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JORGE JULIAO

**Conceptual Design of a Support Documentation System to Assist
Troubleshooting in Manufacturing**

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

PhD THESIS

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CRANFIELD UNIVERSITY

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

DEPARTMENT OF MANUFACTURING SYSTEMS



PhD THESIS

JORGE JULIAO

Academic year 2004-2005

Conceptual Design of a Support Documentation System to Assist Troubleshooting in Manufacturing

Supervisor: Richard Greenough

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Abstract

This research explores the conceptual design of a Support Documentation System (SDS), to assist manufacturing maintenance personnel during troubleshooting.

Manufacturing systems maintenance is a crucial element of any organisation's operating strategy. One of its main goals is to reduce downtime, both by avoiding the occurrence of failures and by effective reaction to breakdowns. Currently, most downtime reduction studies focus on the prevention of failures. Although these studies have made a significant contribution toward downtime reduction, it is impossible to prevent all failures. As such, troubleshooting will always be necessary for maintenance personnel to provide an effective contribution to their organisation.

This research proposes a Support Documentation System that will improve maintenance through documentation management. It is argued that troubleshooting time will be reduced since such a system could provide maintenance personnel with enhanced access to support documentation, particularly to failure records. Until this research, little direct empirical evidence had been collected about the feasibility of such a system, and about the performance of current systems regarding troubleshooting support. There had also been no evidence concerning maintenance personnel requirements for improved support documentation. The objectives of this research are to assess the feasibility of the SDS, to determine why current systems do not effectively support troubleshooting, and to identify key features for the development of the SDS.

To fulfil the objectives of this research, exploratory investigations were conducted. Questionnaire and interview surveys of maintenance practitioners, equipment vendors, and CMMS developers were performed to determine the status of failure records management and the reasons for the failure of current systems. A case study strategy was employed within three companies to identify requirements for the development of the SDS.

The findings of this research are that the development of an SDS is feasible, and that current systems do not effectively support troubleshooting. The research identifies a set of design features for the SDS. It presents the end-user requirements, a ranking of most relevant troubleshooting data to be included in the failure records, and a list of record attributes that are to be used to better identify and classify records. The latter attributes constitute the means to manage failure records in a systematic way.

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“To my lovely wife and adorable daughters”

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Glossary of Acronyms

CM	Corrective Maintenance
CMMS	Computerised Maintenance Management System
DSS	Decision Support System
ES	Expert System
IS	Information Systems
IT	Information Technology
PM	Preventive Maintenance
RCM	Reliability Centred Maintenance
SDS	Support Documentation System
TPM	Total Productive Maintenance
TSS	Task Support System

Chapter I

1 INTRODUCTION

1.1 Background

In recent years, manufacturing organisations have been under considerable pressure to be more competitive in the worldwide market. The modernisation and automation that have taken place in almost all industries, combined with new and more demanding production philosophies (*e.g. Just-in-Time*), have forced managers and engineers to optimise all the systems within their organisations (Duffuaa *et al*, 1999). As one of these systems, maintenance is consequently under pressure to reduce downtime. Moreover, with modernisation and automation, the complexity and amount of maintenance have increased (Neibel, 1994), with maintenance costs rising faster than production costs (Cato and Mobley, 1999). The maintenance function is one area many industries are now turning their attention towards (Wireman, 1994); maintenance is recognised as an essential part of the operations function that adds value to manufacturing (DTI, 1987) and is also seen as a competitive factor in firm's business strategy.

Reducing downtime, both by avoiding occurrence of failures and by quick reaction times in fixing breakdowns, is the most common objective of maintenance; it takes cost, safety, and quality issues into account. Downtime affects a company's productivity by reducing output and increasing operating costs. It also interferes with customer service (Moubray, 1997), and so many new maintenance techniques and philosophies have been developed to reduce downtime, most of which emphasise failure prevention (Finch and Gilbert, 1986). Research in maintenance management traditionally focuses on preventive maintenance ignores corrective maintenance, even though industry considers the latter a critical activity (Sheu and Krajewski, 1994).

Despite the benefits of preventive maintenance (*e.g.* Swanson, 1997a; Dhillon, 2002), it is impossible to prevent all failures (*e.g.* Moss, 1985; Takata *et al*, 1999) and so unexpected failures do occur, which leads to corrective maintenance and in some cases to high levels of downtime. Therefore, it is important to reduce downtime by preventing and repairing failures as quickly as possible. Despite the above arguments, and the fact that corrective maintenance represents almost half of the total maintenance activity (Moore, 1999; Swanson, 1997a), corrective maintenance remains an area in which significant improvements are still possible.

A maintenance strategy cannot remain static; its target will always move with time. Different approaches have been developed through time, whose aim was or is to keep up with the moving target. According to Sherwin (2000) technology is advancing too quickly for us not to learn from older methods, such as RCM, TPM, and move on to something more appropriate to the age of advanced IT.

This research explores a way of improving corrective maintenance (or troubleshooting) with the aim of reducing downtime through the use of IT. It explores the development of a Support Documentation System (SDS) that targets the improvement of failure information management. In order to conduct this study, the general scope of the thesis comprises the following areas of knowledge: (1) maintenance, (2) information systems, (3) classification and coding disciplines, and (4) research methodology (*Figure 1-1*).

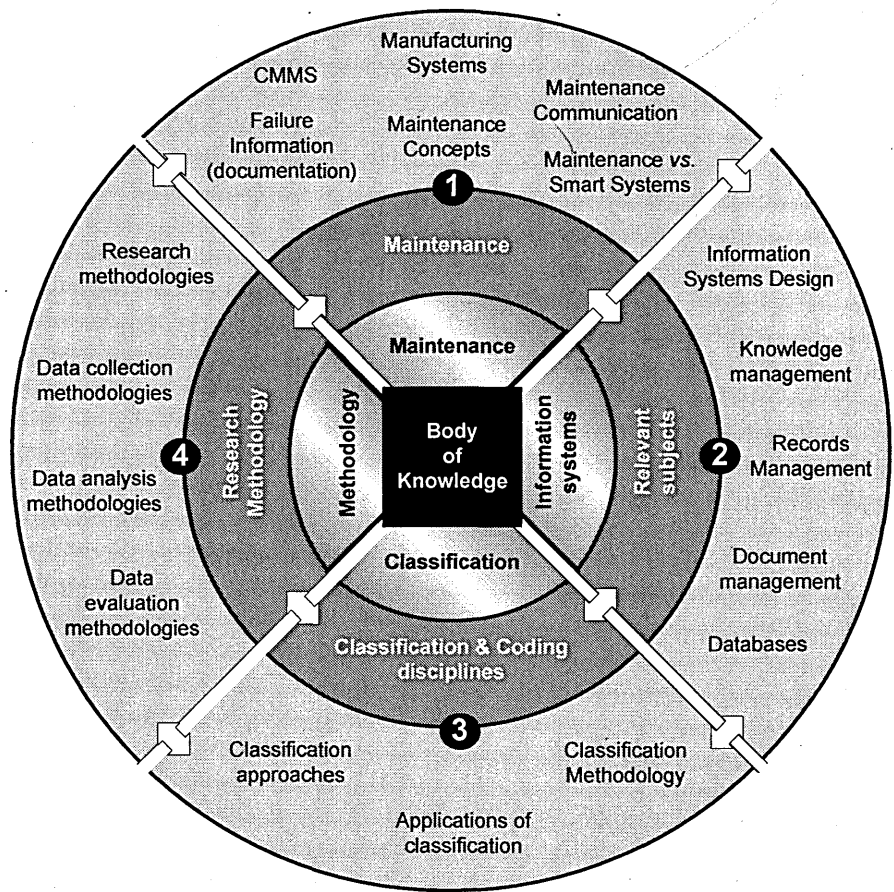


Figure 1-1: Body of Knowledge

1.2 Problem Situation

This section describes how the problem was selected and explains the nature of the research.

The subject was defined through a brief survey of literature and of the “*real world*”. The literature survey was constituted by some initial readings on maintenance and information systems topics. Real-world feedback was achieved by consulting both academics and industry experts. Brainstorming, as an individual process, was used to collect expert ideas about the topic and its feasibility. Some maintenance newsgroups were also consulted about the topic.

This research proposes the development of a SDS that would improve the management and access to maintenance documentation (failure records and documentation). It is argued that such a system would facilitate maintenance personnel access to documentation in a way that would reduce troubleshooting time. However, little empirical evidence is available on the current situation regarding maintenance documentation/failure records management. Moreover, despite the literature showing some contextual issues that illustrate that current information systems are failing to provide the necessary support to maintenance personnel, there is also little empirical evidence to support this argument. There is also no evidence about maintenance personnel requirements regarding the improvement of the management of support documentation. Considering this problem situation, the aim of this research is:

To explore the conceptual design of a Support Documentation System that will best assist maintenance personnel during troubleshooting.

The research aim led to the development of a series of research objectives that can be viewed as proposed outcomes of the research investigation. The delivery of these outcomes will represent a contribution to knowledge. The research objectives are as follows:

- Objective 1:** Assess the feasibility of a Support Documentation System based on failure records to assist maintenance personnel during troubleshooting.
- Objective 2:** Identify reasons why current maintenance information systems (CMMS and documentation systems) do not effectively support troubleshooting.
- Objective 3:** Identify key features for the design of a proposed Support Documentation System that will best assist maintenance personnel during troubleshooting.

1.3 Motivation

This section presents reasons other than those previously stated that explain and justify why this research is being conducted.

Maintenance of manufacturing systems has been a ‘warm’ research activity for a number of years, and it is growing in importance. Many authors and practitioners acknowledge that maintenance is now a major contributor to the performance of manufacturing systems. Maintenance also plays a key strategic role in the optimisation of business processes, since it aims to increase equipment availability. However, as justified in this thesis, it appears that corrective maintenance, as a main maintenance strategy, is receiving little attention by researchers. For example, one of the main supporting systems of maintenance, Computerised Maintenance Management Systems (CMMS), are failing to effectively supporting troubleshooting; this is suggested in literature and confirmed by this research.

From the researcher’s experience and from some preliminary interviews with experts, it appears manageable to indicate that this research would produce valuable results for both researchers and practitioners. In addition, from previous research conducted by peers, it appears that there is an accessible source of data for supporting the research. Finally, it is expected that this research would instigate a research project once the PhD study is completed.

1.4 Scope

This section presents the scope of the research. Defining the research scope helps to establish the boundaries of the research and to define the validity domain of the research objectives and findings. The body of knowledge and surveyed ‘population’ boundaries are defined.

Regarding the body of knowledge maintenance of manufacturing systems is the generic topic of the research (*Section 1.1*). Within this topic, the research focuses on downtime reduction, where an approach to reduce equipment troubleshooting time is proposed. Thus, corrective maintenance is emphasised within the thesis. The proposed approach is based on the premise that failure troubleshooting would be more efficient if maintenance personnel are effectively supported with documentation (failure records and technical documents). Thus, this research investigates a way of restructuring or optimising task support information so that it can provide significantly easier access to information related to troubleshooting. The research investigates key features to develop a SDS to assist maintenance personnel during troubleshooting, and so it also focuses on CMMS and maintenance documentation.

The scope of this research addresses maintenance practitioners, *i.e.* maintenance managers, engineers, supervisors and technicians, equipment vendors (machine tool vendors), and CMMS developers (designers). The questionnaire survey for failure information was administrated worldwide, including different types of industries and typologies, and mainly sought the views of experienced maintenance managers and supervisors. The survey of equipment vendors was limited to UK-based companies, was addressed to managers or equivalent, and included companies where servicing is also a major activity. UK-based interviews were conducted in this survey. Maintenance managers were also interviewed. The majority of these companies operated in the automobile sector and were based in the UK and Portugal. The surveyed CMMS companies were also UK-based. Finally, three case studies were conducted in which mainly maintenance personnel were surveyed and documentation analysed. The companies investigated were: (i) a UK-based machine tool company, (ii) a pulp and paper company based in Portugal, and (iii) a manufacturing and automobile assembly company based in Portugal.

The delimitations were established according to the opportunities given to access information. However, it is intended that the research results can be generalised to other industry types.

1.5 Research Overview

The first phase of the research consists of presenting the research outline (Figure 1-2). It justifies why the research is being conducted, and presents the problem situation and respective boundaries. This is followed by the definition of the problem, which consists of surveying what other researchers have found about the research topics in order to identify the gaps or situations that need improving. This allows the research questions to be defined and guides data acquisition. Stating the research problem, defining the aim and objectives, and identifying the methodology to approach the problem, enables the research to be defined. Once the research is defined, it initiates data collection and analysis. In order to identify the enquiry findings, evidence from different ‘real-world’ sources is collected, compared, and analysed. The research objectives are then discussed, based on literature and the findings of the enquiry. Conclusions about the research objectives are then made, which allows the contribution to knowledge to be stated.

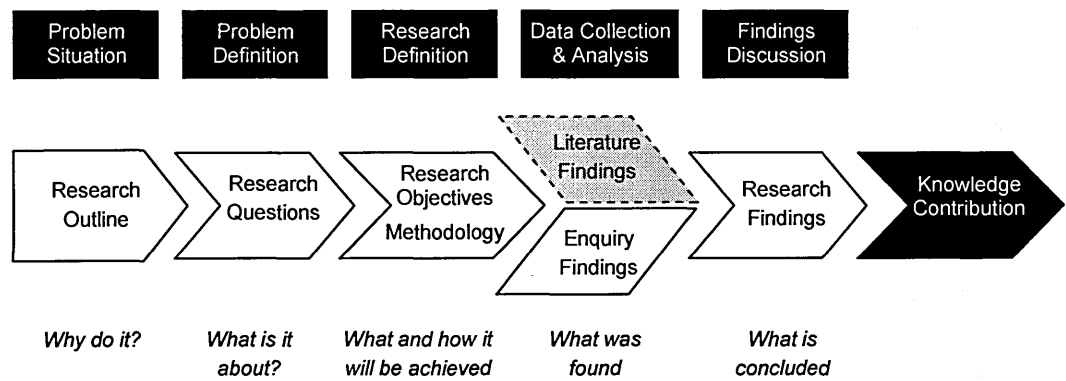


Figure 1-2: Research overview

Collection ‘real-world’ evidence to investigate the thesis arguments is a primary part of the research, and so this section also introduces the research methodology. The research problem is mainly addressed following an interpretivist philosophy and a qualitative methodology (Chapter 3). Survey and case study were found to be the most appropriate strategies to address the research questions. Maintenance practitioners (managers and technicians), equipment vendors, and CMMS developers are surveyed, and case studies are conducted at three manufacturing companies (Figure 1-3). Questionnaires, semi-structured interviews, and document analysis were found to be the most appropriate collection methods to use within the above strategies. Data collection is followed by data analysis. According to the research objectives, data is first compiled and grouped. In order to improve interpretation of results, triangulation from different sources is also made. The enquiry findings are then extracted by clustering and processing all data.

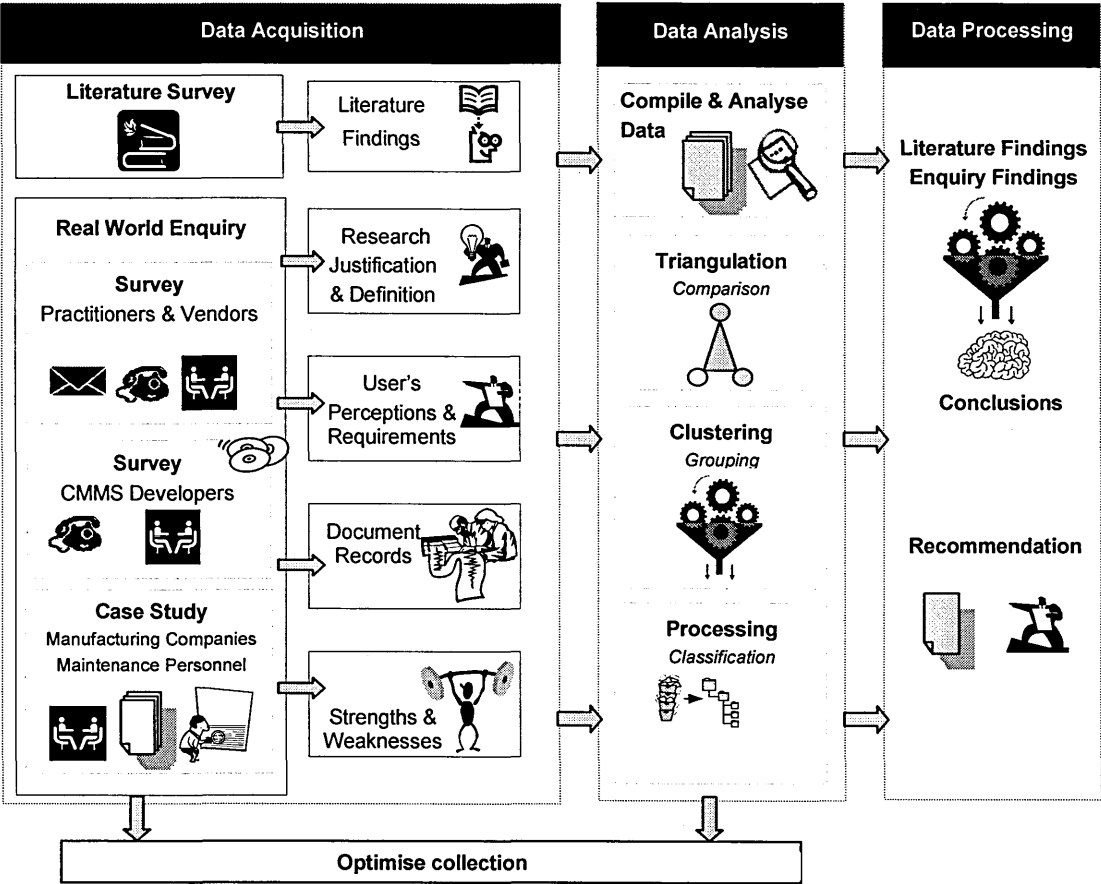


Figure 1-3: Methodology overview

1.6 Main Conclusions

In order to derive the proposed SDS an exploratory investigation was conducted to determine its design requirements. The research investigated the feasibility of such a system, explored the reasons why current systems do not effectively support troubleshooting, and identified key features for the development of the SDS. The main achievements of the research are as follows:

- The evidence presented by this research suggests that the development of a SDS is feasible.
- The research found that current systems do not effectively support troubleshooting.
- The research identified a set of key features to design a SDS, which mainly include:
 - Identification of end-users requirements, system purpose and scope
 - Identification of the most relevant troubleshooting data to be included in the records, and of suggestions for its reporting
 - Identification of the most relevant attributes to characterise and identify failure records
 - Suggestions about the format, tools, and standards that can be used to design the SDS
- It is claimed that the proposed SDS will reduce downtime. The research found that by referring to support documentation, particularly failure records, the quality and speed of troubleshooting can be increased.

1.7 Outline of the Thesis

Chapter 1 discusses the background to the research problem, presents the problem situation, generally justifies why this problem is being investigated, and defines the scope of the research. It provides an overview of what it proposes to do and how it will be achieved, and concludes by indicating some of the key findings and conclusions of the research (*Figure 1-4*).

Chapter 2 reviews published literature within the fields of maintenance of manufacturing systems and CMMS. It presents how the knowledge on the topic is structured and organised by defining the core concepts of the research fields. It then justifies the importance of maintenance to support the research requirement. It also presents limitations and situations to improve within the research topic to sustain the definition of the research problem. The conceptual research framework, together with the research questions, is then defined.

Chapter 3 states the research problem and defines the research aim and objectives. It reviews both research philosophy and methodology to identify the most suitable approach to conduct the enquiry process. The chapter then reviews the research strategies and defines both the enquiry purpose and strategies that best suit each of the research questions. Sampling methodologies and data collection methods are also reviewed. Considering this background and the selected research strategies, the chapter defines sampling strategies and methods that are most appropriate to collect evidence for each of the research strategies. Following selection of strategies and methods, their design methodology is stressed. The chapter identifies the data analysis approach that best suits each type of data. It concludes by stressing the quality assurance of the research, and presenting the methodology that is followed to guarantee the quality of the enquiry process and of the results.

Chapter 4 presents the enquiry results and subsequent data analysis. It presents the results of five enquiries that will help to address the research questions and fulfil the research objectives.

Chapter 5 discusses and concludes the thesis. It discusses and concludes the research objectives, and presents the contribution to knowledge, the limitations of the research, and further opportunities for research arising from this thesis.

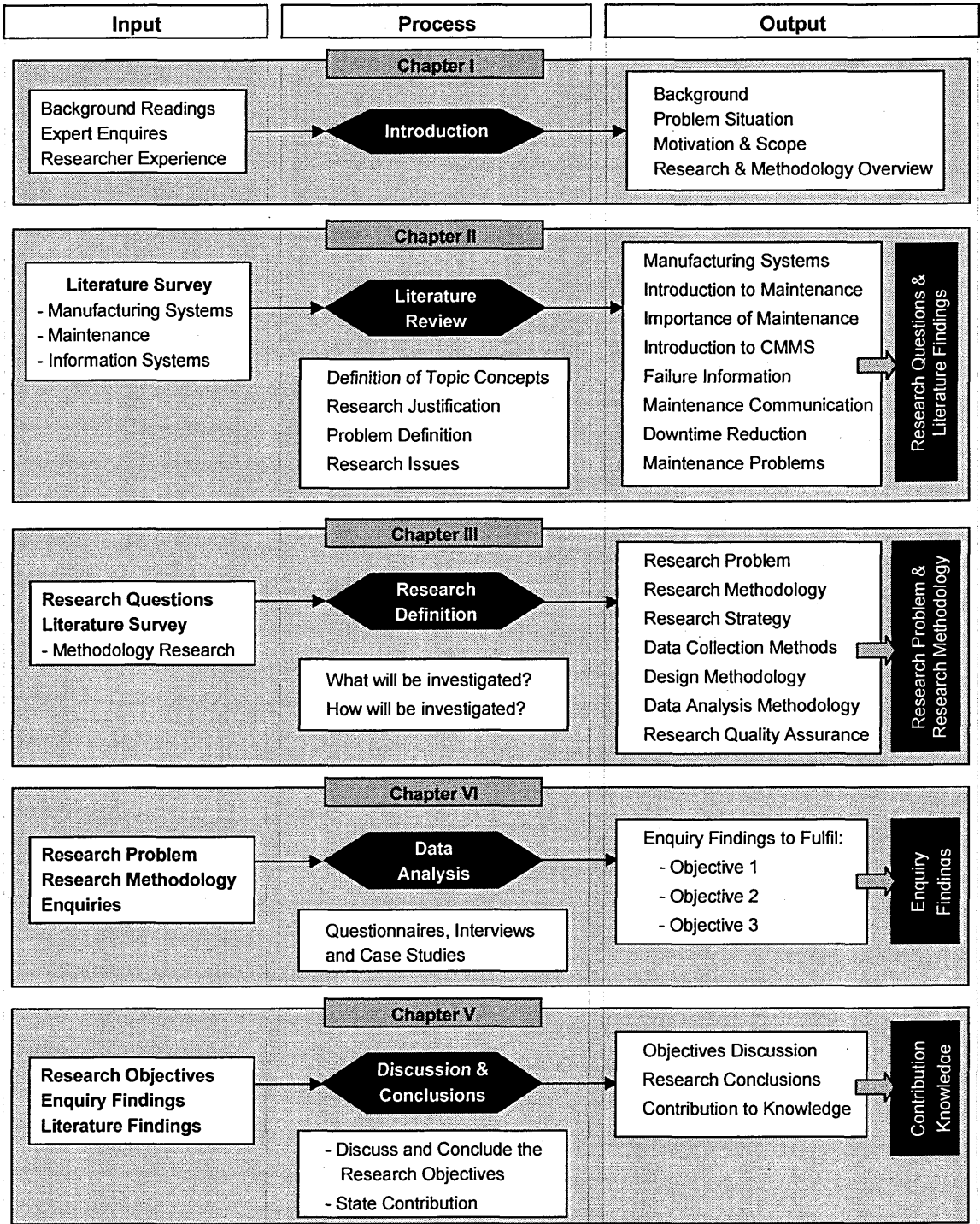


Figure 1-4: Thesis outline

1.8 Chapter Summary

This chapter laid the foundations for the thesis. It defined the body of knowledge and introduced the research problem. The research was then justified by explaining why it is being conducted, and the scope was presented. It also provided an overview of what it proposes to do and how. Some of the most important achievements of the research were then presented. Finally, it presented the thesis outline was presented.

Chapter II

2 LITERATURE REVIEW & PROBLEM BACKGROUND

This chapter presents:

- *How the knowledge on the topic is structured and organised*
- *What is known and unknown about the topic*
- *Why this research has to be carried out*
- *How similar problems have been resolved*
- *What was achieved*

2.1 Introduction

A literature review is an essential part of the research and the research thesis. Burns (2000) argues that, within qualitative research, the literature review is a stimulus for thinking and not a way of summarising the previous work in the area that can blind the researcher to only considering existing concepts and conceptual schemes. The review should be a sounding of ideas, as well as for finding out what is already known and what specific methodologies have been used.

This chapter builds a *theoretical foundation* upon which the research is based by reviewing the relevant literature to identify research questions. The answers to which will provide a potential contribution to knowledge. That is, the literature review is *not an end in itself*, but is a *means to the end of* identifying the worthy research questions (Perry, 2000). These research questions also help in defining the research problem and selecting the data collection methods.

