understood causes of failure, e.g., bearing vibration = noise; worn bearing = increased pulley temperature; Loose belt = increased belt vibration; Loose belt = a need for tensioning or belt elasticity failure; worn belt = shinny surface = reduction in address read rate, etc.	No	Yes indirectly	1
ACS works order requests generated automatically by a CBM system, should be inspect a specific machine or component, rather than change or repair a component or subassembly. Inspection is a more realistic proposal because detected machinery condition deterioration, might be the result of knock on factors from other equipment and parts, within a machines integrated system.	No	No	None
You would need to identify a bench mark set of conditions from which to compare all follow on condition sets, during machinery operation. Benchmark machinery operating conditions should be selected to take into account different types of mail, different mail sorting volumes flowing through the pipeline, and different atmospheric conditions.	No	Yes	None
CBM systems designed to monitor electric motors should be designed to take into account increased torque and possibly increased temperature, during machine start up and possibly when processing high volumes of mail, for long durations or mail items that create a lot of friction as they are processed	No	No	None
You must identify what your CBM system will measure and then determine the best technique to represent and present the information, as a measure of the machines condition.	Yes	No	1, 17, 18 and 19
Provide a facility for displaying the number of CBM system alerts generated within a user selectable periods of time, for one or more sorting machines.	No	Yes	None

Table A.6.2 continued on next page:-

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
A CBM system should sell itself if it is to be accepted at RM, i.e., it must be seen as having a purpose, otherwise it will fail.	No	No	None
Response time of the CBM system in all its functions, should not exceed user accepted patients levels, e.g., approximately 5 to 10 seconds for adults. If response times do exceed these levels, a suitable message should be displayed on the screen informing users to be patient. Such an event might occur when a time-consuming data analysis feature is activated.	Yes	No	None
Identify all critical equipment CBM predictive maintenance practices, would prove more effective than preventative maintenance practices, e.g., reduce asset costs and lengthen machinery longevity. More opportunities exist for predictive maintenance initiatives using CBM at HWDC than any other mail centre. HWDC differs from all other mail centres because it incorporates more machinery of an automated nature, in more combinational mixes than any other.	No	Yes partly	None
Provide access to every computerised maintenance system presently used by Maintenance Engineers, through one common user interface.	Yes	No	16
Design methods of HCI to be as simple as possible.	Yes	No	17, 19 and 28
Display CM information in a numerical format using understandable units on CBM GUIs, and on printable reports. e.g., motor temperature, bearing vibration levels, belt tension or belt speed.	Yes	No	4
Present data analysis results in a format that can be easily learned, correctly interpreted, and used to guide maintenance decisions.	No	Yes	2
Include Pareto analysis as a data analysis technique within a CBM software.	Yes	No	None
Provide the option for presenting equipment wear rates as a linear graphical representation.	Yes	No	None
Use diagrammatical methods to represent the condition of each module incorporating CM equipment, for each IMP, within a mail centre. Use diagrams that portray IMP machines split up according to individual modules. Use colour coding as the method for representing the condition of each module within each IMP machine.	Yes	Yes	20 and 38

Table A.6.2 continued on next page:-

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
Provide the functional capability to click on an IMP diagrammatical representation and zoom in on individual pieces of equipment being monitored. Provide a variety of data analysis tools suitable for analysing individual components.	Yes	Yes	2
Offer the functional ability to compare the condition of each IMP within a mail centre, e.g., how does IMP 1 compare against IMPs 2,3,& 4 etc.	Yes	Yes	None
Display the likely hood of equipment failure along with the level of urgency before a machine requires maintenance. Do so using graphical and numerical methods.	Yes	Yes	32
Using graphical or numerical methods, include the functionality to display a comparison of a machines existing condition against accepted (bench marked) normal conditions. E.g.,. a graphical plot showing a machine's live moving condition plotted between predetermined acceptable control limits.	No	Yes	None
Avoid producing lots of numerical data, likely to confuse and loose people. The CBM system should automatically perform all the number crunching in the background, presenting only the most easily interpretable information.	Yes (partly)	Yes	1 and 4
Present through printable reports or reports presented through digital display units, a prediction of the anticipated maintenance work (corrective action) necessary to repair/replace identified failing equipment.	No	Yes	1 and 4
Present through printable reports or reports presented through digital display units, anticipated consequential effects to other components or machinery or plant or the business, resulting from failing equipment within a machine.	No	No	1 and 4
Provide the optional request within a CBM GUI or report print to, display the number of CBM system alerts generated within a user selectable period of time.	No	Yes	None
Include in printable reports or messages displayed through digital display unit, a list of critical components that might be the cause of deteriorating equipment/machinery condition.	No	Yes	None
Include in printable reports or messages displayed through digital display unit, an indication as to the type of failure or anticipated failure process.	No	No	None