2.1.1 Objectives of Literature Review

The aim of this chapter is to address the following objectives:

Objective 1: Establish, organise, structure and define areas of knowledge that relate to the thesis investigation;

“How is the knowledge on the topic structured and organised?”

Objective 2: Justify the research: demonstrate the importance of the research topic in order to support the research need;

“Why does this research have to be carried out?”

Objective 3: Characterise the problem situation: present limitations and situations to improve within the research topic;

“What is known and unknown about the topic?”

“How have similar problems been resolved?”

Objective 4: Define the research issues: establish the research framework and state the research questions;

“What is intended to be achieved?”

2.1.2 Methodology of Literature Review

The literature survey was conducted through a continuous search of the databases to which Cranfield University is subscribed. An extensive and thorough search into published theses, reports, and books was also conducted within the research topic. This continuous process was initiated in the early stages of the research with a wide search, and maintained narrowing down the topic and iterating its findings with the industrial findings.

A survey of the literature in a thesis focuses on the main discipline of the research problem described in *Section 1.2* (or *parent discipline*), and also includes the *immediate disciplines* of the research problem, referred to here as research disciplines. Phillips and Pugh (1994) descriptively name these two disciplines as background and focus theories, respectively. As such, the literature review of a doctoral thesis tends to extend further than the boundaries of the research problem than it does in most other types of research (Perry, 2000). *Figure 2-1* presents a framework of the research content within this chapter and the methodology used to address all of the issues identified during this phase of the research.

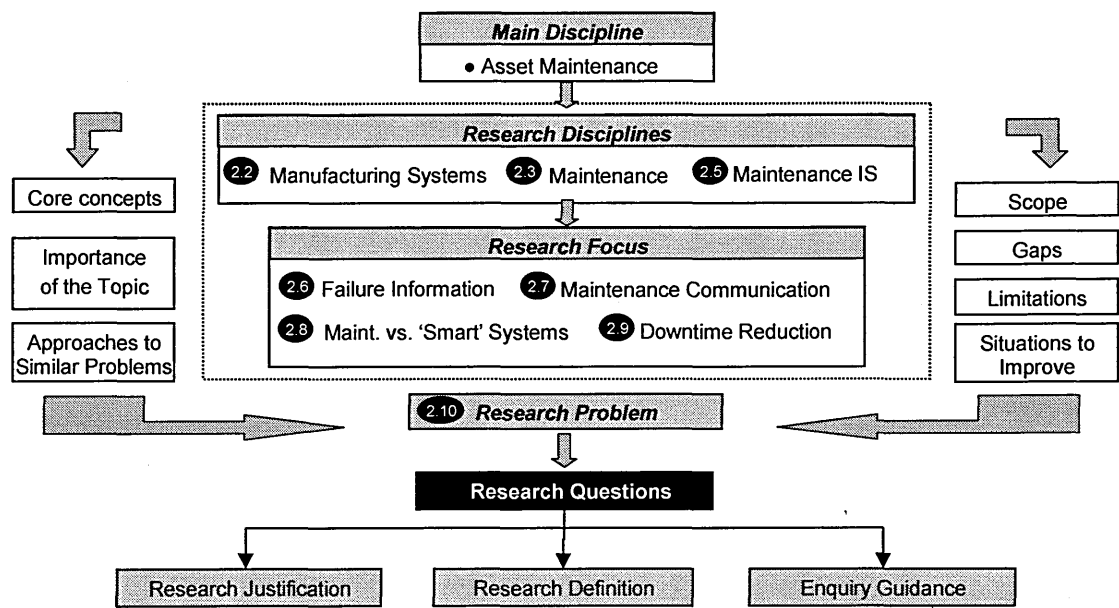


Figure 2-1: Illustration of the literature review methodology

2.1.3 Overview of the Chapter

The literature chapter consists of four parts. Part one introduces the topic concepts and presents arguments that justify the research. It introduces the background of the thesis, *i.e.* it briefly defines the research disciplines (*Figure 2-1*). Since the thesis scope is within manufacturing systems, they are first discussed. It provides a broad view of the maintenance discipline; (i) by presenting its definition and objectives, (ii) by introducing the maintenance strategies and activities, and (iii) by discussing some maintenance philosophies and approaches. It also presents arguments that justify why maintenance is worth investigating, and introduces CMMS. Part two defines the research focus, *i.e.* it shows the direction of the thesis (*Figure 2-1*). It defines and discusses maintenance information and communication concepts, and presents a broad characterisation of ‘smart’ systems (or technologies) applied in maintenance. The downtime reduction problem is discussed, and a comparison between preventive and corrective maintenance is provided. It also presents an approach for downtime reduction, which is based on failure documentation. Part three characterises the research problem (*Figure 2-1*). It presents the main problems (limitation and situations to improve) within CMMS, maintenance documentation, maintenance expert knowledge, and ‘smart’ maintenance systems. Part four states the research questions that emerged from the research problem discussion. These research questions will be the starting point for the research definition and the guidance for the enquiry process.

2.2 Manufacturing Systems

Manufacturing may be viewed as ‘the transformation of materials and information into goods for the satisfaction of human needs (Chryssolouris, 1992). Hopp and Spearman (2000: p190) describe manufacturing as ‘an objective-orientated network of processes through which entities flow’. Within their context, ‘objective’ refers to making a profit, ‘processes’ refer to physical processes (*e.g.* shipping, maintenance), and ‘entities’ describe the parts to be manufactured and information to control.

According to Black (1991), production systems differ from manufacturing systems in that they cover all activities within a company (including design, selection of factory layouts and facilities) except the physical transformation process. Burbidge (1993) also highlights the differences between manufacturing and production systems. However, despite Burbidge viewing ‘manufacturing’ as ‘the making of wares by hand or machine’, and production’ as ‘the manufacture and distribution of goods’, he also says their distinction is not useful when studying manufacturing management. He suggests that both production and manufacturing could be easily viewed as synonymous activities. Nonetheless, from an operational viewpoint, it is reasonable to expect that interpretation of the definitions could vary according to their application by different users.

By way of an overall explanation, there is little difference between what manufacturing is and what manufacturing systems are. As such, within the scope of this research, the terminology may be interchangeable, and so for the purpose of this research, Black’s (1991) definition of a production system will be used.

From a practical point of view, the principal definitions of manufacturing and production systems are representative for any type of manufacturing situation whether they are process, batch or project based industry types. However, different approaches to how the definitions are applied on an individual basis will vary between different styles of organisation and their manufacturing type. Of the many books and articles available, Slack *et al.* (1998) and Hopp and Spearman (2000) provide clear explanations of the commonly known areas of practical manufacturing process types. The main types discussed by these authors are project, jobbing, batch, mass and continuous manufacturing, each in their own way suited to different types of requirement.

Traditionally manufacturing was viewed as a functional area characterised by technical transformation processes (Doll, 1991). However, increased demand on productivity, quality and availability within the context of the definitions and types of manufacturing presented

here has meant that machines are becoming more complex, capital intensive and numerous with the need to respond to factors such as urgent orders, material and tool shortages, energy constraints, and unexpected equipment failures (DTI, 1991; Swanson, 1999, Chao, 2001: ch8). This change in environment has also meant that maintenance of these systems has been without proper integration of suitable techniques (Coetzee, 1999). In particular, those that suit the different approaches to manufacturing that have been sought to improve efficiency, effectiveness, capability, flexibility and competitiveness. Where appropriate, these issues are presented and discussed in greater detail within the following sections.

The research presented in this thesis is focused on maintenance of manufacturing systems, although it is possible to apply the concepts presented in the following sections to other organisational types (e.g. healthcare and transportation). The availability of companies to conduct the research and their importance limited the scope to manufacturing and production systems.

Importance of the manufacturing sector. As stated by the UK Department of Trade and Industry (DTI, 2004);

“The success of United Kingdom manufacturing is crucial to our country's prosperity, now and in the future. It makes up a sixth of the economy, and accounts for over half of our exports, and around 80% of all business research and development. ... It is also a significant contributor to employment – generating around 3.5 million jobs directly – and millions more through the supply chain and related services”

Manufacturing productivity reaches higher values in countries such as France, Germany, and the USA. The UK *Government Manufacturing Strategy Report* (DTI, 2002), also reported that current and future UK prosperity depends on a successful and dynamic manufacturing sector. As such, it recommends increased investment in science and innovation in this area.

2.3 Introduction to Maintenance

Similar to the perceived definitions of what manufacturing is, the terms and concepts used to describe various maintenance procedures also suffer from a lack of agreement, particularly between companies and researchers. Although it is recognised that formal definitions of maintenance standards are needed, the aim of this section is to introduce a broad and generally acceptable view of it.

2.3.1 Maintenance Definition

BS EN 13306 (2001: p8) provides an insight into the maintenance of hard systems (*i.e.* machines, aircraft, buildings etc.) rather than any form of soft system (*i.e.* software). Nonetheless, despite this gap and the known presence of similar maintenance definitions (*e.g.* Willmott, 1992; Mann, 1976), the BS definition is still commonly used and accepted by many practitioners to define maintenance. This standard defines maintenance as a:

“Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”

With the possible exception of certain companies operating in the service sector, all types of organisation operate some kind of maintenance function on their assets. Ensuring equipment availability, guaranteeing safety, and facilitating asset management are the main objectives of this function. A range of maintenance strategies, techniques, tools, and philosophies have been developed to achieve these objectives (*Figure 2-2*). These are introduced in the following sections.

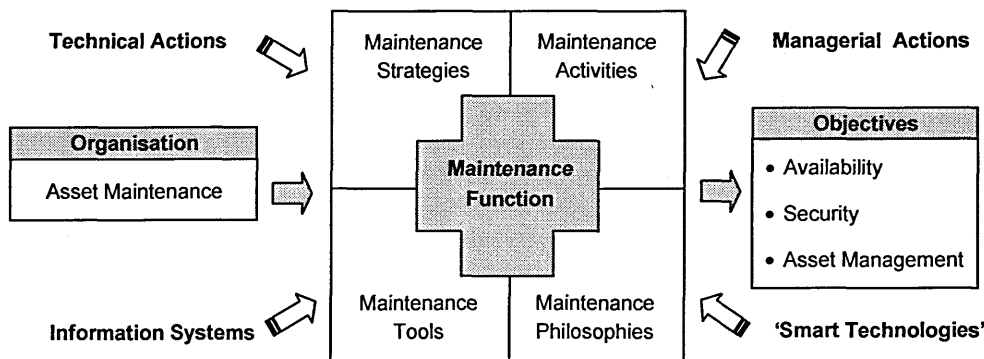


Figure 2-2: Simplified illustration of the maintenance function

2.3.2 Maintenance Objectives

The objective of the maintenance function is typically influenced by an organisation's strategic approach to manufacturing (*i.e. JIT, TQM* etc.) and process operation type (*i.e. flow, process, batch* etc.) (Hunt, 1993: p16-5). As such, it is reasonable to expect (as with defining the role and purpose of manufacturing and or production system/s) that perceptions will differ concerning the definition, objective and purpose of maintenance between different companies.

Again, although maintenance objectives might be dictated by the nature of a company's activity (*e.g. Kelly, 1997b: p89*), some issues are commonly applicable to most organisations regardless of their background, such as:

- *Availability*: The need to ensure availability of items (*i.e. assets*) for a required function;
- *Safety*: Consideration of the safety requirements associated with an item for both maintenance, user well-being and, where necessary, environmental impact;
- *Asset management*: To maintain item (asset) durability, product quality, service provision and, where necessary, extend asset usefulness.

(After BS EN 13306, 2001: p7; Dekker, 1996; Corder, 1976: p3)

In summary, perhaps the most common link between different organisations regarding their maintenance function and subsequent objectives are best described by Kelly (1997) who states that the objective of maintenance is:

“to achieve the agreed plant operating pattern, product output and quality, within the accepted plant condition and safety standards, and at minimum resources costs”

To summarise, reducing downtime is the most common objective of maintenance, both by avoiding occurrence of failures and by quick reaction times in fixing breakdowns, taking the cost, safety and quality issues into account.

2.3.3 Maintenance Strategies

Maintenance strategy characterises a certain approach to maintenance. It also indicates a course of action that has evolved to cope with situations as they arise. For example, in the 1970s, Mann (1976: p1) suggested that maintenance was usually categorised on a ‘when’ basis, *i.e.* emergency maintenance, routine maintenance, and preventive maintenance. Currently, maintenance strategies tend to be classified into two main groups:

- *Preventive maintenance*: actions used to prevent asset failure by taking specific actions at predetermined intervals.
- *Corrective maintenance*: repair after equipment failure.

(*e.g.* Shenoy and Bhadury, 1998: p17; BS EN 13306, 2001: p36; Moynihan *et al.* 2002)

For some, conditioned-based (or predictive) maintenance is considered a main strategy group; this is where continuous or periodic measurement and interpretation of data to indicate the condition of an item is used to determine the need for maintenance activity.

Figure 2-3 presents framework classifying core maintenance strategies. Although a wide variety of terminology and descriptions are used to describe aspects of maintenance, for ease of understanding, recognition and use, the terms preventive and corrective maintenance will be referred to throughout this thesis.

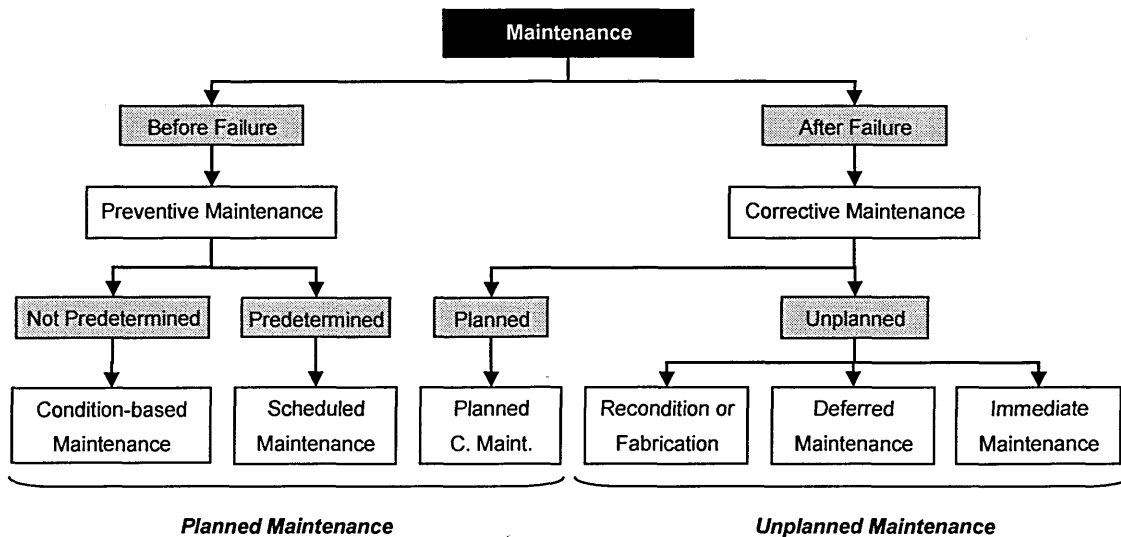


Figure 2-3: Maintenance strategies
(after BS EN 13306, 2001; Duffuaa, 1999; Kelly, 1997a; Corder, 1976)

2.3.4 Maintenance Activities

Maintenance can be defined as a set of activities that are either related to preserving equipment in a specified operating state or restoring failed equipment to a normal operating condition (Shenoy and Bhadury, 1998: p5; Pintelon and Gelder, 1992). These activities consist of a group of maintenance actions carried out for a given purpose and for the fulfilment of the maintenance type objectives. In this context, these activities embrace a number of what are too often thought of as discrete activities, *e.g.* inspection, troubleshooting, fault diagnosis, fault localisation, repair, and inspection (BS EN 13306, 2001: p23 and Patton, 1994). Nonetheless, the concept of maintenance activity assumes different meanings or interpretation among different authors. Therefore, for the purpose of this thesis the definition of maintenance activity provided by BS EN 13306 (2001) will be used.

The definition of maintenance not only covers technical aspects, such as fault prevention and rectification, but also involves administrative and management aspects. As such, the classification of maintenance activities should assume a broader view. For example, Duffuaa *et al.* (1999: p1) classify each maintenance activity according to its purpose, *i.e.* planning, organisation, control, and training (Figure 2-4).

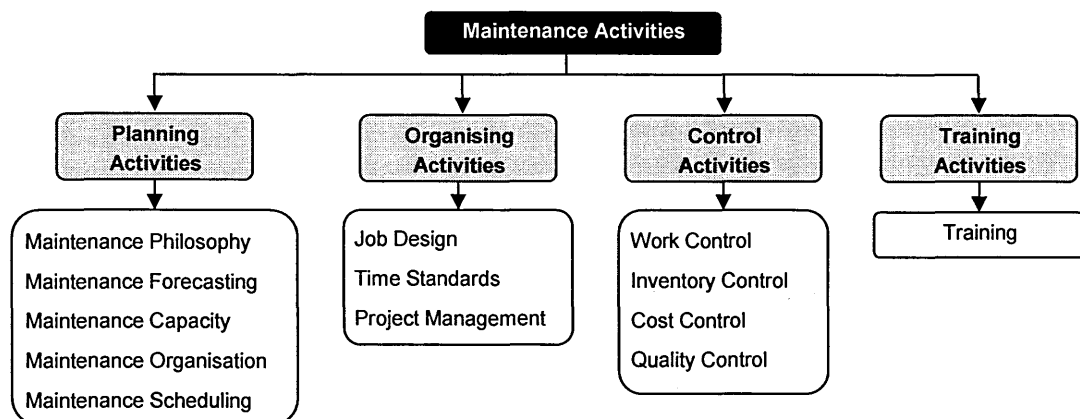


Figure 2-4: Maintenance activities classification
(after Duffuaa *et al.* 1999)

Considered by many as an empirical science (*e.g.* Priel, 1974), maintenance management can be described as the function that provides the policy guidance for maintenance activities, in addition to exercising the technical and management control of maintenance programmes. It covers every stage in the life cycle of technical systems specification, acquisition, planning, operation, performance evaluation, improvement, replacement, and

disposal (Murray *et al.* 1996). In order to fulfil the maintenance objective, it embraces techniques of industrial management that aim to ensure the best utilisation of human, technical, and financial resources. That is, to achieve the perfect balance between the input cost of the resources and the performance of good maintenance practice.

Management of maintenance activities has been neglected because it was felt that, since they were not repetitive in the same manner as operations tasks, maintenance did not lend itself to systemisation (Mann, 1976: p1). The result is that little research has been carried out in the area of automation of maintenance management (Paz and Leigh, 1994a). However, this trend has recently changed. To meet maintenance objectives at an acceptable cost, maintenance management has grown in importance for all industries (Dhillon, 2002).

2.3.5 Maintenance Philosophies and Approaches

This section presents some commonly understood philosophies and organisational approaches a maintenance function may utilise to achieve their objectives. According to BS 4778-3.2 (1991), a maintenance philosophy is a system of principles for the organisation and execution of maintenance. Examples of such philosophies that perceivably increase the efficiency of the maintenance function are terotechnology, Total Productive Maintenance (TPM), Reliability Centred Maintenance (RCM), and asset management (Pintelon and Gelders, 1992; Coetzee, 1999). This section also presents and compares traditional maintenance organisational approaches.

Terotechnology. Maintenance and management of the maintenance function are important facets of terotechnology. This related term was developed in the UK in the mid-1970s (Corder, 1976) as a result of a project commissioned by the British Government to study and report on the state of the maintenance industry (File, 1993: p18-3). It refers to 'a combination of engineering, management, financial, and other practices applied to physical assets in pursuit of economic life cycle costs' (BS 3811, 1993: p2). Terotechnology is concerned with the specification, design, provision, installation, commissioning, maintenance, modification and replacement of plant, machinery, equipment, buildings and structures and with feedback of information on performance design and costs. Moreover, within this concept, the maintenance function is of equal importance to other functions in the business (Cooke, 2002b). Although an interesting concept, it has not been accepted on a large scale within industry, especially in the USA where it has received little attention (Blanchard *et al.* 1995).

TPM. TPM is a maintenance philosophy first developed by the Japanese in the 1970s (Nakajima, 1988) and then followed by Western countries (Hartmann, 1992). It is a group of activities developed initially to support the implementation of just-in-time manufacturing, advanced manufacturing technologies, and to support efforts at improving product quality. TPM is also often defined as productive maintenance involving total participation, *i.e.* it involves every single employee from top management to workers on the shop floor. This approach encourages operator participation in the maintenance of equipment, increasing the level of equipment vigilance and releasing maintainers to more complex jobs (autonomous maintenance). The goal of TPM is to maximise equipment effectiveness through improved availability, more assured quality and labour saving as a result of plant modification, *i.e.* zero breakdowns and zero defects. In order to achieve that goal, investments in human resources are preferred over capital investments (Pintelon and Gelders, 1992). These goals are achieved by eliminating the different losses that interfere with effective operation: downtime losses (failures, set-up and adjustment), speed losses (idling and minor stoppages, reduced speed) and defect losses (defects in process, reduction in yield) (Monden, 1986).

RCM. RCM is a systematic approach for identifying effective and efficient preventive maintenance tasks for equipment and items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks (BS 4778-3.2, 1991). RCM originated in the US Air Force from an extension of the Failure Modes, Effects, and Criticality Analysis (FMECA) methodology, and is being applied to industrial equipment in a slightly adapted form (Pintelon and Gelders, 1992). RCM, also known as Reliability Based Maintenance (RBM), seeks to identify failure mechanisms and then addresses either their cause through preventive maintenance or the conclusion of the failure mechanism by predicting when it will happen and taking appropriate steps to prevent the failure of the equipment function (Picknell and Stell, 1997). This method utilises a ‘zero-based’ approach to determine the maintenance requirements of equipment in its operating environment (Moubray, 1997); it involves two principal stages (Kennedy, 1995):

1. Analysis of the functions, functional failures, failure modes and failure effects of significant items;
2. Evaluation of the consequences of every functional failure and failure mode and determination of the optimum maintenance task.

Although RCM is presented here under the heading of maintenance philosophy, some authors refer to it as a maintenance strategy (Dhillon, 2002: ch6) or as a maintenance management model (Moubray, 1997).

Asset management. Asset management takes a life cycle approach to equipment. Unlike terotechnology and TPM, it emphasises economic and financial aspects rather than being engineering-oriented (Pintelon and Gelders, 1992).

Centralised vs. decentralised maintenance. Centralised, decentralised, and a hybrid of both are the main approaches to organising the maintenance function. In a centralised maintenance organisation, all workers report to a central location (one maintenance head) and are assigned to work in any or all areas. All requests for work are channelled into this central location for scheduling and despatching (Mann, 1976: p12). The approach is commonly used in small and medium sized enterprises housed in one structure, or service buildings located in an immediate geographic area (Dhillon, 2002: ch3). In a decentralised area, maintenance workers are assigned to specific areas or units in the plant and generally work in that area, although all report to the same maintenance head (Mann, 1976: p12). In order to have the best of both approaches, many companies created hybrid systems (Wireman, 1990); this is especially the case for large companies (Dhillon, 2002: ch3). The hybrid approach locates small groups of workers near critical machines, while keeping the main group in a centralised area. The TPM concept of operator-based maintenance is another hybrid approach (Paz and Leigh, 1994a). The selection of these approaches usually depends on the size of the company and the type of manufacturing and production systems (Mann, 1976: p14).

Maintenance methods. In addition to the above philosophies, various maintenance methods (or tools) can be used to achieve maintenance objectives. These methods, which aim to support the maintenance strategies and facilitate maintenance activities, are often classified into the following categories:

- *Proactive methods:* aim to extend equipment life, e.g. root-cause failure analysis, failure mode and effect analysis, fault-trees, etc.
- *Preventive methods:* aim to prevent and anticipate failure, e.g. reliability models.
- *Predictive methods:* aim to predict the condition of equipment, e.g. vibration monitoring, thermography, lubrication analysis.

2.4 Importance of Maintenance

Until recently manufacturers saw little need for developing adequate maintenance strategies in line with increasingly sophisticated manufacturing technology. This was mostly due to the relative ease with which excess stocks could be built and carried, or overtime and extra shifts worked, and spare capacity, as extra machines or quick off-load sub-contract, could be arranged (DTI, 1991). However, since companies are now under increasing pressure to be more competitive they are investing a great deal of time and money in areas of manufacturing/production technology (e.g. flexible manufacturing systems) and maintenance (Swanson, 1999). These issues, driven by short lead times, on-time delivery, quality, responsiveness and equipment availability (Riis *et al.* 1997), have forced managers and engineers to optimise all manufacturing systems processes, including maintenance. (Duffuaa *et al.*, 1999).

More modern demands on the maintenance function have also increased due to the vulnerability of equipment failure within modern manufacturing systems such as increased automation and reduced work-in-progress buffers. These and similar issues make failure diagnosis and correction more difficult (Swanson, 1997b; Durham *et al.* 1997), and so, operations, communication and co-ordination must be improved so that maintenance resources are properly directed to solve problems and to make equipment available (Swanson, 1999).

Operationally, maintenance costs are estimated to be between 15 and 40% of production costs (Dunn, 1987), and for many large-scale systems the cost of system maintenance and support can often range between 60 to 70% of the total overall life-cost (Blanchard *et al.*, 1995). In 1991 findings from a report by the UK Department of Trade and Industry showed that maintenance costs represented more than 5% of a company's turnover and 20% of the total value of equipment. Earlier in 1990 Wireman (1990) in a benchmark survey within the USA found that maintenance costs had risen since 1979 annually by 10-15%, and by 2002 maintenance costs were considered to vary between two to twenty times the acquisition cost (Dhillon, 2002: ch10). Although by 1997 many authors and practitioners acknowledged that maintenance is indeed a major contributor to the performance and profitability of manufacturing (e.g. Coetzee, 1997).

Effective maintenance extends equipment life, improves equipment availability and retains equipment in its proper condition (Swanson, 1997b). Within the past decade maintenance has evolved into one of the most important areas within a business environment (Kutucuiglu *et al.* 2001). So much so, that any company that has invested in new and

demanding production philosophies, automation, new technology and higher quality levels to be competitive, cannot do so without considering maintenance as an essential part of their operations. As observed by Briggs and Atkinson (2000: p1), maintenance is fast gaining the recognition that it deserves and has a crucial role in any organisation's operating strategy. Nonetheless, readjustment has still to be made to improve the efficiency of the function through development of newer maintenance philosophies and the application of computerised maintenance management systems that facilitate new ways of performing maintenance tasks.

Negative view of maintenance. Despite its importance, maintenance is often overlooked (Ashayeri *et al.* 1996), and not viewed as a competitive factor in a firm's business strategy (Swanson, 1999). Maintenance interventions are too often only considered as constraints on production planning and scheduling. A main reason for this negative view is that the benefits of good maintenance are mostly immeasurable or not immediately apparent and are sometimes intangible (Peters, 2003; Priel, 1974), *i.e.* the quality of the service cannot be directly assessed. In another words, a visible outcome is not quantified, and so supervisors and maintenance managers often complain that there is little or no interest in what they are doing and how they are doing it. As such, investments in maintenance are always difficult to justify (Daley and Eyada, 1989). In addition, maintenance is commonly the most affected department, when companies face financial problems and costs need to be reduced. However, what one should ask is:

“What are the business goals: reduced maintenance cost or increased production and lower unit cost”?

Another consideration is the perceived low productivity of maintenance crews. A study by Hedding (2001) showed that maintenance workers are directly engaged in productively performing direct work for only 28% of their time; as so, maintenance departments tend to be viewed as inefficient (Higgins *et al.* 2002; Mann, 1976). According to a survey conducted by Amoako-Gyampah and Meredith in 1989, only 2% of the articles on operations management research were found to be in the area of maintenance and reliability. The direct impact of this negative view is represented by a lack of maintenance investments, which are mainly reflected in reduced human resources and IT investments.

2.5 Introduction to Computerised Maintenance Management Systems

2.5.1 Information Technology and Maintenance

Smith (2000) states that investment in, and use of Information Technology (IT) and systems, would soon account for the most significant investment within organisations. The focus for investment by UK manufacturing companies previously concentrated on the physical assets within a company (*i.e.* machine tools, plant and equipment etc.).

Although it is difficult to define the relationship between IT investment and company performance (Cline and Guynes, 2001), earlier studies have shown that companies who invested in IT for maintenance reported significant improvements in efficiency of operations (*e.g.* Lawrence, 1999).

IT in the form of CMMS, the Internet, computer-aided facilities and mobile computing etc., help provide an infrastructure to manage the vast and diverse data collected and used by maintenance. One example of a maintenance focussed Internet application is online technical help, whereby questions may be asked of an asset vendor's technical department to solve problems quicker than with traditional methods, such as telephone. Using this type of system, Frequently Asked Questions (FAQs) could be used to develop a menu of standard replies that solve common problems for immediate response. This approach could allow a technician to spend less effort and time trying to resolve less common or complicated problems (Higgins *et al.* 2002: p2.110).

As early as 1990, advanced IT was viewed as a critical factor to assist maintenance optimisation, since it was perceived to aid communication, and provide improved capabilities to store, retrieve and analyse information (Huber, 1990). Currently, improved IT functionality presents a better vehicle for sharing information, knowledge, and experiences among plant technicians and external experts (Matusheski, 1999; Swanson, 1999). An important addition to this vehicle is that experts no longer need to be on site to add valuable input to resolving problems, thus allowing teams of experts to work together on a problem to find the best solution (Matusheski, 2001). Therefore, it may be concluded that IT make decision-making more efficient

2.5.2 Information Systems Concepts

Information Systems (IS) are central to this thesis. Information is one of an organisation's most valuable and important resources. Information is often confused with data, and so it is important to distinguish between the two.

Data vs. information. Data consists of raw facts, such as an employee's name, address, and telephone number. When these facts are organised, interpreted or analysed in a meaningful manner, they become information. In other words, information is a collection of facts organised in such a way that they have additional value beyond the value of facts themselves (Bohn, 1994). Moreover, whereas data are valuable only to specialists, information is useful to everyone. For example, within the maintenance domain, maintenance information provides answers to questions such as: *Is there a fault? What is the fault? What is the severity? What is the expected time to failure? What are the repair recommendations?*

Process of transforming data into information. Turning data into information is a process, or a set of logical related tasks performed to achieve a defined outcome (Figure 2-5).

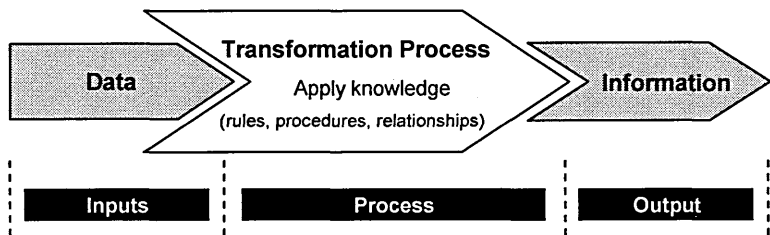


Figure 2-5: Process of transforming data into information
(after Stair and Reynolds, 1999: p6)

The transformation process consists of defining relationships (set of rules and procedures) among data. This process requires knowledge, *i.e.* an awareness and understanding of a set of information and how it can be made useful to support a specific task. Therefore, information can be considered as data made more useful through the application of knowledge (Stair and Reynolds, 1999: p6).

Information system. An IS is a set of interrelated elements that collect (input), manipulate (process and store), and disseminate (output) information to support decision making and provides a feedback mechanism to meet a goal (Stair and Reynolds, 1999: p15; Laudon and Laudon, 2000: p7) (Figure 2-6). The main aim of any IS is to produce valuable

information, which is directly linked to how it helps decision makers achieve an organisation's goals.

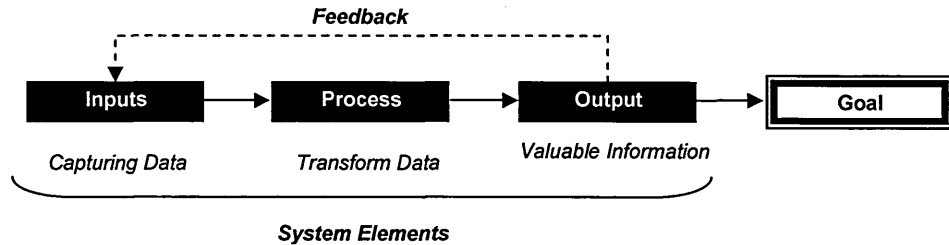


Figure 2-6: Information system definition
(after Stair and Reynolds, 1999: p6)

Types of IS. Although IS can either be manual or computerised, only the latter is considered here. A computerised IS is composed primarily of hardware, software, databases, telecommunication, people, and procedures that are configured to collect, manipulate, store and process data into information (Davis, 1999: ch1). The basic types of IS used within organisations can be classified into four basic groups (Stair and Reynolds, 1999: p33): (i) transaction processing systems (TPS), (ii) management information system, (iii) decision support systems (DSS), and (iv) expert system (ES).

2.5.3 Computerised Maintenance Management Systems

An IT system for maintenance referred to as a CMMS is commonly used to support and improve maintenance management efficiency both technically and financially.

Why are CMMS used? Demand for meaningful and consistent data has come to the forefront for every manufacturing activity, including maintenance, and by providing plant history data and other features, CMMS can play a major role in addressing challenges that face the maintenance function (Hipkin, 1997). As such, information provided by a CMMS could be seen as key to good maintenance practice, particularly in areas of decision making and problem solving (Cato and Mobley, 1999: p125).

Paper-based vs. computer-based systems. IS used to manage maintenance can be classified into two main categories: (i) paper-based and, (ii) computer-based. Paper-based systems require high storage capacity, and generally more difficult to update, and transport (Ventura, 1988). They also require considerable effort and time for those functions involving data storage, retrieval, analysis and communications (Wireman, 1994; Kelly, 1997a). Figure 2-7 presents a summary of problems associated with paper-based systems.

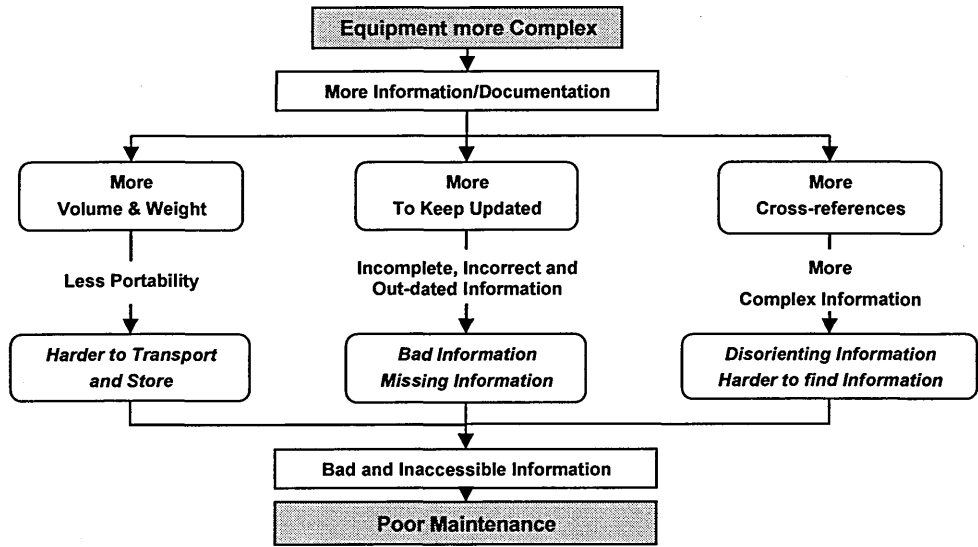


Figure 2-7: Summary of paper-based problems
(after Ventura, 1988)

CMMS perceivably reduce the time, cost and workload associated with maintenance support and repair activities. Using computer based IS technology means that drawings, images, diagrams and video techniques etc. can be accessed and managed by maintenance practitioners more easily than traditional paper-based systems (Landers *et al.* 1989).

Companies still use paper-based systems because they are easy to implement and have low running costs. However, the large amount of failure data required to support the maintenance management function, coupled with the need for its analysis and reporting, demonstrates the need for the use of computer-based systems (Raouf *et al.* 1992).

What are CMMS? CMMS range from simple, manual ‘T’ card work planning and control systems to sophisticated on line, real time, multi access, relational database computer systems that can run as ‘stand-alone’ or ‘main-frame’ (Willmott, 1992: p17). They are a mechanism for converting equipment and process data into information that can be used for expanding knowledge for maintenance improvement (Hipkin, 2001). These systems are now a central component of most companies (Labib, 2001), and are increasingly being used to manage and control plant and equipment maintenance (Swanson, 1997a; Berger, 2001; Weir, 2001).

CMMS functions. According to Raouf *et al.* (1992), a basic CMMS is expected to provide: quality control management; craftsman management; work order management; preventive maintenance management; inventory management; maintenance reports; general considerations; and vendor evaluation. In order to fulfil these requirements, CMMS generally have the following functions (Shenoy and Bhadury, 1998: p98):

- *Equipment maintenance: e.g.* to store failure and repair data;
- *Work order management: e.g.* to create maintenance requests;
- *Inventory management: e.g.* to store and maintain tools and skills data;
- *Vendor management: e.g.* maintain vendor information;
- *Subcontractor management: e.g.* maintain subcontractor data.

CMMS objectives. In general, the main objectives of a CMMS system are to: (Wireman, 1994; Shenoy and Bhadury, 1998; Cato and Mobley, 1999)

- Plan and schedule maintenance activities
- Plan procurement of resources
- Optimise maintenance resources
- Report maintenance performance
- Expedite dispatch and control of breakdown calls
- Automate preventive and predictive maintenance activities

CMMS provide timely and accurate information that will assist maintenance management in planning, organising, budgeting, staffing, directing, and controlling (Patton, 1994: p418).

According to Higgins *et al.* (2002: p2.45), the main purposes of CMMS are to

- Reduce costs (*e.g.* reducing repetitive clerical tasks)
- Increase access to information (*i.e.* information becomes readily accessible by storing data in a retrievable form and by facilitating data manipulation and reporting).

CMMS benefits. The main benefits of using CMMS are shown to be the: (Landers *et al.* 1989; Willmott, 1992: p18; Patton, 1994: p418; Hipkin, 2001; Labib, 2001)

- Usefulness of decision making and problem solving techniques
- Reduced amount of paperwork involved with maintenance
- Ease of access to and retrieval of maintenance historical data and information
- Internal and external communication links between users

2.5.4 Development of CMMS

According to Shenoy and Bhadury (1998), the development of an IS is divided into three main phases: (i) pre-design, (ii) design, and (iii) building and implementation. *Figure 2-8* illustrates this process. The pre-design phase, which involves determining the functional requirements of the system, is primarily exploited within this thesis.

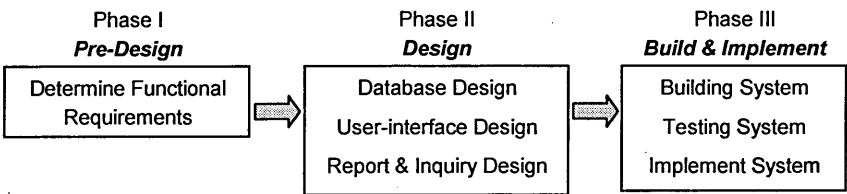


*Figure 2-8: Maintenance IS development
(after Shenoy and Bhadury, 1998: p97)*

Gathering the functional requirements of the system, (e.g. the user and technology requirements) is the first step in developing a CMMS.

Early CMMS development focussed on the number of functions within a system and their ability to work in a multi-user or network manner. Progressively the focus recognised the importance of relational databases to emulate information structures (which now form the basis for corporate systems), to focus on user-interface development (Eason, 1995).

Patton (1994, p420) suggests that maintenance and computer experts should be involved in CMMS development. However, as discussed previously this does not occur in most cases. In this thesis, the user requirements for development were gathered though interviews, questionnaires and document analysis. Shenoy and Bhadury (1998: p98) suggest a similar approach for the collection of user requirements. Although it is generally accepted that each user requirement will be different and that they will evolve in a fairly unique manner, this thesis attempts to demonstrate that patterns do exist. For this thesis the technology requirements are mainly gathered from a literature survey

2.5.5 Failure Data Collection

According to Patton (1994, p78), the word data “is generally used as both a singular or a plural noun meaning a group of facts that can be organised and analysed into information that, in turn, can be the basis for a decision”. Within the maintenance function, data collection is the process of fact acquisition to be used for supporting maintenance strategies, activities and philosophies. For this thesis the focus of research regarding data handling is connected to the issues of failure troubleshooting.

Importance of failure data collection. Maintenance managers have developed methods, hired people, and bought spare parts to support their assets, but they are also aware that data should also be considered an asset (Eason, 1984). According to Patton (1994, p418), “a computerised system is a tool for the maintenance manager to use, not an end in itself”, *i.e.* without the collection and input of failure data, these systems fail to perform their expected function. Although RCM authors commonly argue that there is no need for detailed data (*e.g.* Moubray, 1997), others claim that there is a strong case for comprehensive collection (*e.g.* Sherwin, 2000). A survey by Berger (2001) found that maintenance staff feels that data collection, analysis and reporting is a very important maintenance activity. A principal argument in favour of the collection of detailed data and the provision of integrated IS is that they enable accurate and unchallenged data to become more widely available for analysis and interpretation for the benefit of the company (Sherwin, 2000). Although Sherwin (1990; 2002) argues that every maintenance event must be fully documented, he also recognises that much of the detail has other uses besides setting PM and inspection schedules. It is thus understood, that the collection of detailed data is a function of the maintenance management model that each organisation uses, *i.e.* all failures should be recorded but the level of its detail depends of the data analysis purpose.

Collection Process. Traditionally, failure data (or history records) are collected through work orders, job cards, standard-practice sheets, etc. Different types of data are collected according to the needs of each user and each maintenance strategy or philosophy. According to Matusheski (2000) the types of failure data commonly used are:

- Failure location (*e.g.* equipment ID and type, manufacturer, model number)
- Failure repair data (*e.g.* type of activity, description of the work)
- Location (time) (*e.g.* failure date)

The method of collection should enable quick data entry, its format should be logical and consistent, and it needs to be as complete as possible (Levitt, 1996: p169). However, it should be stressed that, when designing the data collection systems, special consideration should be placed on what data is really needed for so that its collection can be limited. According to Page (2001), the data collection method should include structured and free form sections. The structured sections will ensure that important information is collected, while the use of free form sections and sketches will ensure that unforeseen additional information is provided.

Who enters the data? Page (2001) recommends referring to first line personnel (*e.g.* operators and engineering personnel) for failure data collection. This will enable data to be collected at the point of failure to ensure a more accurate picture of events. However, as noted by Kelly (1997a: p184), in order for first line personnel to conduct good data collection, the paperwork should be simple to handle and software user-friendly. Personnel should be provided with ample time for information input between jobs, and must be convinced that the system will benefit them (Kelly 1997a, p184). Other authors (*e.g.* Mather, 2001), suggest that maintenance planners or dedicated technicians should be used for data collection and input since the information collected is more reliable and first line personnel will have more time to focus on their core functions.

2.6 Maintenance Documentation

Since good quality documentation is a pre-requisite for efficient maintenance (Dhillon, 2002), maintenance documentation and the forms of which it may be represented (failure records, technical documentation and maintenance expert knowledge) are described in these sections.

Although maintenance documentation can have a number of uses (*i.e.* reliability, cost and failure analysis etc.), for this thesis greater emphasis is given to the documentation that may assist troubleshooting. Additionally, for the purpose of this thesis, reference will be given to Sproull's (2001) definition of troubleshooting, in that it can be viewed as the logical art of identifying and repairing a malfunction.

2.6.1 Failure Records

Failure record is defined here as the documentation of work completed. It may draw together data in a meaningful form, or record decisions, results or methodology. The documentation may consist of a single item, or of a series of related items comprising a total file.

The need for sufficient and consistent data on repairs has been recognised, and for many years considerable thought has been given to the development of records that provide information for maintenance (Higgins *et al.* 2002: p1.35; Shenoy and Bhadury, 1998: p7; Kelly, 1997a: p204). Thus, a great number of different failure records are produced by companies, each fulfilling its purpose. The purpose of these records might vary from supporting maintenance strategies, activities and philosophies, to assisting inventory and costs control. Although the use of failure reports generally can contribute to a wide area of activities, in this thesis their contribution to corrective maintenance is investigated. Failure records can be used to assist corrective maintenance by providing maintainers with access to experiences of past failure troubleshooting (Wireman, 1994). Blanchard *et al.* (1995: p125), also point out that proper maintenance procedures for corrective maintenance must be stated and documented clearly for the effectiveness of troubleshooting. Thus, troubleshooting reports are emphasised in this research.

Function of troubleshooting records. For preventative maintenance (Niebel, 1994: p158 and Dhillon, 2002: ch3), troubleshooting records can be used to identify chronic failures, identify and group related work, capture job plans for future work (Army, 2003a), and determine and control maintenance activity (Ikhwan and Burney, 1994). However, their major purpose is to provide information that guides the execution of future corrective jobs, in that they can be used to assist identification of failures, diagnosis, and problem solving (Corder, 1976: p197; Kelly, 1997a: p220; Labib, 1998a).

Importance of keeping troubleshooting records. According to Dhillon (2003, ch3), keeping failure records is one of the main functions of maintenance, since they play a critical role in the effectiveness and efficiency of the maintenance organisation. Wireman (1994: p2) stresses that maintenance of existing equipment cannot be accomplished in a timely and cost-effective manner without accurate records. In addition, according to a study conducted by Hedding (2001), maintenance crews spend around 17% of their time determining a solution to the problems when starting from 'scratch'. As such, improvements regarding assistance of maintenance crews during troubleshooting are crucial if maintenance effectiveness is required. This is particularly relevant in the case of complex equipment (Corder, 1976: p197), because demands on the skills of troubleshooters become higher as systems become more complex (Faulkenberry, 1986: p136). It is believed that providing maintainers with experiences of past failures will make troubleshooting more effective and efficient and, as such, downtime might be reduced (Niebel, 1994).

Keeping troubleshooting records means that solutions for repetitive equipment failures do not need to be looked at over and over again. As Biase *et al.* (2001) state, "whether you are lucky or not, resolve not to solve a problem twice". These records can provide equipment information on troubleshooting breakdowns and areas of concern, which are useful when procuring new equipment (Dhillon, 2002: ch3) and when selecting stock materials (Higgins *et al.* 2002: p2.89). Furthermore, perhaps the best feature of a good recording system is that, when experts are not available, part of their knowledge is available (Priel, 1974: p51). In addition, since part of expert's knowledge will be represented in these records, there is less need for training. Landers *et al.* (1989) argue that these records can also be used for training, which is particularly important when the variety of equipment is so large that in-depth training for each becomes impractical.

Troubleshooting record design. To assure the effectiveness of the troubleshooting records, careful considerations need to be given during its design. Dhillon (1981) presents an extensive list of guidelines to design records, from which the following are distinguished: (i) simplicity and clarity of the failure reporting form, (ii) clarity in terms and definitions, (iii) users need to be involved, (iv) flexibility, (v) elimination of the needs for memorising codes, and (vi) provide feedback in an effective manner to all personnel involved. Moreover, although it is important for repair history to include data on minor and major repairs (Higgins *et al.* 2002: p1.37), greater requirement for standard-practice sheets is in the following (Higgins *et al.* 2002: p1.24):

- (i) cases of large numbers of identical equipment or equipment having identical components that require a repetitive type of repairs,
- (ii) cases of complex repairs, and
- (iii) cases that demand a high degree of skills and experience.

Table 2-1 summarises the type of information that should be kept in the troubleshooting records.

Type of Information	Reference
Description of the failure	Neibel, 1994; BS 5759-5, 1991; Bloch, 1997; BS ISO 14224; Higgins <i>et al.</i> 2002; Kelly, 1997a; Patton, 1994
Description of the diagnosis process	
Description of the repair actions	
Type of repairs	Wireman, 1994: p7
Sequence of operations (step-by-step procedure)	Higgins <i>et al.</i> 2002: p1.24
Methods used	Corder, 1976: p68
Special remarks (e.g. tolerances, alignment, safety aspects)	Corder, 1976: p68
Indication of the cause(s) of the failure	Higgins <i>et al.</i> 2002: p1.40
Technical information (spare parts, materials, special tools, craftsman requirements)	Patton, 1994; Corder, 1976: p68; Higgins <i>et al.</i> 2002: p1.24)
Appendixes (charts, diagrams, graphic, videos, pictures)	(Priel, 1974: p57; Knapp, 1989).

Table 2-1: Type of information included in troubleshooting records

When designing troubleshooting records, one should consider that there is a beneficial aspect of using paperless IS (Knapp, 1989 and Landers *et al.* 1989). For example, preparation and processing times using an IS are likely to be substantially quicker, provide greater accuracy, fewer redundancies, and increase system quality in a timely manner to support effective decision making (Blanchard *et al.* 1995: p126). In essence, paperless improves the information management, and improved information leads to improved decisions (Sherwin, 2003).

2.6.2 Technical Documents

Technical documents are another important resource that maintainers can use to assist them during troubleshooting. Documents typically supplied by most equipment vendors include process diagrams and operation, maintenance, troubleshooting, and design manuals. These documents usually provide recommendations for correct operation and maintenance of the equipment. This section presents their contribution to maintenance.

Traditionally, technical documents provide structural, functional, and failure information. Structural information is usually provided in the form of process diagrams and concerns process typology, *i.e.* information about what equipment is available and how it is connected, *i.e.* parts layout. Functional information is typically available in design manuals and concerns equipment function and operating conditions of the various systems, subsystems, and hardware. Functional information helps maintenance technicians to understand the equipment, to know how equipment operates, and to identify equipment boundaries, complex failures, and causes and consequences of failure. Failure information is commonly presented in the form of troubleshooting manuals (or troubleshooting guides) and concerns the potential malfunction of the equipment, *i.e.* things that might go wrong with the equipment. These manuals contain common malfunction symptoms, causes, and recommendation for repair (Faulkenberry, 1986: p137), and identify many of the common problems that might occur in the equipment. The information provided in these manuals is essential for both effective resolution of plant problems (Moubrey, 1999: ch3) and for training maintenance technicians (Faulkenberry, 1986: p137).

Troubleshooting manuals are similar to troubleshooting records. The main difference is that manuals refer only to standard and common equipment failures identified by the supplier, while the records refer to all (or at least those found more relevant) failures experienced by the equipment user. Thus, particularly for new equipments, for which no failure experiences are known, the collection of troubleshooting records is important.

2.6.3 Maintenance Expert Knowledge

Although reports and manuals provide useful assistance with troubleshooting, maintenance technicians often prefer referring to their own expert knowledge gathered through experience and training (*surface knowledge*) rather than manuals (*deep knowledge*) to solve problems (Gandhi *et al.* 1994, Higgins *et al.* 2002). Similarly, in situations where documented assistance is not available or at hand, maintenance technicians are forced to rely on the knowledge and experience gained through previous troubleshooting. However, as noted by Gandhi *et al.* (1994) it takes years of experience in a maintenance facility to become an expert in fault diagnosis, if at all.