Table A.6.2 continued on next page:-

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
Following the detection of deviations from acceptable normal machinery operating conditions, (failure signatures), present based upon anticipated trend movement calculations (data analysis techniques), an indication of a machines remaining useful life, using graphical or figurative methods.	Yes	No	None
Included on CBM report prints, and or visual display units: An indication of the amount of time machinery can be reliably operated for, before it needs to be stopped for maintenance, e.g., remaining belt life, time till pulley replacement, remaining useful life for motors, etc.	Yes	Yes	None
Using graphical or numerical methods, include the functionality to display a machines recent condition movement against historical condition movements.	Yes partly	No	None
Use low specification robust PCs or dumb terminals for communicating CM information to maintenance personnel on the work area. Avoid spending extra money on high specification computer equipment if it is not necessary, and easily broken.	N/A	No	24
Design CBM systems to automatically generate alarm messages requesting the attendance of maintenance shift personnel, at machinery who's CBM system has detected out of tolerance conditions. The alarm message could take the form of an email, or a flashing message on a digital display unit. Alternatively it could activate a mobile devices ring tone or vibrator.	Yes	No	None
Use elevated coloured lights embedded within sorting machinery to represent the condition of sorting machinery. A three colour coding system, as used in traffic lights would suffice. Acceptable machinery conditions = green light. Changeable or wayward machinery conditions = yellow light. Out of limit machinery conditions = red light.	Yes	No	None
Provide access to CM information in administration offices, for access by all levels of maintenance staff. Link the CBM system into RM's network and make CM information accessible through PCs.	Yes	No	16

Table A.6.2 continued on next page:-

Identified Royal Mail user requirements for a CBM system and its method of HCI	Included in the conceptual design	Recommended as a design improvement	Associated proposed rule or guideline
Provide access to CM information within close proximity to machinery. CM information might be provided via reports that can be printed and taken to the machine being worked on. CM information could be made available through a computer or computer screen/display located near machines. CM information could be made available through mobile devices carried around by maintenance personnel. e.g., PDAs, mobile phones or wireless laptops.	Yes	No	None

Table A.6.2. Comparison of identified Royal Mail user requirements against their inclusion in the conceptual design.