Commonly, maintenance technicians when confronted with a problem they cannot resolve either seek internal support through collaboration or refer to external help (*i.e.* service company, consultants, and equipment suppliers/vendors). As discussed by Faulkenberry (1986: p137) an equipment manufacturer is a particularly good source of troubleshooting information; a telephone call to the manufacturer can save hours searching for a solution to an obscure problem. Internally, operations, engineering, and maintenance tend to collaborate when solving problems especially in light of shared goals (*e.g.* resume production as soon as possible after a breakdown) (Berger, 2001).

In 1994 Gandhi *et al.* stated that "...there are great opportunities if the knowledge of various experts are integrated and validated amongst various experts...". Similarly, in 1995, Levitt stated that sharing information is an important aspect of achieving World Class Maintenance. However, although many companies recognise these benefits and use team based environments for more effective information sharing and problem solving (Matusheski, 1999), what are the pre-requisites for the implementation of knowledge-sharing systems to assist maintenance technicians during troubleshooting? Again, however, although competitors frequently share benchmarking information for overall industry benefit (Berger, 2001), a lack of information suggests that this is not the case for maintenance knowledge issues such as troubleshooting information. Therefore, companies might benefit with particular regard to the maintenance of their equipment if information on failure troubleshooting were shared between manufacturer, owners and users.

The issue here is to know what and how to collect and organise information in such a way that users will benefit and learn from using a maintenance expert knowledge system. According to Ann (1994) and Batty (1995), using standard information representation is a pre-requisite for knowledge sharing. It has also been demonstrated (Bent *et al.* 1999) that related events or initiatives are more likely to have an impact on memory and subsequent learning so that individuals can remember events more easily. For example, the stimuli of past failure events could help maintenance technicians to resolve new or unrecognised failures. It might also be that the failure experiences of others could stimulate the learning of individuals to improve their trouble shooting skills.

This thesis will explore a way of making a base for maintenance expert knowledge more accessible and effective for system users either internally or externally (to an organisation). As such, the core concept of this thesis will be to identify a set of recommendations to design a Support Documentation System.

2.7 Maintenance Communication

Within maintenance, communication is key to the management of failure information (Raymond, 1992), which makes troubleshooting activities highly dependent on how well the actual failure information is communicated (Bloch, 1997: p446). To assist the flow of information, significant developments within computer technology now allow data to be shared efficiently among many systems, giving users access to vast amounts of data (Higgins *et al.* 2002: p2.43). However, productive communication requires a willingness to contribute. For example, individuals who know the facts about a problem might not offer all the information needed to resolve an issue or provide misleading information, purposefully or otherwise.

Identifying the things that can be done to increase the willingness of others to supply the information needed is one of the research issues of this thesis. However, the aim of this section is to present a global frame of communication within the maintenance function in order to define the thesis scope regarding maintenance communication.

2.7.1 Maintenance Interfaces

The maintenance department needs to communicate and interact with most of the organisation's other departments and at some point with external entities, *e.g.* servicing contractors and equipment vendors. *Figure 2-9* presents the general maintenance interfaces.

Within the maintenance department, communication is mainly verbal and occurs between shop floor workers (maintenance and operations) and maintenance supervisors or members of the maintenance investigation team (Kelly, 1997a: p215). Work orders or history reports are used at this level (level 1) to improve communication. At this level, the communication objectives fall mainly in one of the three following categories:

- (i) *Control* - monitor the output parameters of each unit;
- (ii) *Quick reaction to problem* - clear information about problem identification and their causes;
- (iii) *Efficient resolution of problems* – structured information about how to solve the problem.

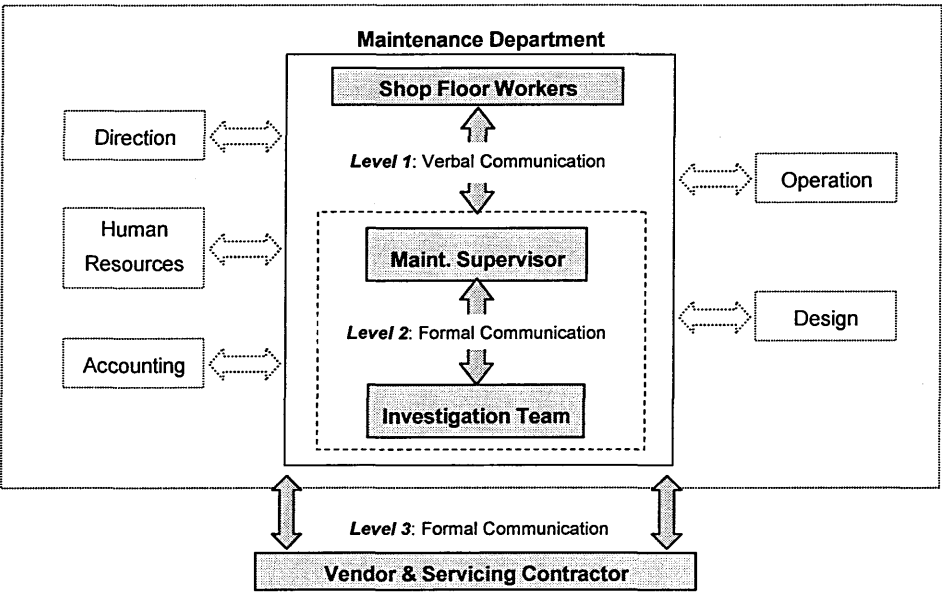


Figure 2-9: General maintenance interfaces

The second level of communication may be defined between maintenance supervisors and the maintenance investigation team. Unlike the first interface level, communication is more formal (Kelly, 1997a), and so IS play an essential role in managing work order and history reports. The maintenance investigation team is usually responsible for planning, scheduling, preparation, root cause analysis, and cost analysis, and so they need to access all relevant failure information in a structured format to efficiently produce the above outputs.

The third level of communication is the interface between the maintenance department and an external entity, *e.g.* service contractor or equipment vendor. Similar to the first level, problems are commonly reported by verbal means, although service records rather than work orders are used to record failure information. Service records are often similar to the history records used by maintenance departments.

Sherwin (2003) claims that those companies that have tried working with their suppliers through mutual analysis of data have found them cooperative. He suggests also that both companies and suppliers would benefit from the data collection and respective mutual analysis. Kelly (1997a: p178) points out that the communication between the various users of a given type of equipment and its manufacturers offer the opportunity for maintenance information to be collected from a much larger pool of experience (Kelly, 1997a: p178). This is particularly important for organisations that have little failure experience, because

when failure occurs it is likely that technicians will have never seen this type of failure before, so it would be useful for them to access a large pool of related knowledge in order to infer a solution. The lack of failure experience might occur either because they rarely happen, for example due to the high equipment reliability or the efficiency of PM, or because relevant data are not collected, *e.g.* “Resnikoff Conundrum” (Resnikoff, 1978 in Sherwin, 2000).

This research therefore also investigates the development of a global database of failure records populated by equipment users and managed by vendors.

2.7.2 Maintenance Information Flow

Maintenance operations mainly include preventive and corrective maintenance, and modification (Figure 2-10). The job flow of maintenance operations can be generically defined as allocation, execution, and report. The reports generated by maintenance operations are stored in a database to complement existing documentation. Traditionally, these reports are verified and revised by control and planning sections, before being introduced into the database. The information contained in the database also needs to be fed back to operations and control and planning to optimise activities.

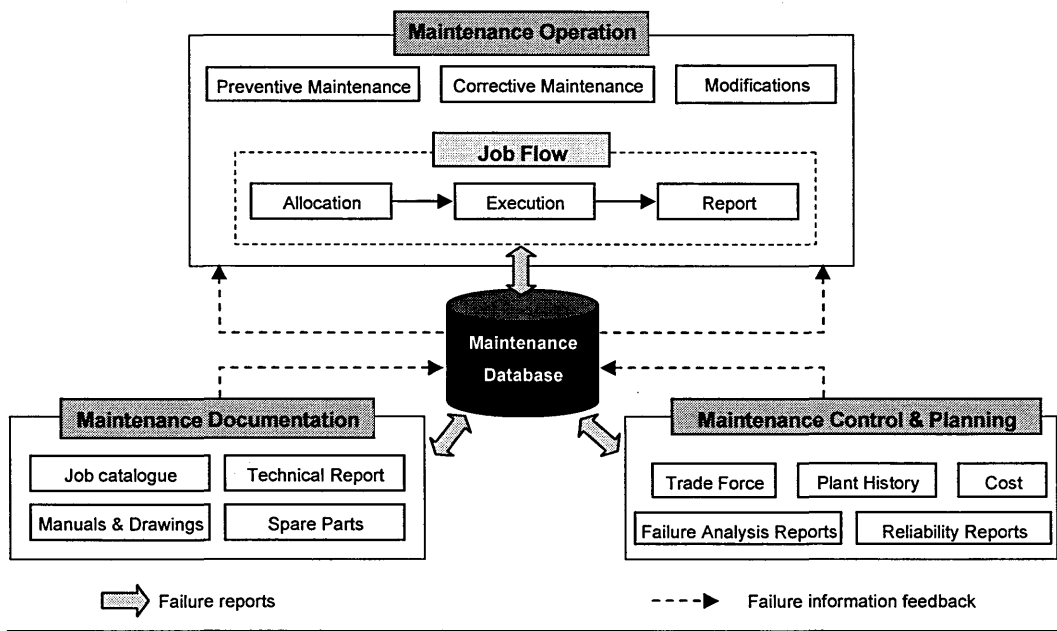


Figure 2-10: Maintenance information flow

2.8 'Smart' Maintenance Systems

The term 'smart system' (or smart technology) applies to a group of adaptive, or intelligent, computing techniques (or tools) that attempt to embody human-like reasoning and decision-making abilities within a computing system (Kermally, 2002). The difficulty for humans in managing and understanding large volumes of data and the need to represent an expert's knowledge are probably the main reasons for the existence of these techniques. Artificial neural networks (ANN), knowledge-based systems (KBS), fuzzy logic, generic algorithms, and case based reasoning are the more popular techniques to which this term applies. They generally perform more rapidly, reliably, and consistently than their conventional, and even human, equivalents. (Kirkham, 1998). This section presents a broad characterisation of the two techniques that appear to have received more attention within maintenance, namely ANN and KBS.

Artificial neural networks. ANN, or simply neural networks, consist of interconnected devices called *neurons*. Loosely inspired by the makeup of the nervous system, these interconnected devices look at patterns of data and learn to classify them (Zahner and Micheli-Tzanakou, 2000). They are characterised by simultaneously exploring many competing hypotheses using massively parallel nets composed of many non-linear computational elements connected by links with variable weights (Knapp *et al.* 2000). They acquire knowledge from examples through the process of training. This knowledge is encoded in its connection weights in a trained neural network and distributed numerically throughout the whole network structure (Jagielska *et al.* 1999). Neural networks are usually classified by their learning procedure, in unsupervised and supervised learning (Ilott and Griffiths, 1997). Further readings about neural networks can be found in Simon, (1999), Callan (1999) and Irwin (2000).

Within maintenance, fault diagnosis and fault monitoring problems are probably the main application of ANN. According to Knapp *et al.* (2000), they can be used to adaptively learn associations between fault conditions of complex machinery and fault symptoms exhibited in measurement data, such as vibration signals, oil analysis, or plant performance measures (current, pressures, temperatures). For example, Ilott and Griffiths (1997) proposed a fault diagnosis system of pumping machinery based on ANN. Weerasinghe *et al.* (1998) investigated the application of a single neural-network for the diagnosis of non-catastrophic faults in an industrial nuclear processing plant. Ungar *et al.* (1990) utilised a back-propagation network for diagnosing context-sensitive faults in a small chemical process system. Knapp and Wang (1992) used vibration data to study the application of a back-propagation network to fault diagnosis of a CNC machine.

Knowledge-Based Systems. KBS, or expert systems, are derived from Artificial Intelligence (Patel and Kamrani, 1996), and concern the design and implementation of programmes that are capable of emulating human cognitive skills such as problem solving, visual perception and language understanding. KBS are characterised by ‘taking’ human knowledge from experts and incorporating it into a computer system that can be used by others (usually non-experts) in decision-making and problem solving (Edmunds, 1988). The objective of these systems is to replicate human decision making for certain types of well-defined problems. KBS encode the domain-dependent knowledge of everyday practitioners in some field, and use this knowledge to solve problems, instead of using comparatively domain-independent methods derived from computer science or mathematics (Jackson, 1999: p4). A particular feature of these systems is that they can provide an explanation of the reasoning process, and suggest remedies (Callan, 2003).

Among other reasons, KBS have been applied in maintenance because they: (i) provide a more efficient, consistent, methodical, and faster diagnosis than human experts, (ii) permit that part of an expert’s knowledge to be always available, (iii) can be used as a training tool, (iv) provide the means for less experienced maintenance worker to conduct complex jobs (Patel and Kamrani, 1996). Fault diagnosis, troubleshooting, testability, and fault isolation are the main areas where KBS have been applied in maintenance (Blanchard *et al.* 1995: p286). Some examples of applications of KBS to maintenance are a system for: maintenance supervisor assistance (Paz *et al.* 1994b), supporting project planning (Moynihan *et al.* 2002), customer restoration and fault testing (Ma and Roger, 1992), maintenance scheduling and fault diagnosis of wire-EDM (Huang and Liao, 2000), assisting maintenance technicians with diagnosis and repair of riveting machines (Daley and Eyada, 1989), analysing failure modes and effects (Wirth *et al.* 1996).

2.9 Downtime Reduction

Previous sections showed that considerable research and work has been undertaken within maintenance. However, this section demonstrates that many problems are still poorly defined and vaguely described. Since it would be difficult to solve a problem without first understanding it, this section (and the following) aim to identify problems within the investigation topic that would allow the research problem to be defined.

2.9.1 General Approach to Downtime Reduction

As described in *Section 2.3.2*, ensuring the availability of equipment is one of the main objectives of maintenance. As such, minimising downtime is one of the most significant contributions that maintenance can offer to an organisation. In order to reduce downtime, both failure frequency and failure severity need to be reduced (Kelly *et al*, 1997), *i.e.* both the amount and duration of maintenance work needs to be minimised (*Figure 2-11*).

A feature of being able to minimise the amount of maintenance work is to reduce the number of machine/asset failures that occur. Traditionally, this has been managed by the use of applying preventive maintenance strategies, tools (*e.g.* FMECA) and, philosophies (*e.g.* RCM). Minimising the duration of the maintenance work is commonly approached by reducing both failure response and troubleshooting times (*Figure 2-11*). Failure response times may be reduced using methods such as automatic work orders, networking the CMMS between production and maintenance departments, and linking the CMMS to alarms and pagers via a programmable logic controller (PLC) (Labib, 1998a). Troubleshooting time is reduced by optimising both failure diagnosis and failure repair. However, in order to optimise these two maintenance strategies towards downtime reduction, the availability of failure information must also be assured.

Once the maintenance approach for downtime reduction has been explained, the following sections present some limitations and situations to improve this approach. Problems within the two main maintenance strategies, preventive maintenance and corrective maintenance, and within failure information management are presented. The identification of these problems (or limitations) will allow greater focus on the research problem.

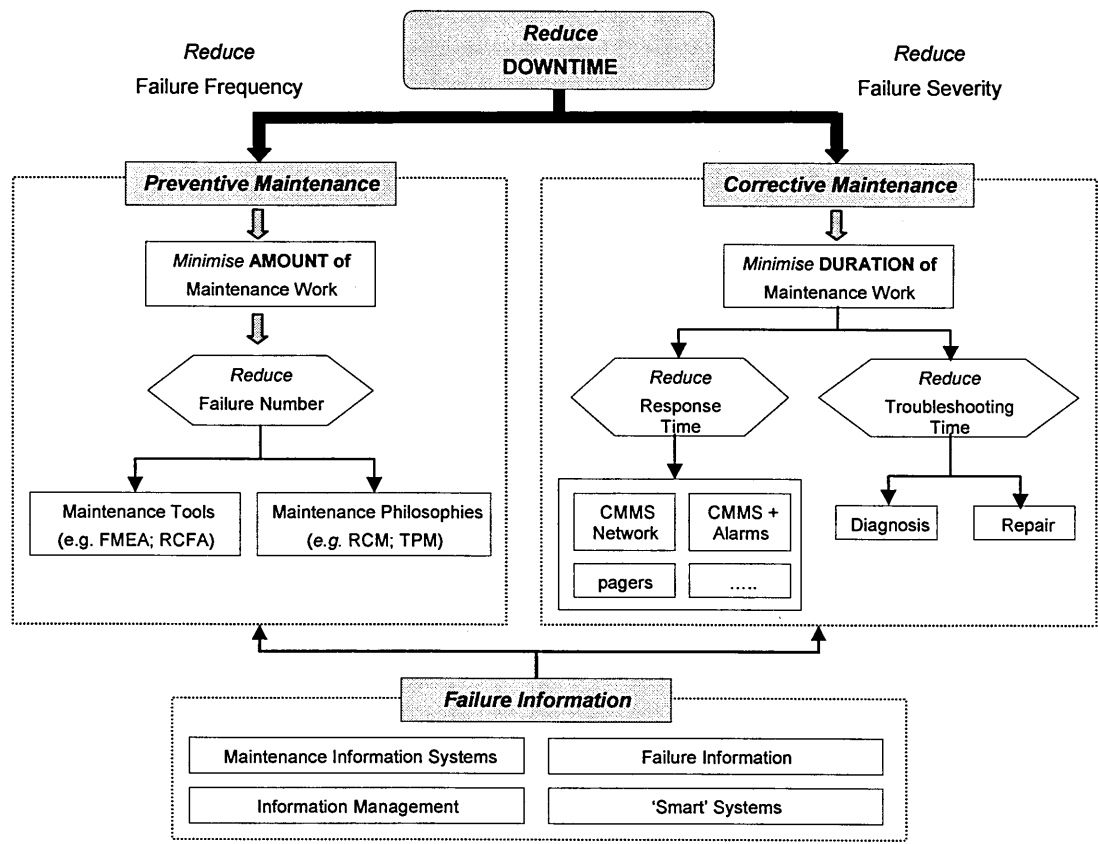


Figure 2-11: General approach for downtime reduction

2.9.2 Preventive vs. Corrective Maintenance

Preventive maintenance (PM) and corrective maintenance (CM) are two traditional strategies to achieve downtime reduction. PM strives to reduce the probability of failure in the time period after maintenance has been applied, while CM aims to reduce the severity of equipment failures once they occur (Paz and Leigh, 1994a).

Attracting greater attention in both industry and research the benefits of PM include reducing the probability of equipment breakdowns, allowing better planning, minimising maintenance costs, decreasing downtimes, and reducing overtime (Gilbert and Finch. 1985; Finch and Gilbert, 1986; Swanson, 1997a; Dhillon, 2002: ch4;). According to Mann (1976: p99), most of the benefits of PM are difficult to prove and can only be predicted. Nonetheless, preventive strategies have undoubtedly made a significant contribution to the reduction in number of failures and consequent downtime, although failures in actual operations are almost inevitable (Moss, 1985; Takata *et al*, 1999; Mobley, 1999).

Additionally though, it is impossible to predict with certainty when failures will occur (Lofsten, 1999), even the most reliable equipment will fail (Petrovic *et al.* 1986). As such, corrective unscheduled maintenance cannot be entirely eliminated, and will be always be an aspect of maintenance management (Finch and Gilbert, 1986).

Which strategy is used more? Since failure occurrence is unpredictable, CM strategies are generally associated with lower performance. Consequently, the potential disturbance caused by breakdowns is higher, which might lead to expensive indirect costs, *e.g.* production losses. Since preventive strategies have been proven to be generally more cost effective than corrective ones, a trend within organisations is to change from a reactive to a preventive approach (Moubray, 1997; Swanson, 2001). Nevertheless, several surveys show that the majority of companies are convinced of the need for PM, although the levels of CM (maintenance man-hour utilisation) in organisations are still high (Davies and Huggleston, 1994; Swanson, 1997a); in some cases higher than the levels of PM. For example, a study conducted by Moore (1999) found that the average level of CM within US manufacturers was approximately 49%. An earlier study showed that this level was 50% (Moore, 1999: p172). A study by Swanson (1997a) showed that the level was around 40%. These results show that there is not, in practice, a strong tendency to reduce the level of CM in organisations. It also indicates that, despite the potential benefits of PM strategies, CM represents almost half the maintenance activity. Dhillon (2002: ch3) supports this argument, quoting that ‘the major proportion of a maintenance organisation’s effort is spent on corrective maintenance’. Moreover, Dekker (1996) noted that the state of affairs in a maintenance organisation is often dominated by unplanned events. To illustrate this argument, *Figure 2-12* presents the work distribution within maintenance.

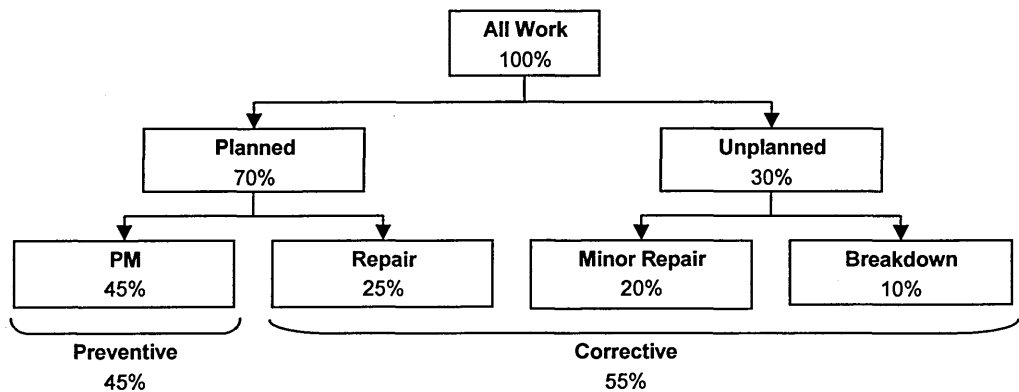


*Figure 2-12: Work distribution
(after Duffuaa, 1999: p44)*

Why are preventive strategies not having the expected integration? Perhaps the main reason why PM strategies have not had the expected integration success in companies is because PM interventions are normally constrained by production scheduling (Lofsten, 1999; Lawrence, 1999) and cause high production disturbance (Swanson, 2001). According to Higgins *et al.* (2002: p1.39), it is better to consider PM only when CM cannot be applied, due to the downtime required to perform PM. Moreover, even within the maintenance department, some people are against the idea of performing PM schedules. It is often claimed that stopping equipment during operation, in order to check its condition and service it, wastes time, effort, and money; and that these activities tend to lead to what is called in manufacturing ‘over-maintenance’ (Labib, 1999). However, there is also a cultural issue, *i.e.* ‘there is more glory in fixing things after they become a problem than there is in stopping them from happening in first place’ (Moore, 1999: p172).

Another issue is that, when PM strategies are applied often, equipment or parts are unnecessary replaced. The Nordic paper industry, which routinely replaced bearings on a PM basis, found on inspection that only 5% could have led to catastrophic failure, 30% had nothing wrong, and 65% had only minor defects (Moore, 1999: p182). Moreover, it is also commonly claimed that PM interventions often expose equipment to possible damage. This is mainly due to what is often called ‘infant mortality’ (Dillon, 2002); *i.e.* the new parts introduced in the equipment are subject to a higher failure rate, especially in the case of mechanical parts. Adding to this is the problem with the spare parts stocks. Generally, when PM strategies are applied, more spare parts are needed (Dhillon, 2002: ch4), which generates a conflict between the desire to reduce stock levels and the parallel target of improving response time to breakdown and reducing downtimes.

Running costs are also an important aspect that might limit the implementation of PM strategies. Generally, CM strategies are less expensive to run than PM strategies (Lawrence, 1999); this is mainly because they do not usually involve the regular change of equipment, and are not so demanding on failure data collection (Tschuschke, 1997). Lofsten (1999) argues that PM strategies are not always cost effective. Finally, the complexity of their mathematical models is a reason for the low utilisation of PM strategies; traditionally the majority of engineers do not understand them because they do not have the mathematical knowledge needed to use these models (Sherwin, 2003; Dekker, 1996). In addition to complexity, these models are commonly only valid under assumptions that are seldom encountered in practice (Kelly *et al.* 1997b).

2.9.3 Focal Approach for Downtime Reduction

While good maintenance programmes exist to address the anticipation and prevention of failures, it is difficult to find methods that ensure the quick resolution of a problem after failure has occurred. Where they do exist however, they are often only for very specific equipment (e.g. expert systems for diagnosis).

Although downtime has many components (Figure 2-13), this research mainly focuses on downtime due to failure diagnosis and failure repair; these activities are among the most important in the troubleshooting process. Moreover, the previous section demonstrated that, even with a commitment to PM, breakdowns will still occur, which makes failure troubleshooting extremely important.