A.6.4. Conceptual Design Feedback, Further Comments

Any other comments. Optional request.	
1	Belt life prediction. - If it will fail in 4 - 16 hours you need to be alerted with instructions: 'Change belt within next 4 hours', to avoid unplanned stoppage. This is a Titanic - it will hit an iceberg - there is a total disconnect between the measured data and the analysis. When I get an alert: 'Change belt', I want the option to immediately zoom in on the actual data so I can judge if the machine is telling me something logical. Is it the belt or dirt on the lens (a sudden jump may indicate dirt on the lens where a gradual increase would fit with wear). OK - it is not a bad thing to have pretty fonts and nice colours but it is the data that tells the story. When acoustic emission drops did the sensor die? Did an envelope fall in front of it? It is hard to beat a display panel where optimum performance is an analogue representation of a pointer in vertical orientation, deviation shown by angle of pointer and yellow and red lights for alert and warning. Press a button to show live data and data history. Most of these wonderful systems don't work because people don't use them. Training and acceptance are much more important than what font or what colour. I did not see one question about training! Procedures are as important as systems. You need to spot a belt failure problem with more than 4 hours to go. If the belt only lasts 24 hours you should change it daily anyway. If it lasts 3 weeks, you should change it when expected life is less than 10%, since with normal variation it could fail anytime. When a light bulb is rated 2000 hours it means that they lit 100 bulbs and half had burned out in 2000 hours – i.e., it is a 50% chance you will make it to 2000 hours. Probably 85% you will make it to 1500 hours though. Probably 95% chance that if it lasts 100 hours it will last 1200 hours. So when do you plan to change it? If you can answer that with your automatic system you have a winner. **balancr@balancr.com**
2	Perhaps a more typical windows environment that had active spreadsheet type information graded for condition colour and perhaps with a deviation from identical peer sets. Also a preferred viewing perspective on login to set the course information set controls; manager; technician; analyst; CBM specialist; CMMS specialist etc. Hope I am not being over critical! **tscott@diagnosticsolutions.co.uk**
3	This can help, but you need an automated intelligent agent to support the CBM decision process. **murray@omdec.com**
4	Pay attention to colours used on the graphical displays. Yellow lines are hard to read over white background. Change either background colour or line colour on the CM charts. **eugenio.rios@astrazeneca.com**

Table A.6.3 continued on next page:-

Any other comments. Optional request.	
5	Greater clarity in information in graphs needed. Graphs too small - need bigger bolder lines. Control lines understated - hashed regions give clearer boundaries. Also summarized machines in alert would be good at beginning. **mike.w.ward@unilever.com**
6	Should also include some background information of the example to allow easier understanding. **lkeng3@yahoo.com**
7	Who is the user. For management, its data overload! What do the various charts show? Keep it simple, especially if you want to communicate to upper management. They need information, not data. Too many charts. Try to combine data to one chart per machine. You are on the right track by combining all machine health information on one dashboard but you need to make it simpler and more intuitive. Hope this helps. Keep me informed of progress. **jim.taylor@machineryhealthcare.com**
8	The graphs etc. are interesting, but it would be good to have a picture on the side of the pages showing the physical part of the machine to which the data/graphs are pertaining. Also your data on the machines seems to spend a large amount of time outside the maximums set... **bob@cuberoot.biz**
9	This could be a very useful tool indeed for a CM practitioner/contractor. There seems to be a lot of emphasis on web page design criteria, and I can find little fault with that. However, from a CBM user's point of view there are several views lacking. There is no cognisance of the diagnostic processes. I suggest you review a paper I did last year at the IMechE (and is therefore in the public domain) on the subject of Condition Monitoring Management to get an idea of what I mean. I am obviously quite happy to discuss the subject further. As stated I have published in this regard before and would be happy to contribute, however this is best done in a face-to-face meeting. I am currently implementing an offshore asset where perhaps 70% of the CM data will be collected and analysed manually. I might add that this is one of the most advanced applications I have worked on during 20 years in this industry. So there will be a lot of manual CM for the foreseeable future. The gist of my feedback was that the CBM GUI does not coincide with the "SCADA" and "CAUSE" thinking in the paper. (i.e., that the process of collecting/analysing/recommending/closing actions are not logically grouped, nor that several techniques (oil/vibration and trend/spectra/baselines) can be viewed simultaneously.) Please contact me at **coetzeeo@bp.com.**

Table A.6.3 continued on next page:-

Any other comments. Optional request.	
10	I build these databases every day and I know what the customers are looking for. What you have is quite good but there are areas that would drive maintenance managers a little bonkers. Most of these issues are in the graphical displays. Lines that are not clearly identified with date marking or that start and end in the middle of the display, will always be suspect and in many cases the "executive summary", is what the manager is looking for. Screening out the normal and focus in on the alarmed equipment. This has prospects but some fine-tuning is required. **johnr@desmaint.com**
11	Good job Philip. **"Morley, Edgar \\(US SSA\\)" <edgar.c.morley@baesystems.com>**
12	Very nice.
13	This is very good demo for CBM system. I wonder how the field engineers feel about it. Is this from a real system? **mluo@simtech.a-star.edu.sg**
14	It appears that your site is designed by engineers, for engineers. I am not an engineer. I am a Marketing person -- if you'll pardon the expression. (You may not want to talk to me now!). I am most comfortable with a site that is inherently a "sell". Where everything is explained in (as closely as possible) layman's terms -- even if it is a technical topic. Why? because engineers, even, are sometime not as "up" on things as you think they are. Further, you may want non-engineer decision-makers to visit the site -- they may be the people with the money to spend on the software. I could go on. But given what I've said so far, I think your site is quite distant from the kind of attractive design, text-rich explanations, and sequencing that will lead the visitor through the software in a step-by-step manner. **Graham Oliver <grahamoliver@oliver-group.com>**
15	May I have one small word on the subject of acronyms, I take this liberty as a CBM practitioner since 1975. I use the acronym CM (Condition Monitoring) to describe the practice of new users of Condition Monitoring techniques. I use the acronyms PdM (Predictive Maintenance) and CBM (Condition Based Maintenance), to describe the activity of users who have integrated CM into their routine work practices. I use the acronym PAM (Proactive Maintenance) to describe a number of actions which make the most aggressive use of PdM/CBM; including: 1) Insertion of CBM tolerance standards into vendor/contractor purchase Specifications. 2) Base lining new equipment and delivered lubricants. 3) Opportunity corrective actions (e.g., dynamic balancing, shaft alignment) of those assets known to drift and which become available through an unrelated plant shut. **Andrew.Tudor@emersonprocess.co.uk**

Table A.6.3 continued on next page:-

Any other comments. Optional request.	
16	I have reviewed your CBM interface paper. I have very few comments to make. There are many interfaces on the market - all do about the same thing. However, I will give you some comments that may be of no value to you in your projects, but have rung true for many years. I have been in the maintenance engineering business for about 30 years and have worked in many parts of the world (I once worked for ESKOM in the RSA) and in many industries from manufacturing plants to power plants. I have installed RCM, CBM, and CMMS for many clients and have prepared detailed maintenance methods. What I have found is that maintenance is universally poor and that includes CBM. Maintenance engineers rarely look at the effectiveness of what they do and what they could be doing. Most CM methods fail to diagnose problems about 70 - 80 percent of the time prior to equipment failure. There are two reasons - the CM technique doesn't perform as advertised (and many times cannot perform as advertised) and the maintenance personnel cannot make the CBM perform as it is supposed to. I have noticed a curious effect. When the maintenance personnel (usually along with their hired outside agency) go to maintenance shows, they present a rosy picture of how they are doing. However, when I get in their plant, I find they typically are doing far less well than they advertise. To be crude about the whole affair, I put the maintenance problems into two categories - 1) Pearls before swine, and 2) Snake oil salesmen although in the end there is only one problem - inadequate management. I believe all maintenance should be cost effectiveness based. This means that management must know how they are doing, how they could be doing and what the costs are. Based on what I know, I think any maintenance interface should incorporate the effectiveness of the maintenance and in the case of CBM should show the number of occurrences where CBM saved the day and the number where CBM was ineffective and the total costs of the CBM program should be gauged against the total costs savings. A manager should be able to see what is being spent day by day for maintenance (including predictive maintenance) and what would have been spent had maintenance been conducted differently - that is, if CBM, RCM, etc, had not been used. When I have been able to do this, I find that more money could be made on simple basic maintenance practices than could be made on any of the fancy programmatic approaches that use a lot of gizmos and computers (even though I sell and install the gizmos and computers). I developed a specification for a maintenance manager's cost comparison interface, but could never get a client to agree to develop the kind of input required. Hope this was of some interest. Arthur Pennington **Arthur Pennington <art_pen@msn.com>**