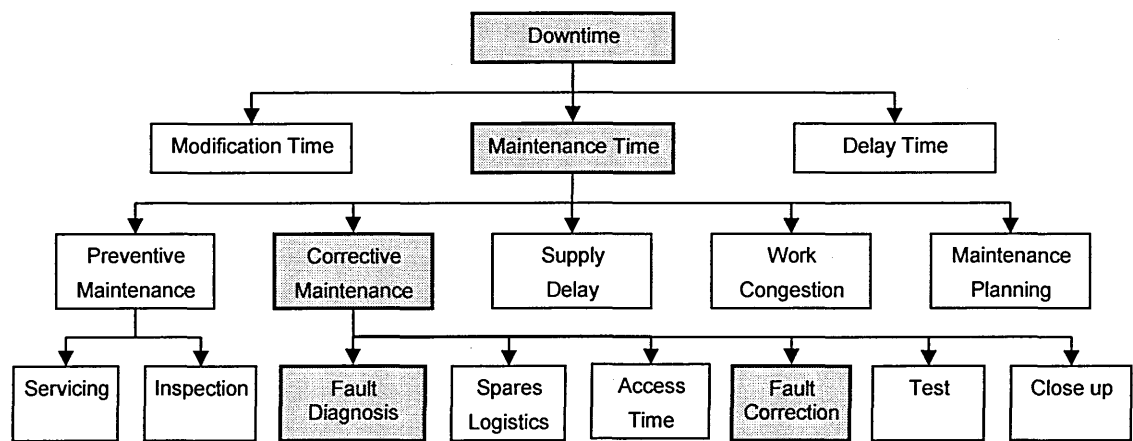


Figure 2-13: Components of machine downtime
(after Muramatsu and Takana, 1982: p11.7.2 and Knotts, 1999)

Reduction of troubleshooting time. When failures occur, maintenance technicians have to diagnose the fault and rectify the failure as quickly and safely as possible (Knotts, 1999). This process is commonly referred to as failure troubleshooting, or simply troubleshooting. The reduction of troubleshooting time involves minimising both diagnosis and repair time (Figure 2-14). Diagnosis time is reduced by making the process of identifying the failures quicker, and by ensuring that the right failure is corrected. Repair time can be minimised by speeding up the time to rectify the failure, and by ensuring that the correct repair procedures are followed. The reduction of both diagnosis and repair time traditionally relies on improving the maintainer's skills (Labib, 1998b), i.e. they are dependent on the maintenance expert knowledge. This knowledge is typically achieved through experience and training, which generally take a long time to acquire, are expensive, and become obsolete at the same time as the equipment (Sherwin, 2000). This has led to the

requirements for maintenance manuals with, for example, diagrams on how to remove and replace parts, and diagnostic charts with solutions for every conceivable set of symptoms.

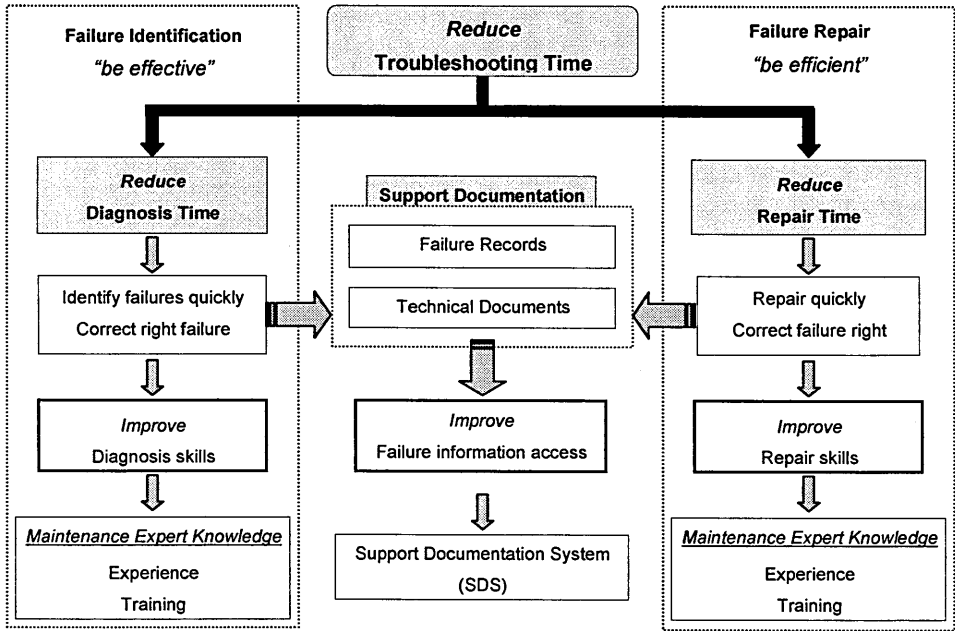


Figure 2-14: Focal approach for downtime reduction

When failures occur maintainers might refer to support documentation to assist both diagnosis and repair, in particular knowledge regarding past failure experiences (Labib, 1998b; Page, 2001). As Kelly (1997a: p174) points out, referring to failure records can significantly support the difficult task of diagnosing the causes of failure and prescribing the corrective action. As suggested by Ruszkiewica (1980), CM activities can be assisted by a database consisting of equipment descriptions, failure diagnosis and repair description, and the resources used. Supporting this Durham *et al.* (1997) demonstrated that failure data collection systems reduce downtime and the labour associated with troubleshooting. They also state that the ability to efficiently retrieve and review failure information is an effective tool for troubleshooting. However, failure records have traditionally not been categorised and aggregated in a way that facilitates their access, and in many cases troubleshooting is simply not documented (Fischer *et al.* 1996); technical documents are commonly not very intuitive, information is difficult to find, and are generally inadequate. Thus this research proposes investigating the development of a Support Documentation System (SDS) to assist troubleshooting.

2.10 Maintenance Problems

This section discusses some of the problems associated with using CMMS, particularly those related to failure information management.

2.10.1 CMMS Problems

Lack of CMMS utilisation. Currently CMMS are the most popular systems for managing failure information within maintenance. However, it appears that these systems are not fully coping with maintenance requirements. According to CMMS vendors, their clients use less than half of the information potential of their asset management systems (Haugham and Stirrman, 1996). According to Cato and Mobley (1999: p126) there is only a 9% overall utilisation of CMMS, mainly due to the complexity of most systems. Even when installed according to Weir (2001), only 5 to 10% of the available CMMS functions will be used (Weir, 2001). The difficulty of retrieving/accessing information is another reason for the lack CMMS utilisation (Matusheski, 2001; Army, 2003a). Consequently, unless sufficient training is provided data are rarely effectively used for maintenance activities (Army, 2003a). A survey by O'Hanlon (2003) not only supports these general arguments, but also showed that overall companies have been disappointed with the results of their CMMS implementation and use.

CMMS development. CMMS are often a poor fit to maintenance requirements because the generalists and IT experts that design them usually do not have sufficient experience of maintenance management (Herbaty, 1990: p306; Mulcahy, 1999). This might be one of the reasons for the majority of users reporting that their systems require further development to meet their specific needs (Jones and Collis, 1996). According to Raouf *et al.* (1992), designing a proper and effective CMMS requires the designer to have an adequate understanding of the maintenance functions and their purpose in the maintenance organisation. Billo *et al.* (1996) argue that a solution to this problem is for manufacturing engineers and IT specialists to view the development of these systems not merely as an IT project, but as a larger integrated project where user requirements are considered. They also stress that there is a critical need for IT researchers to establish standard functional and information requirements for manufacturing systems applications.

CMMS troubleshooting assistance. Kelly (1997a) argued that any CMMS should be capable of identifying problems that trigger corrective investigations. However, according to Cato and Mobley (1999), data fields describing what happened (history of failures) when failures occurred are not among the main fields usually included within a CMMS. As such, rather than using these systems to assist failure troubleshooting, CMMS are often used to evaluate failure trends, provide information to prevent future breakdowns, and evaluate costs (Cato and Mobley, 1999). Compounding this were the findings of a survey by O'Hanlon (2003) who found that only 20% of maintainer's track 100% of their maintenance and repair work in a CMMS; emphasising the low utilisation by maintainers of CMMS identified by Swanson (1997a). As such it may be seen that maintenance supervisors and planners remain the beneficiaries of using CMMS rather than maintenance technicians.

CMMS data collection. Some authors (*e.g.* Franklin (2000b) argue that CMMS collect a significant amount of data since no quantifiable point exists at which failure data becomes useful. Nonetheless, it is more practically accepted that data collection/acquisition is time consuming, difficult and expensive with the added pressures of daily work impeding useful data collection (Kelly, 1997a: p174; Levitt, 1996: p169; Patton, 1994: p81). According to Sherwin (2003), the usual objection to comprehensive data collection is the cost. Also, since the features of using CMMS are not particularly aimed at the maintenance technician it is difficult to get maintainers to collect failure data. As such, consideration regarding the benefits of use by the maintainer has to be given (*i.e.* motivation), especially as they are the primary source for collecting information. One approach to this issue would be to design a CMMS in such a way that they could provide useful information to assist maintainers during failure troubleshooting.

2.10.2 Problems with Maintenance Support Documents

This section discusses problem issues associated with maintenance support documentation, which need to be improved for increased usability by maintainers. The areas under discussion here are technical manuals, failure records and failure record storage

Technical manuals. During troubleshooting maintenance technicians may refer to technical support in the form of equipment manuals provided by the equipment suppliers. Although these manuals contain information to assist troubleshooting, they are limited in their application in that they do not consider operational environments (*i.e.* the context in which equipment is operating), are limited to standard failure modes and are often considered too verbose and confusing (Bennett and Jenney 1980; Moubray 1997; Higgins *et al*, 2002.

Additionally, whereas maintenance technicians previously relied extensively on external knowledge (Bohn, 1994), equipment supplier recommendations are increasingly being questioned and replaced by a company's past experiences obtained from failure records (Hipkin, 2001). In addition, a study by Cooke (1999) demonstrated that the skill requirements for maintenance work are much wider than the information provided in existing technical manuals.

Failure records. Recording failure experiences in the form of a report is a method for collecting tacit knowledge from maintenance technicians. This knowledge transfer process can be useful for inexperienced maintenance technicians who can later refer to the expert documentation to support their actions rather than make decisions by 'guessing'. This process is also important in that part of the expert's knowledge will always be available. However, one of the main problems of failure records is how to generate written reports. As discussed earlier, maintenance technicians are not generally motivated to complete failure reports if they feel that they could see no direct benefit, or what they were for. Although a study conducted by Hipkin (2001) showed that, according to managers, the quality of information improved once they had explained to craftsmen why that information was needed.

The usual work pressures of maintenance technicians, combined with poorly designed collection forms, makes failure records rare within most companies. There is also the fear that information records will be used to replace people (Tobin, 2001). As such, most of the experiences gained by maintainers concerning equipment history is 'inside people's heads' (Weir, 2001); consequently, it not available for others to use. In the author's experience, is still not unusual to hear a maintenance technician state:

'John is the one who knows the job' or 'I hate to think what would happen if Smith goes'

Despite stressing that failure reports might contain relevant information to assist troubleshooting, maintenance technicians often fail to refer to them. This might be due to the difficulty of accessing current paper-based information or that reports often miss out the information needed to aid troubleshooting. However, since assisting corrective maintenance is not viewed as a main function of most CMMS, it is still unlikely that failure reports are being designed to assist maintenance technicians.

Failure records storage. In order to improve access to failure information, it is important to improve the methods by which many CMMS have traditionally stored failure records. A common trend of these systems is to classify failure reports using equipment attributes, *i.e.* equipment identification codes are assigned to failure information. These attributes are undoubtedly important for classifying failure records. However, in order to allow searches by similarity, these attributes must be independent because different equipment might have similar failure modes and repair actions. Moreover, searches for failure information within equipment with an extensive number of failure records tend to be time consuming because no other attributes (*e.g.* failure attributes) are commonly used to restrict the searches. Since the failure reports traditionally have a field (notes field) where failures are described, searches by keywords (or text matching) through these fields are also possible with some CMMS. However, since individuals would describe failures in their own way, it does not always facilitate the failure information retrieval process.

2.10.3 Problems with Maintenance Expert Knowledge

Despite maintenance documentation being an important support tool to assist maintenance during troubleshooting, technicians commonly refer to their expertise to solve the problems (Higgins *et al.* 2002). Nonetheless, the task of identifying, diagnosing, and repairing failures has become increasingly more difficult and more demanding as technologies and equipment become more complex (Husband and Basker 1982; Paz and Leigh, 1994a; Cooke, 2002b). In order to cope with this evolution, the issues concerning the deployment of maintenance skills and knowledge are a strategic importance in the competitiveness of an organisation (Cooke, 2002a), particularly in terms of quicker response and repair times.

Experiential knowledge is considered *post facto*, *i.e.* it is knowledge gained from past experiences used to overcome current or future problems or issues. For example, a maintenance technician confronted with an equipment problem (or failure) uses their expert knowledge gained from a previous similar problem to help identify a solution (or repair). During this process, experiential knowledge is acquired about the problem, which will increase their future expert knowledge base (*Figure 2-15*). This process is commonly known as ‘learning from experiences’, and is probably the most important way of improving maintainers’ skills. As Hippel (1998) states, ‘those who solve more of a given type of problem tend to get better at it’.

Certain authors on tacit skills and knowledge (*e.g.* Manwaring, 1984; Pavitt, 1991) argue that tacit knowledge obtained through experience is of central importance in organisational competence. However, difficulties with acquisition and representation are central problems

with experiential knowledge. The problem is that expert knowledge tends to be tacit, with only a small portion being explicit. Sometimes referred to as ‘know-how’, tacit knowledge is characterised for being difficult to represent because it is contextualised, personal and intuitive, difficult to communicate, and is job specific (Davenport and Prusak, 1998; Sternberg and Horvath, 1999; Patel *et al.* 1995). As such, although experts are highly skilled in solving problems within their own domain, they often have difficulties in articulating their knowledge or sometimes even in understanding their own decision-making processes (Jagielska *et al.* 1999). The problem is how to collect and represent this knowledge. According to Cooke (2003), technicians are interested in becoming involved and managers should provide opportunities and structures for their involvement in order to harness their talents.

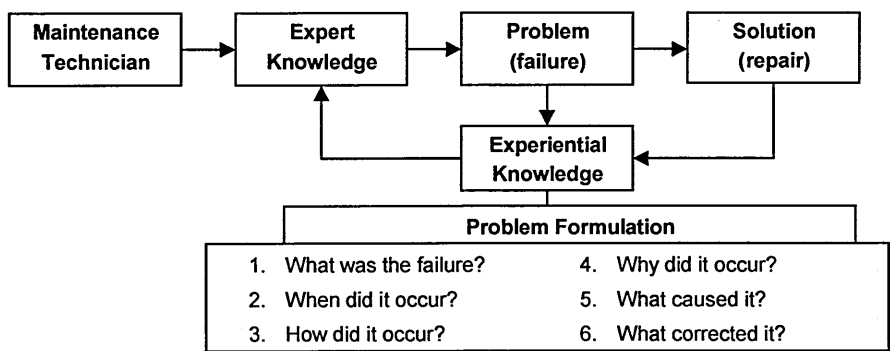


Figure 2-15: Process of expert knowledge acquisition

Technicians confronted with new problems that are difficult to solve often call on their own experiences of past failures or those of others. The main risk with this approach is that experts are not always available and so it is useful to gather and represent their knowledge. This knowledge can be gathered through failure reports (Moubray, 1997), which usually include a description of the way failures were previously diagnosed and repaired. Supporting this argument, Kelly (1997a) points out that referring to the failure records can significantly support the difficult task of diagnosing the causes of failure. Therefore, it is clear that failure records that include a clear statement of how failures were diagnosed and repaired are important to the efficiency of the maintenance function.

Repairs are often delayed because the maintenance technician assigned might lack the knowledge and experience required to quickly isolate and correct the problem (Daley and Eyada, 1989). Practitioners have confirmed that effective plant performance requires a well-trained maintenance staff (Varma 1996; Weir, 2001), and so companies often use training to increase the maintenance expert knowledge. However, training is costly and

time-consuming, and the knowledge imparted becomes obsolete at the same time as the equipment (Sherwin, 2000). Consequently, maintenance urges an approach that can minimise training needs.

2.10.4 Problems with ‘Smart’ Maintenance Systems

Despite their potential benefits, ‘smart’ systems are restricted in their application due mainly to high costs and the time usually involved in their development (Tombs, 2004). Commonly, these systems are applied only for critical equipment, where failures might cause severe production, quality or safety losses (Daley and Eyada, 1989), and for complex equipment where many different faults are likely to occur (Starr, 2000; Blanchard *et al.* 1995: p286). Although ‘smart’ systems are available for maintenance applications, this section pays particular attention to KBS (or expert systems), due to their relevance to the research topic. The purpose here is to justify why this research takes a different approach from expert systems.

Expert system (ES). Stair and Reynolds (1999: p510) state ‘The computer is better than humans at transferring information, ...but humans are better at all other attributes of intelligence’. This is probably why most maintenance managers tend not to rely on computer-based information to make decisions but prefer to get information from people (Labib, 1996: p 43). Labib also suggests that this happens because people add value to raw information by interpreting it and adding context.

According to Stair and Reynolds (1999: p510), ES are not yet widely used because:

- They are difficult to use
- They are limited to relatively narrow problems
- They cannot readily deal with mixed knowledge
- They present the possibility for error
- They cannot refine their own knowledge base
- They are difficult to maintain
- They have high development costs
- Their use raises legal and ethical concerns

Among other difficulties associated with ES development is the extraction of expert knowledge, there is no common storage programme format for the data, no common operating system within which the data is stored, and not all data are in electronic form (Kirkham, 1998). Kirkham (1998) also says that ES are often dismissed for not providing expected rewards and that bad experiences develop a negative attitude in companies

considering further investment in these potentially beneficial techniques. However, ‘to bridge this gulf’ Kirkham says that data must be in a suitable format, be reliable, and allow representation of all the outcomes of the process to be modelled.

A function of an ES is to gather expert knowledge and represent it as a rule-based IS for use by non-experts to solve problems. In addition, ES are not achieving what they set out to do because they are expensive and not functionally straightforward, creating poorly understood operational problems (Tombs, 2004). Tombs also concluded that records management is now emerging as the preferred tool for information storage because it is easily understood by all, relatively low cost, highly adaptable and low in staffing costs.

Expert System vs. a System for Experts. Hirschheim and Klein (1989) present a case where the maintenance costs increased by 13% following the implementation of a diagnostic ES. They found that technicians relied too heavily on computer decision, which produced errors that were mainly due to the difficulties in formalising the knowledge base. As such, the ES was changed to a ‘system for experts’. With this new approach, technicians conduct the diagnosis based on their experience and knowledge, and refer to the system to confirm and clarify any thoughts.

The approach that is proposed in this thesis differs from ES because its aim is to create a system where information is gathered from experts for use by other experts. This means that it is not necessary to create a ruled-based system. The purpose is not transforming information into knowledge, but attempting to create a better management of knowledge represented in records.

2.11 Development of a Support Documentation System

Section 2.9.3 proposed the development of a Support Documentation System (SDS) to reduce troubleshooting time. This section presents the methodology that is traditionally followed to develop a documentation system, and describes how this methodology is used in this research.

Most of the problems reported in last chapter, regarding the management of maintenance documents, can be resolved through the development of an electronic document management system (BS ISO 15489-1, 2001; BS EN 82045-1, 2001). This type of system is referred to in this thesis as an SDS. Moreover, as demonstrated in Section 2.10.4, records management is emerging as a preferred tool for information storage when compared with ‘smart’ systems.

In order to design and implement a sustainable record system, a design and implementation methodology is essential (BS ISO 15489-1, 2001). Figure 2-16 presents a methodology for the design and implementation of a such a system. This methodology is not designed to be linear, *i.e.* the tasks may be undertaken in different stages, iteratively, partially or gradually (BS PD ISO/TR 15489-2, 2001).

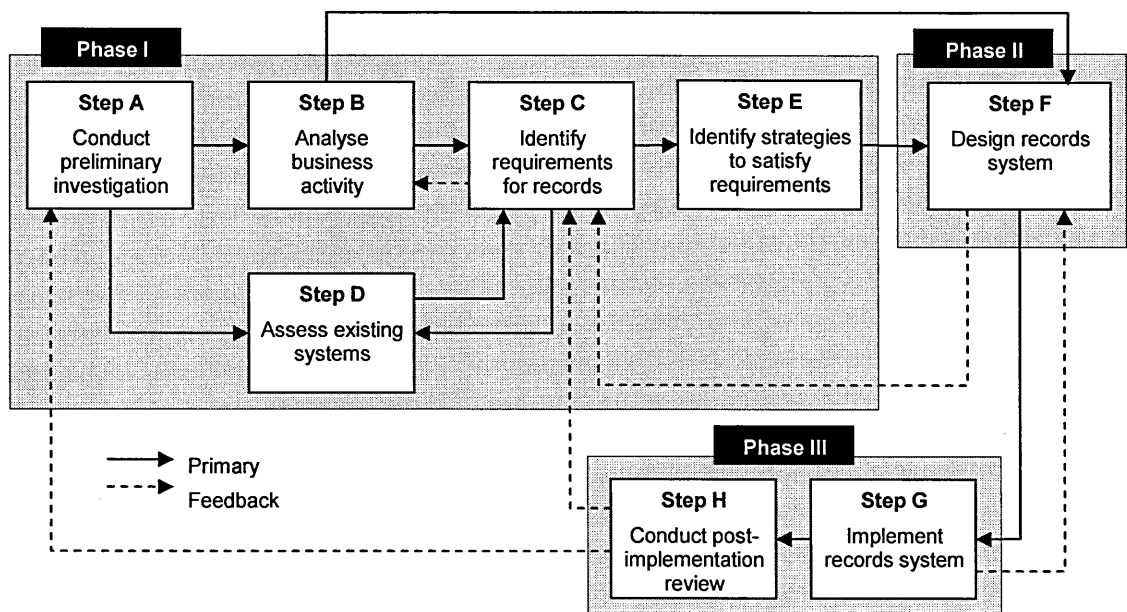


Figure 2-16: Methodology to design and implement a record management system (after BS PD ISO/TR 15489-2, 2001)

Figure 2-16 also shows the three phases of an information system design, which are as follows: (Shenoy and Bhadury, 1998: p97)

Phase I - Pre-design: determine requirements

Phase II – Design: database, user-interface, and report & enquiry design

Phase III – Implementation: build, test, and implement the system

This thesis only investigates the *Phase I* of development of the proposed SDS, *i.e.* only *Steps A* to *Step E* are studied. This comprises mainly the identification of both the content and the format of the records, and the tools suitable for creating and managing the records (*e.g.* Greenough, 2004; Robeck, 2000; Watts, 2000).

Steps	Key actions
Step A: Conduct preliminary investigation	<ul style="list-style-type: none">• Identify the system purpose and scope• Identify problems, weakness and strengths associated with records• Assess feasibility
Step B: Analyse business activities	<ul style="list-style-type: none">• Identify what the organisation does and how it does it• Identify the metadata strategies• Identify a thesaurus of terms to control the language for titling and indexing records
Step C: Identify requirements for records	<ul style="list-style-type: none">• Identify organisation's requirements• Identify contents and record's structure
Step D: Assess existing systems	<ul style="list-style-type: none">• Survey organisation's existing systems• Assess performance of current documents and systems
Step E: Identify strategies to satisfy requirements	<ul style="list-style-type: none">• Identify policy, standards, procedures, practices, and tools to satisfy requirements

*Table 2-2: Key actions of pre-design steps for documentation system design
(after BS ISO 15489-1, 2001; BS PD ISO 15489-2, 2001)*

2.12 Summary of Chapter

2.12.1 Summary of Findings

The chapter has argued that maintenance is one of the most important functions within manufacturing operations. It also shows that in order to fulfil a main maintenance objective, downtime reduction, considerable research and work has been undertaken within maintenance. Despite that, this chapter demonstrates that many maintenance problems are still poorly defined and vaguely described.

The chapter shows that most maintenance studies have been in failure prevention (preventive maintenance). These studies have undoubtedly made a significant contribution towards downtime reduction, although it is impossible to predict and prevent all failures. Moreover, it demonstrates that most companies are convinced of the need for preventive activities, yet, in practice, the level of corrective activities in organisations is still very high. Despite that, corrective activities have received little attention within research, and are still mostly dependent on the expertise and skills of practitioners. As such, the research proposes an approach to reduce troubleshooting time based on the optimisation of the management of support documentation, particularly of failure records. It suggests that if practitioners could easily access records of failure past experiences, troubleshooting would be performed more efficiently.

The chapter reviews then CMMS, maintenance support documents, expert knowledge, and 'smart' maintenance systems, in order to assess the current situation and to identify issues to improve, limitations, and gaps. This review identified that current CMMS are generally designed to provide more support to preventive rather than to corrective activities, a trend confirmed by the low CMMS utilisation rate by maintenance technicians. Moreover, literature suggests that practitioners' requirements are not being effectively considered when designing these systems. The chapter also identifies that maintenance support documents suffer from a lack of aggregation that inhibits their use by practitioners. Technical documentation and failure records tend not to be joined in a single database, which would promote cross-references between the different information types. Furthermore, findings also suggest that a study of a common format to classify and organise support maintenance documentation has never been attempted.

Consequently, practitioners rely on their experience and skill. It also suggests that potentially the failure information contained in the failure records would be of great benefit to practitioners. If the failure records can be aggregated and grouped into a single knowledge based, individual knowledge contained in each record can therefore be transformed into group knowledge.

The chapter also discusses the use of paper and computer-based systems to manage maintenance support documentation. Literature findings suggest that computer-based systems have a clear advantage over the paper-based systems, and that the use of digital manuals appears to potentially increase support documentation usage.

The chapter also describes 'smart' maintenance systems. Literature suggests that, despite their potential benefits, 'smart' systems are not fully meeting maintenance requirements. It is suggested that regarding the management of maintenance support documentation for practitioners' usage, a system for experts is potentially more efficient than an ES. A system for experts is more similar to a database of maintenance documentation, a repository of documents, where all documents are stored and linked. The systems provide potentially useful information while decisions are left for the users.

2.12.2 Conceptual Framework and Research Questions

This section outlines a framework of the maintenance function through which the forthcoming chapter on the enquiry process can be better understood. This new conceptual framework, which has not been developed previously, together with literature findings, are used to develop the research questions about which data will be collected in later chapters. This conceptual framework is simply the current version of the researcher's map of the territory being investigated that specifies *who* and *what* will be studied. *Figure 2-17* presents the conceptual framework of this research.

This research investigates practitioners within manufacturing systems that somehow are related to the maintenance function, namely, maintenance practitioners (managers and technicians), equipment vendors, and CMMS developers. Failure records contain the most frequently used technical failure information associated with equipment. The primary users of this information include maintenance personnel (*e.g.* technicians), and the secondary users of the information are the managers/supervisors (Duel, 2003). Thus they are surveyed. The equipment vendors are also surveyed because they have an active participation in the success of failure troubleshooting. CMMS developers (or designers) are

surveyed because these systems are the backbone of most organisations’ maintenance activity.

The research also investigates systems within the maintenance function that are related to the management of failure information, namely, CMMS, maintenance support documents, and maintenance expert knowledge. The purpose is to assess how these systems are coping with troubleshooting support.

The desired outcome of this investigation is a framework of key features to develop a support documentation system based on failure records and technical documents to assist maintainers during troubleshooting.

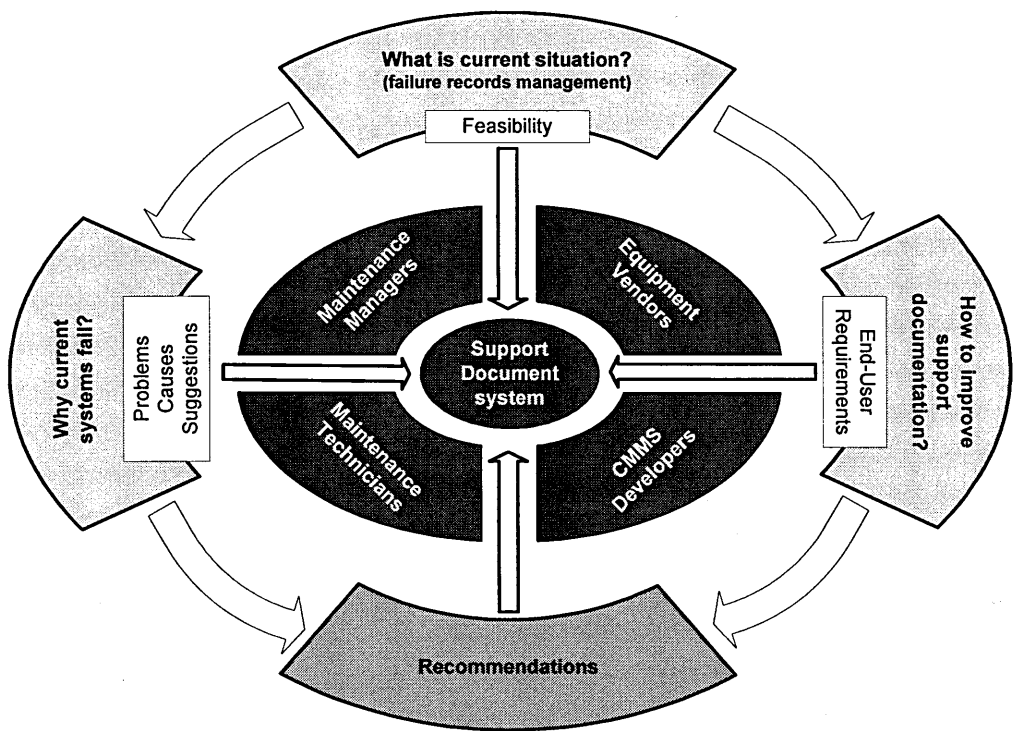


Figure 2-17: Conceptual framework

This research has a ‘theory’ building character (or purpose), as justified in the next chapter (Section 3.4.3). As such, hypotheses and propositions have not been defined (Eisenhardt, 1989); instead research questions are derived. According to Blaikie (1993: p4), social research is about exploring, describing, understanding, explaining, changing or evaluating some aspect of social work. These activities can be grouped according to the research purpose into three main categories of research questions: ‘what’, ‘why’ and ‘how’ questions (Table 2-3).

Question Category	Research Purpose
'What'	Exploration and description of some phenomenon
'Why'	Understanding or exploring some characteristics of the phenomenon, e.g. to make predictions
'How'	Practical outcomes with ways in which change might be brought about.

Table 2-3: Categories of research questions according to the research purpose
(after Blaikie (1993; p4)

Considering these categories, the conceptual framework, and the literature findings, the following research questions were derived for this research:

Research Questions

- Question 1:** *What is the current situation regarding failure records utilisation within maintenance of manufacturing systems?*
- Question 2:** *What are the reasons why current maintenance information systems do not effectively support troubleshooting?*
- Question 3:** *How can support documentation be improved to provide better aid to maintenance personnel during troubleshooting?*

These research questions were reformulated several times during the research, *i.e.* resulted from several iterations according to the evolution of the research. Having settled the research questions, the next issue is to define how they will be answered, *i.e.* the definition of the research methodology. Considering these research questions, the following chapter will define the research problem, stating the research aim and objectives. Moreover, the research methodology will be described and justified.

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Chapter III

3 RESEARCH DEFINITION: Research Problem & Methodology

This chapter defines the research problem and the research methodology.

- *It presents the research aim and objectives*
- *It describes and justifies the methodology used in this thesis*

3.1 Introduction

The previous chapter presented and defined the main concepts of the research topic, justified why this research is being conducted, and identified some maintenance problems within the research topic. It characterised the problem situation, which has not been previously addressed and from which the research question emerged.

3.1.1 Chapter Objectives and Overview

The aim of this chapter is to define both the research problem and research methodology. In order to fulfil this aim the following objectives were defined:

Objective 1: To define and state the research problem;

Objective 2: To explain the research philosophy and methodology adopted;

Objective 3: To explain the research strategies and methods adopted;

Objective 4: To explain the design of the research strategies and the collection methods;

Objective 5: To describe data analysis methodology;

Objective 6: To explain the quality assurance of the research.

The chapter begins by defining the research problem. It considers the main findings of the literature review and research questions, and defines the research aim and objectives (*see Figure 3-1*). Following the research problem definition the chapter reviews both research philosophy and methodology in order to select the most suitable approach to conduct the enquiry process. Considering these approaches and the nature of the research problem the chapter then reviews the research strategies and defines both the enquiry purpose and strategies that best suit each of the research questions.

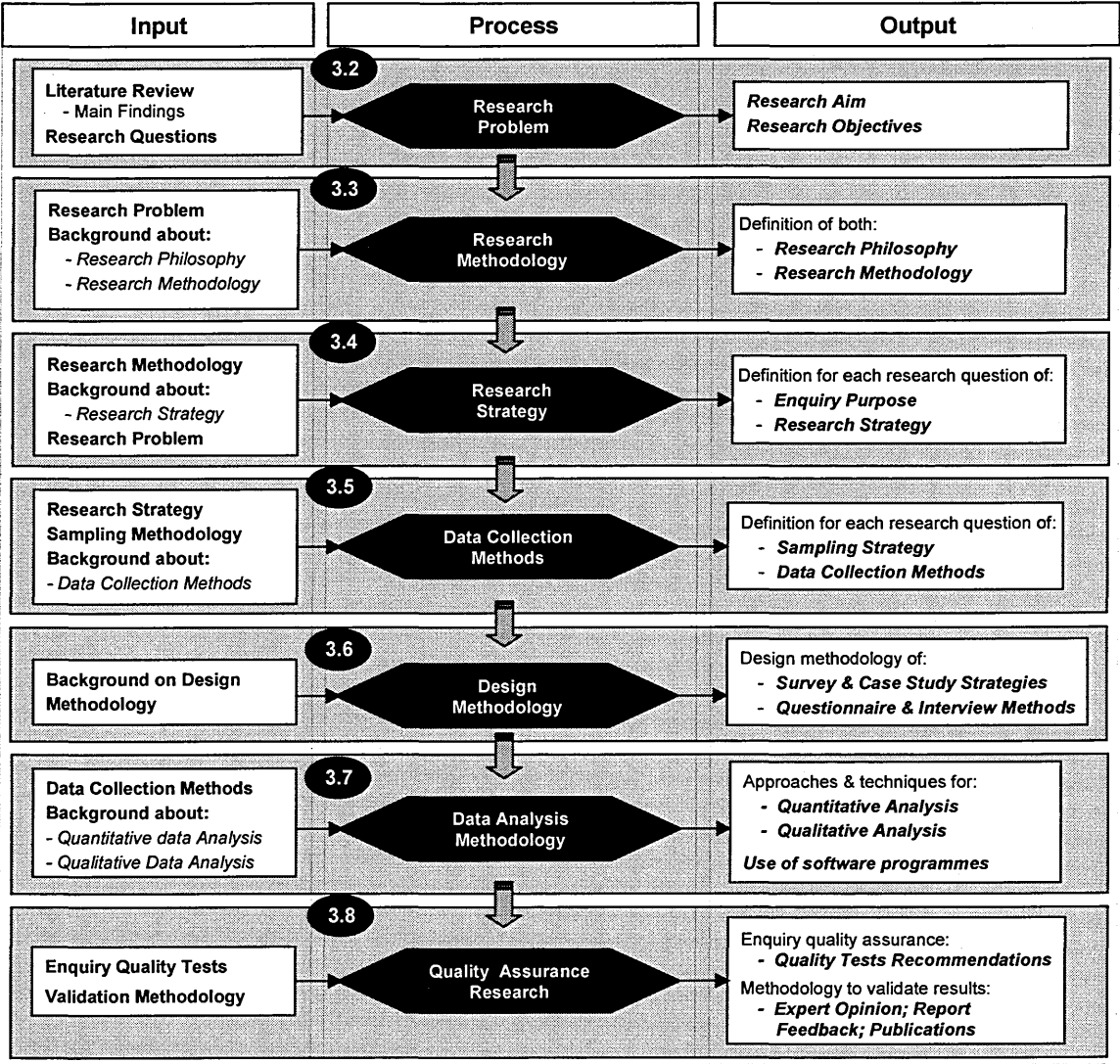


Figure 3-1: Chapter overview

The chapter reviews both sampling methodology and data collection methods. Considering this background and the selected research strategies the chapter defines both sampling strategies and collection methods. Once strategies and methods are selected the chapter stresses their design methodology, indicating the steps that are followed. The chapter then considers these methods and some background about data analysis, and identifies the data analysis approach that best suits each type of data. The chapter concludes by stressing the quality assurance of the research. It presents the methodology that is followed to guarantee the quality of the enquiry process and of the results.

3.2 Research Problem

This section considers the research issues from literature and defines the research problem, *i.e.* states the problem and defines the research aim and objectives. The definition of the research problem will guide the definition of the research methodology, which is described in the following sections.

3.2.1 Problem Statement

The literature review identified that downtime reduction is one of the most important objectives of maintenance, and that organisations traditionally apply preventive and corrective strategies to achieve this goal (*Section 2.9.1*). However, evidence suggests that, despite the high levels of corrective activity in organisations, these activities have received little attention from researchers (*Section 2.9.2*). This research proposes an approach to reduce troubleshooting time based on the optimisation of the management of support documentation, particularly of failure records (*Section 2.9.3*). It is suggested that if maintenance technicians could easily access records of experiences of past failures, troubleshooting would be performed more efficiently. However, the lack of an empirical study that characterises the current situation regarding failure records management limits the development of such a Support Documentation System. Furthermore, as far as the researcher is aware, the development of such a system has never been attempted, *i.e.* there is no evidence about the practitioner requirements regarding the improvement of the management of support documentation, particularly of failure records. Published literature also illustrates the awareness of some contextual issues showing that current CMMS and support documentation are failing to provide efficient assistance to maintenance personnel. However, there is little empirical evidence to support the above argument.

Considering the above situation, the nature of the research problem considers IS applied to maintenance of manufacturing systems, dealing with the interaction of people and technology.

3.2.2 Research Aim and Objectives

In order to clarify the direction of the research study and enable the definition of research the aim and objectives, the research questions that emerged from the literature review are re-stated here.

Research Questions

Question 1: What is the current situation regarding failure records utilisation within maintenance of manufacturing systems?

Question 2: What are the reasons why current maintenance information systems do not effectively support troubleshooting?

Question 3: How can support documentation be improved to provide better aid to maintenance personnel during troubleshooting?

The literature review and the emerging research questions indicate the existence of a need for empirical research that investigates current situations regarding failure information management. Therefore, the research aim that will guide the process of addressing these questions can be stated as:

Research Aim

To explore the conceptual design of a support documentation system that will best assist maintenance personnel during troubleshooting

The research questions and aim led to the development of a series of research objectives that can be viewed as proposed outcomes of the research investigation. The delivery of these outcomes will represent a contribution to knowledge, which is discussed in the final chapter. The research objectives are as follows:

Research Objectives

Objective 1: Assess the feasibility of a support documentation system based on failure records to assist maintenance personnel during troubleshooting.

Sub-Objectives:

1. Identify if failure records are important to assist maintenance;
2. Identify reasons for failure records collection and non-collection;
3. Identify current trends in managing failure records;
4. Assess the satisfaction and usage of current systems used to manage failure records;
5. Assess the relationship between equipment users and vendors with regard to maintenance;
6. Assess the creation of a database of failure records populated by users but vendor managed;
7. Analyse if there is any relation between failure records collection and company type, company size, and process type.

Objective 2: Identify reasons why current maintenance information systems (CMMS and documentation systems) do not effectively support troubleshooting.

Sub-objectives:

1. Identify the utilisation rate and the degree of satisfaction of CMMS and documentation systems in troubleshooting assistance;
2. Identify the causes, effects, and suggestions of problems with CMMS and documentation systems when supporting troubleshooting;
3. Evaluate end-user involvement in CMMS and documentation systems development.

Objective 3: Identify key features for the design of a proposed support documentation system that will best assist maintenance personnel during troubleshooting.

1. Identify the goals and requirements of the maintenance personnel regarding the use of documentation to support troubleshooting;
2. Identify and classify repair data that can be used to support troubleshooting;
3. Identify and rank attributes to characterise and classify failure records;
4. Identify how equipment identification data is being classified.

3.3 Research Philosophy and Methodology

One of the purposes of this chapter is to examine the various approaches that can be used to design the research methodology. Research methodologies are traditionally classified into two main approaches, namely qualitative and quantitative (Robson, 1995: p18). Each of these approaches is based on a particular paradigm, a patterned set of assumptions concerning reality (ontology), knowledge of that reality (epistemology), and the particular ways of knowing that reality (methodology) (Guba, 1990: p17-30). Some investigators distinguish between quantitative and qualitative research not on the basis of the type of evidence but on the basis of wholly different philosophical beliefs (*e.g.* Lincoln and Guba, 1985). As such, this section describes and establishes the connection between research philosophy and methodology. It provides a brief overview of the two main philosophical positions of social research, and describes how these standpoints are closely related with either qualitative or quantitative methodologies.

The aim of this section is to present a concise justification for the methodological approach employed in this thesis, which is believed to best meet the research objectives. *Appendix A* complements this; it defines some basic methodological concepts, and presents strengths and weaknesses of both research philosophies and methodologies.

3.3.1 Research Philosophy

A research philosophy is a belief about the way in which data about a phenomenon should be gathered, analysed and used. According to Myers (1997), the most pertinent philosophical assumptions are those that relate to the underlying epistemology that guides the research. The term epistemology (*what is known to be true*) as opposed to ontology (*what is believed to be true*) encompasses the various philosophies of research approach (Davison, 1998). These philosophies are traditionally distinguished in two main contrasting schools of thought, commonly labelled as the *positivist* and *interpretivist* paradigms (or epistemologies) (Galliers, 1992). Although other authors (*e.g.* Blaikie, 1993) considered other approaches to social enquiry, *critical rationalism*, *critical theory*, and *realism*, only the positivist and interpretivist approaches are considered within the scope of this thesis. *Table 3-1* summarises the key features of the positivist and interpretivist philosophies. *Section A.2 (Appendix A)* presents a more detailed description of these two philosophies.

Positivism (or Natural Sciences) Emphasis on:	Interpretivism (or Naturalistic) Emphasis on:
• Experimental methods	• Non-experimental methods
• Deductive theorising, <i>i.e.</i> hypothesis testing	• Inductive theorising, <i>i.e.</i> hypothesis seeking
• Preordained research design	• Emergent research design
• Objectivity	• Subjectivity
• Detachment	• Participation
• Quantitative data to determine significance of results	• Qualitative data to give meaning to results
• Significance or otherwise of outcomes	• Meaning of processes that lead to outcomes
• Demonstration of changes that have occurred	• Meaning of changes that have occurred
• Isolating the elements of behaviour for investigation	• Importance of context in shaping behaviour
• Constructing evidence	• Searching for evidence in context

Table 3-1: Key features of the positivism and interpretivism philosophies
(after Gillham, 2000a; p8)

3.3.2 Research Methodology

Although research methodologies can be classified in various ways, one of the most common distinctions is between quantitative and qualitative (Robson, 1995: p18; Hancock, 2002: p1). Despite some authors (*e.g.* Myers, 1997) referring to these approach as methods, following the definitions presented in *Section A.1 (in Appendix A)*, they are designated as methodologies within this thesis. Within systems theory, the quantitative approach is known as ‘hard systems thinking’ and the qualitative approach is known as ‘soft systems thinking’ (Checkland, 1994).

Quantitative Methodology. The quantitative methodology is based on positivism (Sale *et al.* 2002). The activity of quantitative methodologies is to establish well-tested knowledge about the world and our place in it. The ontological position of the quantitative approach is that there is only one truth, and an objective reality that exists independent of human perception. Epistemologically, the researcher and the researched are independent entities (Sale *et al.* 2002). Its method involves carrying out reductionist, repeatable experiments that aim to test hypotheses to destruction (Checkland, 1978: p99). Quantitative approaches are built upon a foundation of premises and beliefs, including the assumption that data must yield proof or strong confirmation of a theory or hypothesis in a research setting. The purpose of the quantitative approach is to develop causal laws, where data are derived from the use of strict rules and procedures, which are fundamentally different from common sense (Robson, 2002).

Qualitative Methodology. The qualitative approach is traditionally based on interpretivism (Secker *et al.* 1995), although it can also be positivist or critical (Myers, 1997). Within a qualitative methodology, the world is seen as problematic and such that it should be studied systematically. Ontologically speaking, there are multiple realities or truths based on one's construction of reality (Sale *et al.* 2002). Epistemologically, there is no access to reality independent of our minds, no external reference by which to compare claims of truth (Smith, 1983). According to Checkland (1988), qualitative methodology is best suited to 'messy' real-world problem situations dominated by different attributes of meaning. His soft systems methodology provides structured guidelines for examining the social context of any scientific intervention in real world affairs. Gerson and Horowitz (2002) suggest that this approach is concerned not only with objectively measurable 'facts' or 'events', but also with the way that people construct, interpret and give meanings to the experiments. It offers ways of examining the intervention itself, as well as the problem situation, as both a social system and a political system (Checkland, 1994). According to Mingers (1984), qualitative research is action-oriented, the purpose of which is to facilitate taking action in the real world in order to bring about change. The approach typically includes attention to dynamic processes rather than static categories or the people and events they observe.

Summary. Debates about whether to use quantitative or qualitative approaches in social research often confuse the underlying epistemology with the technical aspects of each (Glesne and Peshkin, 1992). According to Miles and Huberman (1994) researchers should not be preoccupied with the qualitative-quantitative debate because it will not be solved in the near future, and this discussion does not get research completed. As such, no further discussion is taken about this issue, and only the main features of both approaches are presented (*Table 3-2*). *Section A.3 (Appendix A)* presents the strengths and weakness of both quantitative and qualitative approaches.

Although *Table 3-2* illustrates the type of research philosophy that best suits either quantitative or qualitative approaches, this is not exclusive. This means interpretivism can be associated with quantitative and positivist with qualitative (Chua, 1986). Moreover, although this thesis distinguishes social research into qualitative and quantitative approaches, other authors have different opinions. For example, Onwuegbuzie (2003) de-emphasise the terms quantitative and qualitative research and, instead, subdivides research into exploratory and confirmatory. In addition, a combination of both approaches is also possible. Miles and Huberman (1994) present a series of authors who argue for the utilisation of both approaches, as and when appropriate.

	Quantitative	Qualitative
Assumptions	Reality is objectively given (objective)	Reality is socially constructed (subjective)
	One truth	Multiple truths
	Usually associated with positivism	Usually associated with interpretivism
	The method is the focus	The subject is the focus
	Variables are identifiable and relationships measurable	Variables are complex and often not measurable
Purpose	Generalisation	Contextualisation
	Prediction	Interpretation
	Test a theory or hypothesis	Derives hypothesis & ground theory
	Casual explanations	Understanding actors' perspectives
	Deductive / Experimental	Inductive / Descriptive
	Explanatory: What are the relationships between variables?	Exploratory: what are the variables involved?
Approach	Starts with hypothesis and theories	Starts with research questions
	Ends with casual laws	Ends in hypothesis & ground theory
	Uses formal instruments	Researcher is the primary instrument
	Component analysis	Searches for patterns
	Seeks consensus	Seeks pluralism
	Reduces data to numerical indices	Makes minor use of numerical indices
Researcher Role	Detachment and impartiality	Personal involvement and partiality
	Objective portrayal	Empathic understanding

Table 3-2: Comparison between quantitative and qualitative methodologies (after Glesne and Peshkin, 1992; Perry, 2000; Robson, 2002; Hancock, 2002)

3.3.3 Research Philosophy and Methodology Adopted

This section justifies the adopted research philosophy and methodology. This selection is based on the key features, strengths, and weaknesses of both research philosophy and methodology (presented in *Appendix A*), and the nature of the research problem,

Philosophy of the research. Analysing the features of both research philosophies and the nature of the research problem, interpretivism appears to be the most suitable research philosophy for this research. First, according to Miles and Huberman (1994), one of the characteristics of interpretivism research is to “explicate the ways people in particular settings come to understand, account for, take action and otherwise manage their day to day situations” suggesting that an interpretivist philosophy is most applicable to this research. Second, positivist philosophy is characterised by using experimental methods to collect evidence. However, this strategy of data collection is not the most suitable to answer the research questions of this thesis (as later in *Section 3.4*). Third, the research does not aim to

identify cause and effect relationships. Since reality is continually being constructed and influenced by the values and motivations of those involved, there is little opportunity to identify the link between causes and effects. Fourth, positivism aims to generalise findings; but in human behaviour generalisation from one group to other, or one institution to another, is often questionable (Guillham, 2000a; p6). Fifth, the questions asked by the researcher and the context in which they are discussed are expected to influence the way in which relationships are presented. Consequently, the findings are the result of the interaction between the meanings evolved by the researcher and the meaning offered by the participant. Sixth, this research involves an IS (*Information Systems*) investigation within which positivism is only applicable if there is evidence of formal propositions, quantifiable measures of variables, hypothesis testing, and drawing of inferences about a phenomenon from sample to stated population (Orlikowski and Baroudi, 1991: p5). The previous section showed that this is not the case in this research; which research aims to generate a theory. Finally, regarding the nature of the research questions, it is expected that the data is mainly qualitative, and the research is focused on exploratory and inductive purposes. From what have been discussed above regarding the nature of the research problem and the features of the research philosophies, interpretivism is the most appropriate philosophy to address the research problem.

Interpretivism is the most appropriate research philosophy to address the research problem

Research methodology adopted. In order to maximise the amount of information about the research problem, a research methodology based on the kinds of information that we seek should be chosen (Falconer and Mackay, 1999). The purpose of the research is focused on exploration (justified in the following section) of a social world problem within IS applied to the maintenance of manufacturing systems. The intention is to look for depth and richness of meaning that might well be context specified. The overall aim is to develop a new and empirical grounded ‘theory’ to improve the management of maintenance support documentation. The quantitative approach is not recommended for studying either the social world or IS (Jones, 1978) because their complexities are best addressed by methods of social sciences (Symons and Walsham, 1989: p405). Despite much CMMS research following the traditional conventions of scientific methods (Tranfield, 1983), the qualitative approach has been applied successfully to IS development (Symons and Walsham, 1989: p406). This methodology was also been successfully applied by Ince (2000) and Silva (2002) when developing a methodology for capturing user requirements for IS design and

optimisation. According to Avison *et al.* (1999), the qualitative and quantitative approaches are now of equal value for IS research. Qualitative approaches do not have the intention of creating rigorously testable models of the system, despite the role played by empirical observation (Jones, 1978). McKie (2002) also argues that qualitative research is appropriate where potential outcomes are not clear in advance.

Based on the above arguments, the strengths and weaknesses of each approach, and awareness that there is no perfect methodology to conduct research (Garson, 2002: p22), the qualitative approach was found the most suitable methodology for carrying out the research. Despite this, both qualitative and quantitative data collection methods are used in this research, as justified later (see *Section 3.5*).