Table A.6.3 continued on next page:-

Any other comments. Optional request.	
17	I've had a quick look, and really, to me its nothing more than a first attempt of probably 100 that you will need to make based on what I see. It conveys so little information that there are no logical answers for the huge query list you would like filled in hence this reply. Its little more than a few ideas about how data is to be reported and nothing about what is to measured, how and why and what limits. I think you would be better to do something else and the RM buy a commercial package, which has useful reporting. Cheers John Morey **Tensor Systems <tensorsystems@alphalink.com.au>**
18	Thanks for your mail and paper giving lots of information about work you are carrying out. Incidentally I was part of Bently Nevada India after sales service for a couple of years, and am now working with Jacobs India, handling the engineering of large rotating equipment in refineries and petrochemical projects. If you know modes of malfunction operation (as an effect on process variables and machine dynamic behaviour), failures which can be avoided, by a combination of preventive and predictive maintenance programs, condition based monitoring can be more cost effective as far as sensing devices and monitoring system is concerned. Please find attached a link for an article written by me giving this aspect of design safety. Hope you may find it interesting and if you have any comments please let me know. Regards Shirish Mandke http://wtui.com/articles/condition_monitoring_of_rotary_e.htm **shirish mandke <mandkeshirish@yahoo.co.in>**

Table A.6.3. Conceptual design feedback form, additional comments.

A.7. Proposed Generic CBM Software GUI Design Rules and Guidelines

Proposed CBM software design rules and guidelines		Level of importance if known
1.	**Design CBM software GUIs in accordance with accepted Graphic User Interface design rules.**	**Average**
Examples:		
1.1.	Design the CBM software to satisfy the intended audiences requirements.	High
1.1.1.	Use language targeted at the intended audience, for icon descriptions, menu option descriptions, label and title names, and help assistance.	High
1.1.2.	Ensure GUIs are visually appealing to the intended audience.	High
1.2.	Make suitable use of tables when designing the CBM GUI.	High
1.3.	Provide users with the capability to manually adjust the appearance and functionality of certain features provided in the CBM GUI.	High
1.4.	Use recognisable and understandable icons designed for direct manipulation control. Do not reinvent icons that are already in popular use.	Average
1.5.	Design each screen with consistency, using templates of a recognisable design, e.g., the windows design structure.	High
1.6.	Select an intuitive navigation technique for all GUIs, e.g., drop down menus, right click activated menus, hyperlink text and hyperlink buttons.	High

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
1.7.	Classify and structure information contained in CBM GUIs to improve visual clarity. Avoid cluttering up screens. Group like for like controls into bordered or boxed areas on the screen. For example, all chart appearance controls to be located together, data analysis selection controls located together, start, stop, save and load buttons located together, etc.	High
1.8.	Use text size and font type appropriately in CBM software GUIs.	Average
1.9	Design in error protection features, to prevent users from making errors or to undo actions, whilst using the CBM software's GUIs.	
1.10.	Design CBM software GUIs to be user friendly, logical and easy to operate, e.g., out of box user friendly.	
1.11.	Provide help assistance features in the CBM GUI, which explain the purpose and function for all control features.	
1.12.	Design all GUI user selectable control features to respond with the minimum of time delay, e.g., within 1-5 seconds as an average.	
2.	**Design CBM software GUIs with due consideration for the CM technique/s incorporated with the CBM system.**	**High**
Examples:		
2.1.	Design the CBM GUI to cater for design requirements imposed by one or multiple CM techniques, e.g., display machinery condition parameters from one or multiple CM techniques, monitoring a single machine.	High

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
2.2.	Design the CBM software to identify deteriorating equipment and machinery conditions as they arise during its operational life.	
2.3.	Design the CBM software to aid and assist maintenance decision-making, at a live and predictive level.	
2.4.	Identify the best techniques to represent and present machinery condition information, for the CM techniques being used.	High
2.5.	Make provision for recognising and distinguishing between different machines being monitored by CM equipment. Especially important in situations where multiple machines are being monitored.	
3.	**Design CBM GUIs to communicate the condition of machinery using techniques and methods selected specifically for easy interpretability.**	**Very High**
Examples:		
3.1.	Provide user type access right control features, aimed at directing users to specific GUIs containing information targeted specifically at their user requirements. For example, different user types, namely: engineers, analyst, managers, are each given access rights to a select group of GUIs, according to their recognised login user type status.	
3.2.	Provide access to a variety of different machinery condition and performance reports, designed with easy interpretability in mind.	Very High

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
3.2.1.	Reports, which show a prediction of a machines remaining useful operating life, before maintenance work must be performed.	
3.2.2.	Reports, which list anticipated maintenance work requirements, based upon measured component condition deterioration, for one or multiple machines.	
3.2.2.1.	Prioritise anticipated maintenance requirements lists with respect to factors such as: 1) The advancement of component deterioration before complete failure. 2) Anticipated consequential effects to other plant and equipment. 3) Anticipated time to perform the maintenance. 4) Production and operational constraints.	
3.2.3.	Reports, which identify predicted anticipated consequential effects to other plant and equipment, in the event of component failure. Predictive results of this nature will prove useful in calculations designed to indicate the urgency or importance of maintenance.	
3.2.4.	Reports, which show possible or known causes for deteriorating machinery component condition, i.e., high current draw, power loss, contaminated oil, increased bearing friction, loose belt, etc.	
3.2.4.1.	Identify the name/s of those components whose deteriorated condition requires maintenance attention.	
3.2.5.	Reports, which show the results from machinery condition comparison analysis, and machinery performance comparison analysis.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
3.2.6.	Provide design features, which enable authorised users to control the contents of CBM reports, the frequency when CBM reports will be released, and the individuals or groups of individuals CBM reports will be released too.	
3.3.	Use graphs appropriately for communicating machinery condition, and assisting maintenance decision-making.	Very Important
3.3.1.	Make use of graphs for comparison purposes, e.g., for comparing a machine's live operating condition, against historical operating conditions.	
3.3.2.	Provide graphical controls for altering the x and y-axis scales.	
3.3.3.	Provide a full range of manual graphical plot appearance adjustment controls. E.g., controls enabling users to alter line, back ground, chart and warning control indicator colours. Provide maximise and minimise chart buttons, provide zoom in and zoom out buttons, and an ability to vary between panoramic or compact chart views.	
3.3.4.	Incorporate clearly visible upper and lower control limits, on machinery condition graphs, incorporated on GUIs or CBM reports.	
3.3.5.	Provide control features for graphically presenting peer-to-peer machinery condition comparisons.	
3.3.6.	Provide the capability for showing component condition wear rates as linear graphical representations.	
3.3.7.	Clearly label all graphs with date markings and line markings references. Avoid where possible showing graphs with lines starting and ending in the middle of charts.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
3.3.8.	Design graphs with visual clarity and interpretability in mind.	
3.4	Communicate machinery condition using colour-coded images, which accurately portray all those parts within a machine being monitored.	High
3.4.1.	Select recognisable colours for communicating machinery condition, suited to the intended audience, and environment.	High
3.4.2.	Provide the functional capability to drill down from the overall machinery image representation to individual machinery component level representations.	
3.5.	Select recognisable units of measure to represent machinery condition, understandable by the intended audience.	
4.	**Design CBM software GUIs with features for controlling and monitoring alarms. Alarms designed to attract a user's attention, in the event of identified deteriorating machinery conditions, exceeding control limits.**	
Examples:		
4.1.	Design the CBM software to emit audible sounds that are appropriate to the environment, the intended audience and fit for the intended purpose.	
4.2.	Provide control features that enable users to manually select the type of alarm/s activated, when component operating conditions exceed control limits.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
4.3.	Provide access to recorded alarm events in the form of an alarm log.	
4.3.1.	Provide controls that enable users to specify the duration they wish to view alarm events between.	
4.4.	Provide controls for adjusting condition parameter levels at which point alarms are activated, i.e., controls for manually adjusting control limits on component Condition Monitoring sensors.	
4.5.	Provide users with a method of rapidly accessing component condition data, for those components whose condition has resulted in an alarm, e.g., a single mouse click action.	
5.	**Design CBM software GUIs with a selection of data management control features.**	**Very High**
Examples:		
5.1	Design data management features with due consideration towards the chosen CBM system's database design.	Very High
5.2	Incorporate data archiving control features for moving, storing, filtering and deleting CM sensory data located in the systems database/s.	Very High
5.3.	Provide control features for extracting data from CBM databases, converting it into a saveable file, and making it available in a user's desirable format.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
6.	**Design CBM software GUIs to cater for anticipated networking and data integration requirements.**	**High**
Examples:		
6.1.	Make provision for providing access to CM information from multiple locations, i.e., at or near machinery being monitored, in administrative offices, at other sites any where in the country or from another country.	
6.2.	Provide control features for comparing machinery condition from multiple machines networked into a single CBM system.	
6.2	Provide control features for sharing and integrating information and data made available by a CBM system, with other maintenance software applications, e.g., computer maintenance management (CMMS) software applications.	
6.2.1.	Provide controls for accessing and reviewing maintenance work completed records, stored on an external CMMS's database.	
6.3.	Make provision in the design of CBM GUIs for displaying sensory data from one or multiple different types of CM techniques, and single or multiple machines, integrated together.	
6.4.	Design CBM GUIs to operate with 100% functionality on all the most widely used operating system/s and platforms.	
6.5.	Design CBM GUIs capable of operating on web site Browsers, over the Internet or on an Intranet.	
6.6.	Make provision for including selectable hyperlink text or hyperlink buttons, designed to open other software applications, regularly used by the intended customer.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
7.	**Design CBM software GUIs to account for restrictions imposed by the environment.**	**Average**
Examples:		
7.1	Account for restrictions imposed by small visual display screens, and thick heavy glass, whilst designing the CBM GUI.	
8.	**Design CBM software with the intension of tailoring certain aspects of its GUIs to a customer's own requirements.**	**High**
Examples:		
8.1.	Design the CBM software using programming techniques specifically aimed at software tailor-ability, i.e., modularise the design of the CBM software program into recognisable sections, designed to perform specific identifiable functions.	Very High
8.2.	Design the CBM software to incorporate design features targeted at different user groups, which can be switched on or off.	
9.	**Design CBM software with adequate security measures aimed at preventing unauthorised access or software and data corruption.**	**Very High**
Examples:		
9.1.	Design CBM software to incorporate password and user name authentication login controls.	Very High