A qualitative approach is the most appropriate research methodology to address the research problem

3.4 Research Strategy

This section introduces the research strategies used to conduct the enquiry process. It presents the criteria for the selection of research strategies and justifies the strategies used within the thesis. The key features of the research strategies are presented in *Section A.4 (Appendix A)*, and the design issues are discussed later in this chapter.

Research strategies are methodologies of enquiry that define the way researchers collect data (Walsh, 2001). Just as there are various research philosophies and methodologies, so there are various research strategies - sometimes referred as research methods. Survey, case study, and action research are examples of some key research strategies (see Robson, 1995; Yin, 1994; Galliers, 1992; Walsh, 2001). There are research strategies that are more typically used according to each research philosophy and methodology. *Table 3-3* presents a taxonomy of research strategies identified by Galliers (1992: p149), indicating whether they typically conform to the positivist or interpretivist paradigms.

Positivism	Interpretivism
Laboratory experiments	Subjective/argumentative
Field experiments	Reviews
Surveys	Action research
Case studies	Case studies
Theorem Proof	Descriptive/interpretative
Forecasting	Futures research
Simulation	Role/game playing

Table 3-3: A taxonomy of research strategies
(after Galliers, 1992: p149)

It should be stressed here that other taxonomies of research strategies exist (e.g. Bennett, 1991; Jenkins, 1985; Gill and Johnson, 1991; Yin, 1994; Robson, 1995; Blaxter *et al.* 1996). Many of the strategies suggested by these researchers are related, some only differ in the nomenclature, while others can be seen as versions or extensions of main strategies. Despite the awareness of most research strategies, this thesis only introduces the strategies that are generally applied in social research, and particularly in qualitative research. According to Robson (2002), experiment, survey, and case study are the most often used research strategies. Action research is also introduced due to its relevance and utilisation within social research. These strategies are presented in *Section A.4 (Appendix A)*.

3.4.1 Criteria for the Selection of Research Strategies

Considering the enquiry purpose (or research purpose) is one way of selecting a research strategy. For example, Robson (1995: p42) identifies three potential purposes of enquiry, namely exploratory, descriptive, and explanatory, that are widely accepted and used. He also notes that these enquiry purposes are not mutually exclusive, *i.e.* one study might have more than one enquiry purpose. *Table 3-4* summarises the key features of each enquiry purpose and indicates the appropriate strategy according to each purpose.

Enquiry Purpose	Key Features	Suggested Strategy	Typical Questions Type
Exploratory	Find out what is happening, seek new insights, ask questions, and assess phenomena in a new light	Case study	How, what, when and where
Descriptive	Portray an account profile of persons, events or situations	Survey	How and what
Explanatory	Explain a situation or a problem, usually in the form of casual relationships	Experiment	Why

Table 3-4: Features of enquire purposes
(after Robson, 1995: p42; Yin, 1994: p6; Hart, 1998: p47)

Each research strategy can be used for any or all purposes (Robson, 1995: p45), and all research strategies might be relevant for some research purposes (such as exploratory research) (Yin,1994: p9). However, there are strategies that are more appropriate to use according to the purpose of the enquiry (Robson,1995: p43). *Table 3-4* also indicates the type of research question typically used within each research purpose (Hart, 1998: p47).

While the enquiry purpose provides some guidance for the selection of the research strategy, three other factors can also be used to complement the selection process, namely: (Yin (1994: p6)

- The type of research question (most important);
- The degree of control that the researcher has, or wishes to have, over events; and
- The focus on current or past events.

Table 3-5 presents the way these three factors are related to the research strategies.

Strategy	Factors		
	Research question type	Requires control over events?	Focus on current events?
Experiment	How, why	yes	yes
Survey	Who, what, where, how many, how much	no	yes
Case study	How, why	no	yes

Table 3-5: Factors influencing research strategy selection
(after Yin, 1994: p6)

Inductive vs. deductive strategies. Regarding the enquiry purpose, research strategies can also be classified as inductive or deductive and so the distinction between both is made in this section. The inductive strategy corresponds to a popular conception of the activities of scientists, *i.e.* of persons who make careful observations, conduct experiments, rigorously analyse the data obtained, and hence produce new discoveries or new theories. With a deductive strategy, the researcher tests a theory by gathering appropriate data. Hypotheses or research questions are derived from the theory, concepts and variables are operationalised, an instrument is used to measure the variables in the theory, and finally hypotheses are verified (Hart, 1998: p192). The deductive strategy begins with a question or a problem that needs to be understood or explained. Rather than starting with observations, the first stage is to produce a possible answer to a question or an explanation for the problem (Blaikie, 1993: p144). In the inductive structure, the researcher gathers information and data (without selection), questions are asked about the phenomenon, the data are classified and placed into categories without using hypothesis, patterns are looked for in the data and potential theories are proposed, and finally theories are tested and developed and patterns compared with other patterns and theories (Blaikie, 1993: p137).

3.4.2 Research Strategy Adopted

Enquiry purpose. The purpose of the enquiry is one factor that influences the research strategy selected, and so describing the enquiry purpose is an initial step in defining the research strategy. According to Robson (1995: p38), the research strategy (or strategies) must be appropriate for the research questions. The research questions (*Section 3.2.2*) are of the ‘what’ and ‘how’ type, which, according to *Table 3-4* eliminates the explanatory purpose. Explanatory research aims to find causal relationships, is based on hypotheses generated from previous work, and is often used to test already established knowledge, which is not the case of this research, as discussed in the problem definition.

The first research question aims to characterise the current situation regarding failure records utilisation within maintenance of manufacturing systems, as such its purpose is more descriptive. The second and third research questions are about finding out what practitioners know and think, and about determining practices and recommendations for the development of a documentation support system. They aim to identify what is happening, to seek new insights, and to explore and increase understanding based on the premise that research to date has failed to establish a ground ‘theory’ about the research problem. Based on this, it may be concluded that the purpose of the second and third questions is mainly exploratory.

A novelty of this research lies in its desire to create a framework of key features to develop a support documentation system that assists maintenance of manufacturing systems. This framework is not based on an assumption of an existing theory, from which research questions or hypotheses are derived. Rather, the research aims to produce new discoveries (or ‘theories’) that contribute to both academia and industry, and to be implemented and tested in future research. The new framework would also be context specific, would reflect the particular attitudes and beliefs of the subjects, and would not be claimed to be reliable and valid in all situations. The nature of the research thus reflects the objective of contributing to a new ‘theory’ rather than to testing existing ‘theory’ following an inductive strategy.

The enquiry purpose of the first research question is mainly descriptive

The enquiry purpose of the second and third research questions is mainly exploratory

The research follows an inductive strategy

Research strategy. According to Yin (1994:p9), more than one strategy in a given study can be used, e.g. a survey within a case study or a case study within a survey. Situations in which a specific strategy has a distinct advantage can also be identified, as described in *Section A.4 (Appendix A)*. Before discussing the selection of an appropriate strategy for each research question, the reasons for excluding experiments and action research from this research are discussed.

Experiments were excluded because they usually involve hypothesis testing through measurement of a small number of variables (Gill and Johnson, 1991: ch4). This research does not aim to test any hypotheses derived from existing theory, and the number of variables is expected to be considerable. Experiments are only feasible when the researcher has control over events and can manipulate behaviour directly, precisely, and systematically (Yin, 1994: p8; Robson, 1995: p44). The research questions are concerned with practitioner views and their perceptions and utilisation of failure information, and so are related to ‘what’ and ‘how’ type questions. In addition, no control over events is likely to be needed during the investigation, and the research questions suggest focusing on current (contemporary) events.

Action research is rejected because it is a strategy that attempts to apply the principles of experiment (Gill and Johnson, 1991; ch5), which, as described above, do not suit this research. Action research is particularly applicable to situations where the researcher has a direct intervention in the problems and becomes involved with organisations to help them achieve certain objectives (Miles and Huberman, 1994). It is traditionally restricted to a single organisation (Whyte, 1991), while this research aims to investigate more than one organisation, not with the purpose of generalising findings, but to explore different situations and to identify multiple sources of evidence. Furthermore, the explorative nature of the research means it is aimed at minimising the influence of the research in the findings. If action research was applied, it would be necessary to find a way of accounting for the effect of the preconceptions of the researcher to increase the rigour of the investigation, which is a difficult process. Moreover, the focus of action research is traditionally on a specific problem in a defined context, and not on obtaining scientific knowledge that can be generalised (Burns, 2000; p444). Action research also lacks the systematic methods required to conduct this type of research strategy (Robson, 1995).

Experiments and action research are rejected

Section 3.4.1 identified four criteria that can be used to guide the selection of the most appropriate research strategy to collect evidence to answer each of the research questions; namely, (i) enquiry purpose, (ii) research question type, (iii) degree of control over events, and (iv) focus on current or past events. Table 3-6 presents these criteria, together with sample size, for each research question and shows the respective appropriate research strategy according to the criteria values.

INPUT	Criteria					OUTPUT
	PROCESS					
Research Question	Question Type	Control over events?	Current events?	Sample Size	Enquiry Purpose	Research strategy
Question 1	What	no	yes	Large (more than 50)	Descriptive	Survey
Question 2	What	no	yes	Medium (10-20)	Exploratory	Survey
Question 3	How	no	yes	Reduced (1-5)	Exploratory	Case study

Table 3-6: Selection of the research strategies

The *first and second research questions* aim to establish what practitioners think and know, and if their organisation shows particular features. As such, it can be stated that the research would be more valuable and credible if it were to capture more than just a small sample of practitioners. Consequently, case study appears not to be the most suitable strategy to answer the first two questions, since it typically focuses on a single or small number of cases. Moreover, surveys are among the analyst’s most important sources of information about user problems, requirements, and satisfaction (Davis and Yen, 1999: ch17). As stated previously, surveys can be used purely for data gathering rather than traditional hypothesis/theory testing. The first and second research questions are also characterised for being ‘what’ type questions, for not needing control over events by the researcher, for referring to current events, and for having either a descriptive or exploratory purpose, which suits the survey features. According to the nature of the first and second research questions and the characteristics of survey types (*Table A-1 in APENDIX A*), it may be concluded that to address the first research question, both analytical and descriptive survey types are appropriate, and to address the second research question, an analytical survey is more appropriate.

Both analytical and descriptive surveys are the most appropriate strategies to address the first research question

An analytical survey is the most appropriate strategy to address the second research question

Although descriptive surveys are traditionally associated with quantitative research, a number of authors (e.g. Sale, 2002; Easterby-Smith, 2002) state that it is possible to combine qualitative and quantitative methods in the same study. It is even recommended to be applied in studies that have different enquiry purposes (Sale, 2002), and in complex investigations that require data from a large number of perspectives.

The *third research question* is typically a ‘how’ and ‘why’ question about a contemporary set of events over which the investigator has little or no control, which suggests the use of a case study strategy. The exploratory nature of this question also suggests that a deeper level investigation would be required than that obtainable through a survey strategy, where a relatively small amount of data is typically gathered from a sample. According to the nature of the research question, a qualitative case study strategy was found to be most suitable for investigating the problem. The reasons for this are as follows. First, it enables an in-depth and detailed study of the chosen cases, producing a wealth of detailed data about a small number of cases (Patton, 1987: p9-19). Second, it is particularly suitable for unconstrained data collection by predetermined categories of analysis (Patton, 1987: p9). Third, it is suitable for capturing the richness of people’s experiences in their own terms and emphasising the importance of understanding the meanings of human behaviour (Patton, 1987: p10, 20). Fourth, it stresses the importance of getting close to the people and the situations being studied (Patton, 1987: p17). Fifth, it employees interview and documents analysis, which are found the most important methods to collect evidence to support the design of record management systems (BS ISO 15489-1, 2001).

Gill and Johnson (1997) state that the case study is relevant if there is a need to combine research with practice in the real world. Voss *et al.* (2002) argue that the case study strategy is good not only at investigating ‘how’ and ‘why’ questions, but is also particularly suitable for developing new theory, testing, and refining theory. In addition, according to Yin (1994) the case study strategy is no longer considered weak when compared to techniques used for qualitative research. These arguments support the selection of case study strategy to address the third research question.

In addition, regarding the case study design, ‘multiple-cases’ type seems to be most appropriate. The ‘single-case’ design is justifiable where the case represents a critical test of existing theory, where the case is a rare or unique event, or where the case serves a revelatory purpose (Yin, 1994). As such, this type of case study design is rejected from this research. On the other hand, ‘multiple-cases’ design is often considered more compelling, and the overall study is therefore regarded as more robust (Yin, 1994). Moreover, the multiple-cases type is considered as one that takes multiple experiences and evidences, and towards replication.

Case study is the most appropriate strategy to address the third research question

3.5 Data Collection Methods

This section describes the methodology used for sample selection, and discusses the data collection methods (or techniques) that will be used within the selected strategies

3.5.1 Sample Selection Methodology

Sampling is closely linked to external validity or generalisation of findings in an enquiry (Robson, 1995: p135). Sampling strategies are traditionally divided in two main groups, namely probability sampling and non-probability sampling (Robson, 1995: p137;140; Burns, 2000: p456).

Probability sampling. Probability sampling is also termed classical sampling (Flick, 2002). It enables the researcher to specify the probability of including an element of the population in the sample, make estimates of representativeness of the sample, and generalise the result back to the population (Burns, 2000: p465). Probability sampling is a strategy for obtaining an estimate from a population by studying, measuring, or interviewing a subset (or sample) of the population (Broida, 1999). Statistical significance is the aim, which is heavily dependent on the number of people involved (Gillham, 2000a). The use of an appropriate sampling design allows the analyst to make valid statistical inferences about the population (Davis and Yen, 1999: ch17). In addition, since generalisation from a sample to the general population is the objective, sampling has a major role in avoiding bias. One relatively easy way to avoid introducing bias is to use random samples (Robson, 1995: p137). A sample is considered random if each member of the population has the same chance of being selected (Broida, 1999). The advantage of sampling is that a well-selected sample yields an estimate of the target parameters in much less time and at much less cost than studying, measuring, or interviewing the entire population (conducting a census) (Broida, 1999). *Table 3-7* summarises some of the most important techniques of probability sampling.

Non-probability sampling. Non-probability sampling is also known as theoretical or purposeful sampling (Glaser and Strauss, 1967). There is no way of estimating the probability of an element being included within this strategy, *i.e.* there is no guarantee that every element has had an equal chance of being included (Burns, 2000: p465). Non-probability sampling is acceptable where there is no intention or need to make statistical generalisation (Robson, 1996: p140).

Probability Sampling Techniques	Key Features
<i>Simple Random Sampling</i>	<ul style="list-style-type: none"> - Selection at random from a list of the population - Each member of the population has an equal chance of being selected - The selection of one member is independent of the selection of any other - Requires full list of the population
<i>Systematic Sampling</i>	<ul style="list-style-type: none"> - Selection of a starting point in the sampling frame at random, and then select every <i>n</i>th member, <i>i.e.</i> sample is drawn at fixed intervals - Requires full list of the population
<i>Stratified Random Sampling</i>	<ul style="list-style-type: none"> - Divide the population into a number of groups, where members of a group share a particular characteristic(s) - Select randomly members from each group
<i>Cluster Sampling</i>	<ul style="list-style-type: none"> - Divide the population into a number of units, or clusters, each of which contains individuals having a range of characteristics - Sampling of entire natural groups rather than individuals - The clusters themselves are chosen on a random basis - Sub-population within the cluster is chosen - Particular useful when a population is widely dispersed and large.
<i>Multi-Stage Sampling</i>	<ul style="list-style-type: none"> - Is an extension of cluster sampling - Selection of the sample in stages, <i>i.e.</i> taking samples from samples, on a random basis
<i>Opportunity sampling</i>	<ul style="list-style-type: none"> - Only used when no other alternative exists or due to some sort of constraints - No proper sampling involved and no possible generalisation to population - Valuable in exploratory studies

Table 3-7: Techniques of probability sampling
 (after Robson, 1995: p137-139; Burns, 2000: p83-92)

This type of sampling is traditionally associated with the process of data collection for generating theory whereby the analyst jointly collects, codes and analyses the data and decides what data to collect next and where to find them; this helps to develop the researcher's theory as it emerges (Glaser and Strauss, 1967). The strategy is usually associated with qualitative research (Flick, 2002), where samples are not meant to represent large populations. Rather, small, purposeful samples of representative respondents are used because they can provide important information to add new insights to the development of understanding, not because they are representative of a general group (Reid, 1996). That is, sampling seeks to demonstrate the representativeness of findings through the random selection of subjects (Hancock, 2002) rather than finding statistical significance from the size of the sample involved (Gillham, 2000a;p 87). Samples tend to be small because the methods to collect qualitative data are time consuming (Hancock, 2002). The selection of further cases is driven by the emerging theory, *i.e.* 'what has been revealed so far and where should the researcher look next to develop the understanding'. The traditional

meaning of the sampling size is also closely related to external validity (Robson, 1994: p135). Nevertheless, the sample size is relevant if inferential statistics is used, *i.e.*, when inference are drawn from samples to a population (Fitz-Gibbon and Morris, 1987: p9). According to Yin (1994: p107), regarding holistic multi-case studies, the theoretical replication across cases is also a way of achieving external validity. This replication becomes stronger as the number of cases supporting the assumption increases (see *Section 3.7.1*). This type of strategy is commonly used in case studies (Burns, 2000: p465) and small-scale surveys (Robson, 1995: p140). Finally, several techniques can be used within this sampling strategy. *Table 3-8* summarises some of the most important techniques used in this type of sampling.

Non-Probability Sampling Techniques	Key Features
<i>Quota Sampling</i>	<ul style="list-style-type: none"> - Interviewers are given a quota of each category; within each category, convenience sampling is normally used - Try to do same as probability sampling, in the sense of aspiring representativeness - Traditionally applied to survey sampling
<i>Dimensional Sampling</i>	<ul style="list-style-type: none"> - Extension of quota sampling - The various dimensions thought to be important in the survey are incorporated in such a way that at least one representative of every possible combination of dimensions is included - Traditionally applied to survey sampling
<i>Convenience Sampling</i>	<ul style="list-style-type: none"> - Select the nearest and most convenient respondents - It does not produce representative findings - One of the most widely used and least satisfactory techniques of sampling - Traditionally applied to survey sampling
<i>Purposive Sampling</i>	<ul style="list-style-type: none"> - The principle of selection is the researcher's judgement as to typicality or interest - Sample is built up which enables the researcher to satisfy her specific needs in a project. - Commonly used within case studies
<i>Snowball Sampling</i>	<ul style="list-style-type: none"> - The researcher identifies one or more individuals from the population of interest - After interviewing some persons, they are used s informants to identify other members. - Commonly used within case studies

Table 3-8: Techniques of non-probability sampling
(after Robson, 1995: p140-142)

From what was discussed above, and considering the purpose and nature of the research strategies, the following conclusions are established:

Probability sampling is the most suitable strategy to select the sample for the descriptive survey

Non-probability sampling is the most suitable strategy to select the sample for the analytical survey and the number of case studies

3.5.2 Key Features of Data Collection Methods

Research is about creating knowledge, whatever the disciplines are, with evidence being the raw material of research. As justified in the previous section, both survey and case study strategies are used to collect evidence for this research. As so, this section focuses on data collection methods used within these two strategies. Table 3-9 presents the traditional data collection methods used within survey and case study research. The purpose of this section is to review these methods in order to select those most likely to be suitable to collecting evidence to answer the research questions, and to justify why other methods were rejected.

Research Strategy	Data Collection Methods
Survey	<ul style="list-style-type: none">• Interviews (personal or phone)• Questionnaire (mailed or interviews)
Cases Study	<ul style="list-style-type: none">• Interviews (personal or phone)• Document analysis: documentation & archival records• Observation: direct & participant• Physical artefacts

Table 3-9: Data collection methods used within survey and case study strategies
(after Yin, 1994: p80: Alreck, 1985: p193)

The type of evidence collected by each method is an important feature that allows the first distinction between the methods to be established (see Table 3-10).

Method	Type of evidence
Interview	What people say
Questionnaire	What people report
Observation	What do I see them doing
Physical artefacts	What they produce or use
Documents & Records	What documents/records show

Table 3-10: Collection methods vs. type of evidence

Table 3-11 summarises the key characteristics of the above methods. The analysis of this table helped to conclude that both observation and physical artefacts are not the most suitable methods to collect the necessary evidence to answer the research questions.

Observation. Observation is commonly used as a research method to monitor the actions and behaviour of people. It consists of watching what people do, listening to what they say, recording this in some way and then describing, analysing and interpreting what was observed (Robson, 1995). This method is excellent for collecting views, feelings, attitudes, and the natural reactions of people. It not only collects what people have said or written, but what they actually do. Observation is not used for data collection in this thesis. Time-constraints is one of the main reasons for this, since a major problem with observation is that it is highly time-consuming (Gillham, 2000a: p47). Observing people is slower than asking them about what they do, getting to know the case is a slow process, and data collected from observation is traditionally more difficult to analyse and report (Gillham, 2000a: p47). As such, it is difficult to commit the time to do this within the PhD schedule. Difficulties were also found with identifying companies willing to provide the accessibility that the method implies. Furthermore, observing behaviour is clearly a useful enquiry technique, although asking people directly about what is going on is an obvious short cut in seeking answers to the research questions (Robson, 2002: p272). Gillham (2000a: p49) suggests that observation is used as a main method when the primary purpose is explanatory description, which is not the purpose for any of the research questions. Observation might be useful for the developing of future research, as will be discussed in the final chapter. As justified latter, other methods such as document analysis and interviews were found to be more suitable for the research.

Methods	Key Features	Strengths	Weaknesses
Document Analysis - Documentation - Archival Records	<ul style="list-style-type: none"> Nearly relevant to every case study purpose Aim to corroborate and augment evidence from other sources 	<ul style="list-style-type: none"> Can be reviewed & repeatedly Not created as a result of the cases study Precise, quantitative, and allow broad coverage 	<ul style="list-style-type: none"> Can be of low retrievability Biased selectivity - If collection is incomplete Archival records - access restrictions
Interviews	<ul style="list-style-type: none"> Essential to collect human affairs and individuals perceptions Identify other relevant sources of evidence 	<ul style="list-style-type: none"> Focuses directly on the case topic Provides perceived casual inferences 	<ul style="list-style-type: none"> Bias due to poorly constructed questions Response bias & poor recall Interviewee gives what interviewer wants to hear
Observation - Direct/detached - Participant	<ul style="list-style-type: none"> Field visits, meetings observation and/or participation, sidewalk activities Monitor the actions and behaviour of people 	<ul style="list-style-type: none"> Covers events in real time Covers context events Participant – insightful into interpersonal behaviour and motives 	<ul style="list-style-type: none"> Time-consuming Selectivity & reflexivity Difficult to gain access Traditionally costly Participant – bias introduced by investigator
Physical Artefacts	<ul style="list-style-type: none"> Have less potential relevance in the most case studies Collect physical and cultural artefacts 	<ul style="list-style-type: none"> Insight into cultural features Insight into technical operations 	<ul style="list-style-type: none"> Selectivity Availability
Questionnaires	Can be used in both mail survey and interviews		
<ul style="list-style-type: none"> Mailed 	<ul style="list-style-type: none"> Traditionally well structured Mainly close questions Questions and possible answerers predetermined 	<ul style="list-style-type: none"> Easy to analyse Less time consuming 	<ul style="list-style-type: none"> Many people ignore them and do not complete them properly Discovery is reduced (what is behind)
<ul style="list-style-type: none"> Interview 	<ul style="list-style-type: none"> Less structured Mainly open questions 	<ul style="list-style-type: none"> Collects personal opinions, believes or judgements More motivation Easy to detect misunderstandings Talk is easy than writing 	<ul style="list-style-type: none"> Analysis more difficult Less number questions but more complex More troublesome to answer

Table 3-11: Summary of key characteristics from data collection methods
 (after Yin, 1994; Gillham, 2000b; Oppenheim, 1992)

Physical artefacts. Physical artefacts was also rejected because it has less potential relevance in the most typical case studies (Yin, 1994: p90). Moreover, the research does not aim to analyse cultural aspects, and gain insight into technical operations. Similar to observation, other methods were found to be potentially more suitable for the research.

An initial analysis of the data collection methods (Table 3-11) indicates that (i) interviews, (ii) questionnaires, (iii) and document/records analysis appear to be the most suitable methods to collect the necessary data for answering the research questions. In order to sustain this selection, Section A.5 (Appendix A) presents an in-depth analysis of these three methods.

3.5.3 Data Collection Methods Adopted

First research question. Previous sections demonstrated that the enquiry purpose of the first research question is mainly descriptive, and that a descriptive survey appears to be the most suitable research strategy to address this question. Exploring the current situation regarding failure records utilisation within maintenance of manufacturing systems is the purpose of the first research question. It does not aim to find any explanations or causal relationships between variables. Rather, it aims to portray accurately the characteristics of maintenance experts and organisations, and to make inferences to the population. As such, the nature of the survey is mainly quantitative. These features suggest that a questionnaire survey would be the most appropriate method to collect evidence to answer the first research question. It should be stressed that interviews might also be used.

A questionnaire survey is the most appropriate method to collect evidence to answer the first research question.

Second research question. The second research question aims to identify the reasons why current CMMS and support documentation fail to effectively assist maintenance technicians during troubleshooting. It aims to find information about practitioner's problems, requirements, and satisfaction, and so the purpose of this research question is mainly exploratory. The above sections demonstrated that an analytical survey appears to be the most suitable strategy to address this research question. The second research question is also about finding out what practitioners know and think, and determining practices and recommendations for the development of a documentation support system. It aims to identify what is happening, to seek new insights, and to explore and increase understanding. Considering the nature of the research question and the features of both interviews and questionnaires, the former appears to be the more appropriate approach for collecting data to answer the second research question. Semi-structured interviews appear to better suit the enquiry purpose, since they traditionally address qualitative research and are recommended for situations where the aim is to collect the interviewees' perception of reality when the interviewer has already identified the issues to address.