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
9.2.	Provide GUI user type access right capabilities, which restrict access to certain GUIs and information available through the CBM software, to specific user types.	
10.	**Provide a selection of data analysis capabilities and associated control features into a CBM GUI, appropriate to the type/s of CM techniques being used.**	**Very High**
Examples:		
10.1.	Data analysis control features for selecting the time period data will be analysed between.	
10.2.	Data analysis control features for selecting the choice of data channel (data type) a user wishes to analyse.	
10.3.	Data analysis control features for selecting the type of data analysis technique users wish to use.	
10.4.	Data analysis control features for selecting data filter options.	
10.5.	Present data analysis results in a format that can be easily learned, correctly interpreted, and used to guide maintenance decisions.	
10.5.1.	Avoid producing lots of numerical data, likely to confuse and loose people. Number crunching should be performed automatically in the background. Target information produced following data analysis routines at the intended user group.	
10.6.	Make provision for some form of intelligent agent within CBM software to support the maintenance decision process.	

Table A.7.1 continued on next page:-

Proposed CBM software design rules and guidelines		Level of importance if known
11.	**Design CBM software with due consideration for marketing and after sales design considerations.**	
Examples:		
11.1.	Design CBM software with due consideration for after sales support.	
11.2.	Design CBM software with opportunities for software upgrades.	

Table A.7.1. Proposed Generic CBM software GUI design rules and guidelines.