Semi-structured interviews are the most appropriate method to collect evidence to answer the second research question.

Third research question. The third research question aims to identify the practitioner's recommendations/requirements to improve CMMS and support documentation in order to provide greater assistance to maintenance technicians with during troubleshooting. Therefore, the novelty of this research lies in its desire to create a framework of key features to develop a SDS to assist the maintenance of manufacturing systems. The research aims to produce new discoveries (or 'theories') that contribute to both academia and industry, and to be implemented and tested in future research. The exploratory nature of this question also suggests that a deeper level investigation would be required than that obtainable through a survey strategy. In this context, it was demonstrated that a qualitative case study appears to be the most suitable strategy to address this research question.

Other reasons that support this choice are as follows. First, it enables an in-depth and detailed study of the chosen cases, producing a wealth of detailed data about a small number of cases (Patton, 1987: p9-19). Second, it is particularly suitable for unconstrained data collection by predetermined categories of analysis (Patton, 1987: p9). Third, it is suitable for capturing the richness of people's experiences in their own terms and emphasising the importance of understanding the meanings of human behaviour (Patton, 1987: p10, 20). Fourth, it stresses the importance of getting close to the people and the situations being studied (Patton, 1987: p17). Fifth, it enables the manager's opinions to be cross-checked against actual operating results (Berry *et al*, 1995). Sixth, Gill and Johnson (1997) state that the case study is relevant if there is a need to combine research with practice in the real world. Voss *et al*. (2002) also argue that the case study strategy is good not only at investigating 'how' and 'why' questions, but is also particularly suitable for developing new theory, testing, and refining theory.

Interviews, documents and records analysis, observation and physical artefacts are among the most widely used methods within case study research. Both observation and physical artefact are rejected from this research (as discussed in *Section 3.5.2*). As stated in *Section 3.5.3*, interviews appear to be the most suitable method for the cases study data collection, and so they are used as the primary data collection method. The enquiry purpose of this research question is similar to the second research question, and so semi-structured interviews appear to be the most appropriate data collection technique. Although interviews are the main data collection method used within the case study, other methods are also used in order to corroborate evidence, to establish data triangulation, and to provide more perspectives on the phenomena being studied. This approach allows the increase of internal validation (or credibility) and data quality (Robson, 2002: p 476). Many authors defend this

multi-method approach, *e.g.* Yin (1994), Burns (2000), Perry, 2000, Robson (2002) and Sale (2002). The multi-method approach accumulates data by different methods but concentrates on the same issue. A similar approach was followed by other research that conducted similar research within the maintenance topic, *e.g.* Lofsen (1999) and Cooke (2002b).

Document/records analysis, and questionnaires are the other methods used to complement the interviews. As stressed in *Section A.5.3 (Appendix A)*, document and records analysis is a method of data collection that is likely to be relevant to most case study topics. The method is used here because documents/records can be helpful in verifying the results from the interviews, since differences might exist between what people say and write. Furthermore, documents/records were not created as a result of the case studies, and so they lack the bias of interviews. Documents/records might also provide other details than those gathered from interviews.

Questionnaires will also be used as a complementary method. Gillham (2000a: p59), stresses that questionnaires are not usually used in case study research, although they can have a place in simple information collection. The use of questionnaires will supplement the case study with a quantitative analysis that will complement the case (Robson, 2002). Questionnaires are also among the analyst's most important sources of information about user problems, user requirements, and user satisfaction in IS development (Bowerman, 1999).

Semi-structured interviews, documents/records analysis, and questionnaires are the most appropriate methods to collect evidence to answer the third research question.

3.6 Design Methodology

The previous sections discussed and justified the adopted strategies and data collection methods for this research. It was argued that both survey and case study are the most appropriate strategies to collect evidence to answer the research questions. Moreover, questionnaires and interviews were justified as the main data collection methods used within the selected research strategies. In this section, the application of these strategies and methods are described, *i.e.* some general aspects of design and execution are discussed. The main purpose of this section is to present and discuss the enquiry research process.

The primary goal of research is to arrive at valid conclusions through systematic enquiry. Valid conclusions can only be reached if bias can be minimised or even eliminated. According to Dunn *et al.* (2003), bias is defined as ‘a systematic deviation from the truth that can potentially take place in the design, implementation, or analysis of a study’. Although bias cannot be eliminated in some cases, there are various considerations, aspects of design, and procedures that can be followed to minimise it. As such, this section presents a plan for each of the enquiry processes, which seeks to minimise bias. It also aims to provide sufficient guidance to other researchers who want to replicate the research.

3.6.1 Survey Design

As described in *Section 3.4*, descriptive and analytical surveys are employed in this research. The main process of the survey research is presented in this section, *i.e.* the main steps to design and execute both survey types (after Robson, 2002; Burns, 2000; Alreck and Settle, 1985). *Figure 3-2* summarises the main survey steps taken in this thesis, which are described below.

Step 1: Survey planning. Survey planning involves considering the research questions and objectives, and defining the topic to investigate, *i.e.* state the purpose of the survey. Once the survey purpose is established, the survey objectives and the target population (to be investigated) are defined. Methods and resources are also considered in order to make the survey feasible. The population is selected in accordance with the objectives of the study.

Step 2: Sample Selection. Sample selection involves choosing accessible elements from the target population and building a study sample that is representative of the population. For the descriptive survey, this selection follows a probability sampling strategy; a non-probability sampling strategy is followed for the analytical survey (see *Section 3.5.1*). The elements of the study sample are mainly selected from the contacts of the Manufacturing Systems Department of Cranfield University, a list of members of MTA (Manufacturing

Technologies Association), Yellow Pages, and APMI (Portuguese Association of Industrial Maintenance).

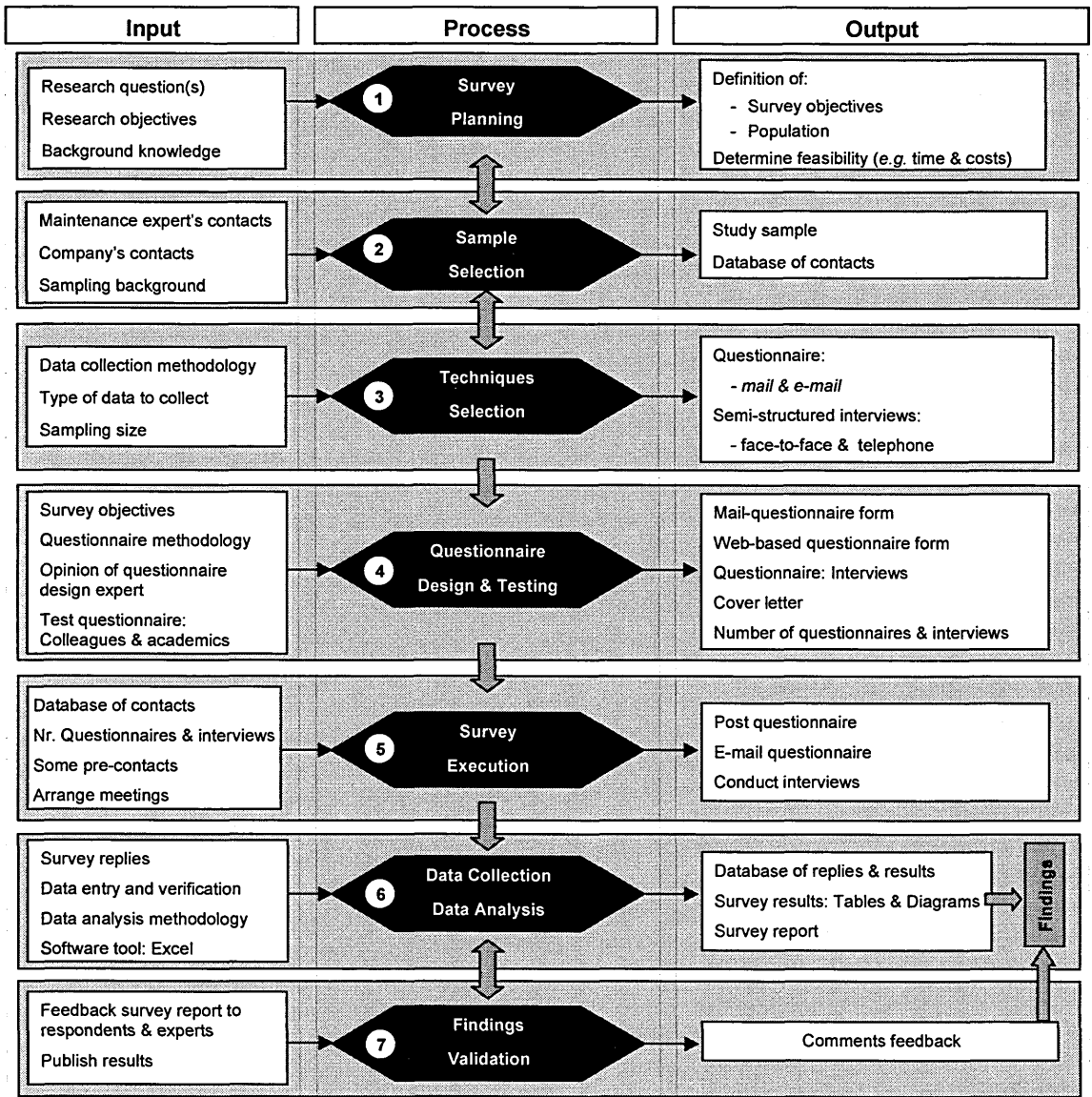


Figure 3-2: Survey process

Step 3: Technique Selection. Technique selection involves deciding which process is used within each data collection method to approach respondents. Both traditional mail and e-mail are used for the questionnaire survey. E-mail is used to post an online-questionnaire into a maintenance newsgroup, while face-to-face and telephone techniques are used to conduct the semi-structured interviews.

Step 4: Questionnaire design & informal testing. Questionnaire design and informal testing consists of writing the questions, planning the format, and testing the questionnaire in order to produce the desired results. Regarding the design of the questionnaires, it was considered the objectives of each enquiry, and the questionnaire design methodology (see Section 3.6.3). An expert on questionnaire design was also consulted. The questionnaires were informally tested with colleagues and academics.

Step 5: Survey execution. According to the survey type, survey execution involves posting (mail and e-mail) or conducting the interviews, *i.e.* carrying out the survey. Regarding the questionnaire, in some cases some pre-contacts were made in order to potentially increase the response rate. Interview meetings were arranged at the convenience of the respondents.

Step 6: Data collection and analysis. Data collection and analysis involves gathering all replies into a database and analysing all data using clustering techniques and a software package. In order to facilitate analysis, tables and diagrams were built to summarise the results. Finally, survey reports showing the main findings were made to feedback to respondents.

Step 7: Validation of findings. In order to validate findings and reduce research bias, findings were returned to respondents and feedback collected and compared with the initial findings for iteration. Results were also published at conferences and in journals.

3.6.2 Case Study Design

Many authors suggest steps for the case study progress that can be carried out sequentially, iteratively, or even in parallel (*e.g.* Eisenhardt, 1989; Yin, 1994; Miles and Huberman, 1994). According to Yin (1994), case study research involves the following main steps: (i) case study design, (ii) preparing for data collection, (iii) collecting evidence, (iv) analysing evidence, and (v) reporting results. *Figure 3-3* summarises the approach followed in this thesis and compares the results from the approaches suggested by Yin and Eisenhardt.

Step 1: Case study planning. Similar to survey planning, case study planning involves taking the research questions and objectives, and defining the topic to investigate. Once the topic is established, the case study objectives and the target population (to be studied) can be defined. This provides a better grouping of construct measures.

Step 2: Sample Selection. Sample selection involves selecting the cases. In this thesis, cases were selected following a non-probability sampling strategy (see Section 3.5.1), *i.e.* cases that replicate or extend ‘theory’ by filling conceptual categories are selected.

Step 3: Methods Selection. Methods selection involves considering the data collection methodology, the type of data to collect, the data sources, and selecting the methods or instruments that would best suit the enquiry purpose. As justified in *Section 3.5.3*, semi-structured interviews, document/records analysis and questionnaires are the methods selected for use within the case studies for data collection.

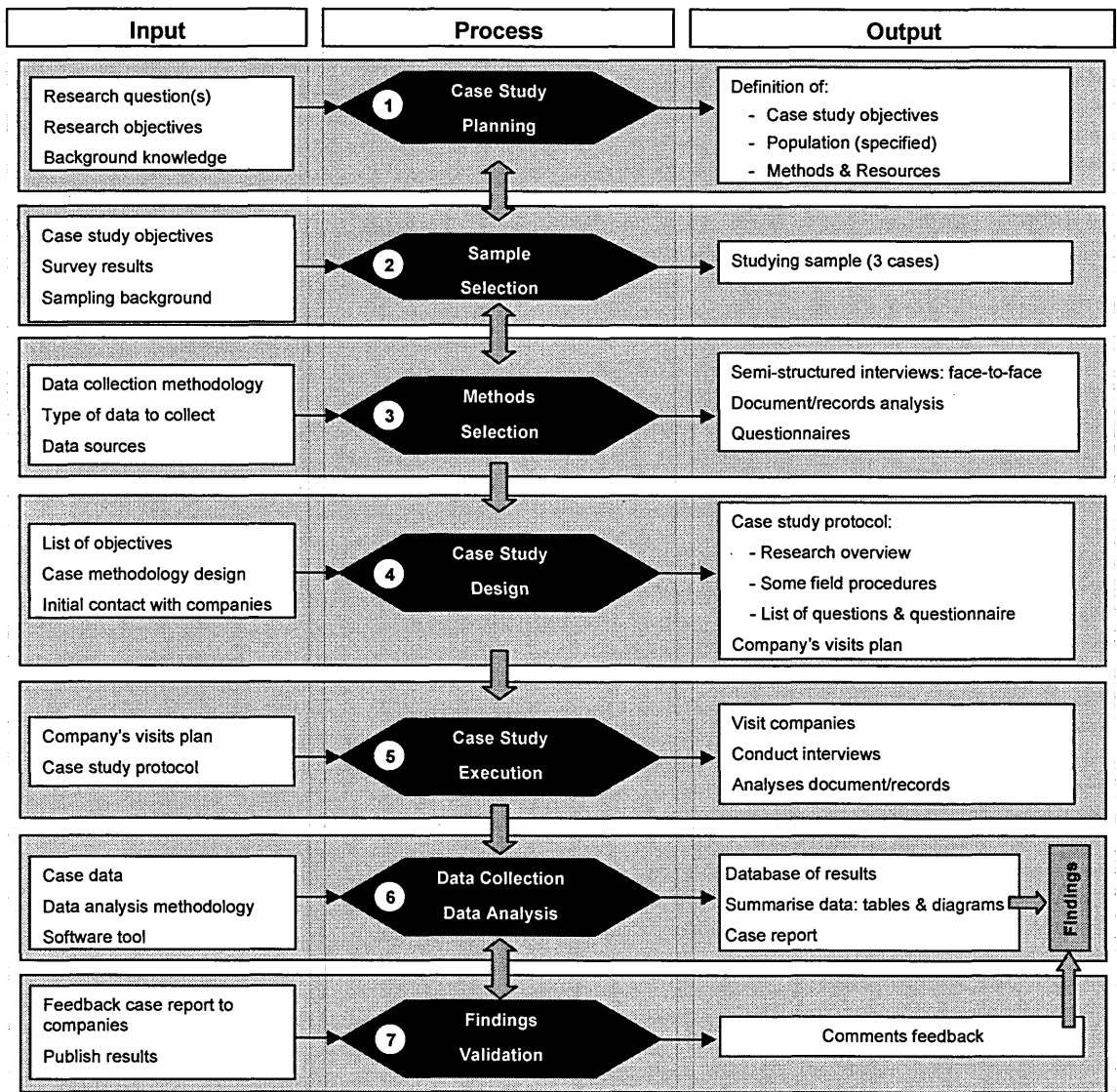


Figure 3-3: Case study process

Step 4: Case Study Design. Case study design consists of defining a plan, often referred to as a protocol of procedures, instruments, and rules to conduct the enquiry process. Guaranteeing that the evidence will address the research question(s) is the purpose of this plan. The case study protocol of this research essentially comprises a research overview, some field procedures, a list of questions, and a questionnaire.

Step 5: Case Study Execution. Case study execution involves carrying out the company visits and performing the case protocol, *i.e.* conducting the interviews and analysing documents and records according to the procedures and rules of the protocol.

Step 6: Data collection & Analysis. Data collection consists of gathering all evidence from the case and compiling it into a database. It is important to stress that there is some iteration between data collection and analysis, because analysing the first set of data enables the researcher to become familiar with data, which might generate further collection. Once collected, the data is summarised into tables and diagrams and analysed. The final stage involved building a case report.

Step 7: Findings validation. As with the case of surveys, case reports were returned to companies to assess the findings. The findings were also published.

3.6.3 Questionnaire Design

A questionnaire is an important research instrument and a good tool for data collection, as briefly introduced in the previous *Sections*. Carefully designing the questionnaire to be used is one of the best ways to reduce error when conducting surveys (Bowerman, 1999). As such, this section presents some general aspects regarding the design of questionnaires.

Each questionnaire has its particular purposes and problems, but it is possible to present some general considerations that are common to most questionnaire designs. The questionnaire design plan followed in this thesis involved the following steps: (after Oppenheim, 1992: p101; Bowerman, 1999; Gillham, 2000b: ch4)

Step 1: Select type of data collection method. Consists of establishing the main method of data collection that will be used, *e.g.* mail questionnaire or standardised interviews (see *Section 3.5.3*).

Step 2: Define method to approach respondents. Within this thesis the methods used to approach respondents are as follows:

- Mail questionnaire: traditional mail and e-mail
- Standardised interviews: face-to-face and telephone

Step 3: Build modules of questions and questions ordering. Group questions according to the enquiry objectives and decide on the sequence of questions. In order to reduce the impact of question ordering and response ordering, the context in which the survey questions are asked is carefully described. Moreover, questions are defined and ordered taking into consideration the data analysis techniques and the aimed output.

Step 4: Select the question type. Considering the use of *open* and *closed* questions (see Section A.5.2 in Appendix A).

Step 5: Define response options. Response options are pre-defined, *e.g.* ‘yes’ or ‘no’, for the case of the close-questions. In this thesis, response choices are carefully selected so as not to overlap and cover all relevant possibilities. Explicit alternatives are also stated.

Step 6: Working questions. Working questions consists of analysing the used language and phrasing. In order to make questions understandable and to elicit a precise answer, questions are made as clear and precise as possible. As such, attempts are made to use a natural and familiar language. Attempts are also made to avoid words or phrases that might show bias. Whenever possible, questions are coded to facilitate analysis.

Step 7: Design the questionnaire form. Designing the questionnaire form consists of making the questionnaire attractive and accessible. The mail questionnaires are carefully designed to ‘invite respondents to look into it, and potentially increase the response rate.

Step 8: Prepare a cover letter. Write a cover letter to explain the purpose of the questionnaire. A cover letter is designed to make clear to respondents what the research is about, why data is being collected, and where it will be used. It is also used to inform respondents what they would get in return.

3.6.4 Interview Design

Together with questionnaires, interviews are a main method of data collection in this research. In Section A.5.1 (Appendix A) interviews are defined, some advantages and disadvantages are discussed, the methods to approach respondents are presented, and the interview types are characterised. This section discusses the interview design and some issues regarding its execution, *i.e.* interview preparation.

The main steps taken to design each interview are as follows (after Guillham, 2000a; Davis, 1999b; Burns; 2002; Patton, 1987):

Step 1: Select type of interview. Identify the interview type that best suits the study. Only semi-structured interviews are conducted in this research (see *Section A.5.1 in Appendix A*);

Step2: Write the interview guide. Frame and structure the enquiry questions considering the interview objectives. This interview guide serves as a basic checklist during the interview to ensure that all relevant topics are covered. Some of the questionnaire design steps are also considered here:

1. Frame the questions that will fulfil the objectives that came from research questions;
2. Group questions by topic and introduce some prompts, *i.e.* things about which to remind the interviewee;
3. Test the questionnaire with peers;

Step 3: Scheduling the interviews:

1. Identify key people and familiarise oneself with organisations;
2. Arrange meetings at the interviewee's convenience;
3. Set interview time: limit the length of the interview to no more than one hour;

Step 4: Prepare interview itself:

1. Consider using a tape recorder wherever possible;
2. Prepare a small presentation: what the research is about, who we are, why they were selected, what they will get in return, etc.
3. Be prepared to take notes when a tape recorder cannot be used;

Step 5: Interview transcription and follow up. The notes transcription and analysis are performed as soon as possible after the interview itself. A summary report is then written and, whenever possible, returned to interviewees.

After sketching out the design aspects of both strategies and methods of the research, the following sections present stress for the methodology to analyse the collected data, and for the quality assurance of the research.

3.7 Data Analysis Methodology

Data analysis consists of examining, categorising, tabulating, or otherwise recombining the evidence (data) to address the research questions (Yin, 1994: p102). Since data in its raw form has little meaning, analysis needs to be conducted to summarise the mass of data collected and to present the results in a way that communicates the most important features. Finding answers to the research questions is the aim of data analysis. In order to identify trustworthy answers, the analyst (researcher) has to treat the evidence fairly and without bias, and conclusions must be compelling, not least in ruling out alternative interpretations (Robson, 1995: p372). As such, interpretation is an associated concept to analysis. According to Patton (1987: p 144), interpretation ‘involves attaching meaning and significance to analysis, explaining descriptive patterns, and looking for relationships and linkages among descriptive dimensions’.

Organising all the collected materials and constructing a database is the first step following data collection. These materials include questionnaires, records from interviews (written notes and audio files), specific documentation, reports, and software programs. In this ongoing process, materials are stored as soon as they are collected and classified by topic. The aim is to facilitate both the data analysis and the findings report. It is also a means of ensuring reliability and credibility. During the data set creation, the policy adopted for ‘missing data’ was to eliminate records where data was missing. According to Youngman, (1979: p21 in Robson, 2002: p396), this policy is the most acceptable solution to deal with the problem of missing data. Finally, it should be noted that ideas about analysis and interpretation commonly occur when gathering data. This overlapping of data collection and analysis is likely to improve the quality of both the data collection and the analysis (Patton, 1987: p144).

3.7.1 Quantitative Data Analysis

Quantitative methods typically involve counting and measuring, and usually produce numeric data. Quantitative analysis traditionally involves a systematic manipulation of data, either objective data (*hard*) or subjective data (*soft*). It involves plotting and interpreting numeric data, most often obtained from surveys or laboratory experiments. As such, quantitative data analysis is traditionally associated with statistical analysis. Depending on the amount of data and the research purpose, this analysis might range from a simple organisation of data to a complex statistical analysis. Moreover, depending on the enquiry purpose, the ways in which statistical techniques can be applied will differ.

Approaches for quantitative analysis. The approaches to conduct quantitative analyses can be classified according to the type of statistical technique applied and the research purpose. *Table 3-12* summarises some of the key features of each statistical technique and shows the respective purpose.

Statistic Technique	Key Features	Purpose
Descriptive (univariate)	<ul style="list-style-type: none"> • Convert raw data into indices that summarise or characterise datasets • Uses averages, percentages, frequencies, bar & pie charts, etc. • Characterise events or situation • Usually looking at one variable at a time 	To describe phenomena
Exploratory (bivariate & multivariate)	<ul style="list-style-type: none"> • See if there are any patterns in data • Seek for relationships and explanations • Explores relationships (or differences) between two or more variables 	To generate hypotheses To test relationships
Inferential	<ul style="list-style-type: none"> • Draw inferences • Extent of correlations, significance of differences between groups, significance of changes following an intervention, etc. • Uses probability and information about a sample to draw conclusions (inferences) about population • Confirm something or establish relationships to test a 'theory' 	To test hypothesis To generalise findings

Table 3-12: Statistical techniques

(after Fitz-Gibbon and Morris, 1987: p9; Robson, 2002: ch13; Gillham, 2000a: p80)

As justified in *Section 3.4.3*, the enquiry purpose of the research questions is both descriptive and exploratory, and so inferential statistics will not be used for the analysis of the quantitative data of this research. According to Robson (2002: p450), for descriptive surveys, the analysis techniques of descriptive statistic, such as frequency distributions, graphical displays such as bar and pie charts, summary statistics such as means and percentages, might be all that it is needed. Conversely, for studies seeking to explain or understand what is going on, exploratory statistics are likely to be more appropriate (Robson, 2002: p451). Further discussion about the application of both descriptive and exploratory statistics to this research occurs in the following chapter.

Use of software programs. The use of software programmes for manipulating, analysing and presenting quantitative data is essential to cope with the statistical requirements of most research even with small amounts of data. These software programmes can be classified as specialist software (e.g. *SPSS – Statistical Package for Social Sciences*) and spreadsheet software (e.g. *Microsoft Excel*). The question here is *when is it justifiable to use specialist software?* Pelosi *et al.* (1998: p392) point out that specialist software might not be required for simple statistical texts. Specific software also appears to be more orientated toward

confirmatory (inferential) rather than exploratory analysis. Robson (2002: p400) states that this is the case for *SPSS*. In addition, consultations with an expert in quantitative data analysis, particularly using *SPSS*, identified that power software tools (such as *SPSS*) demand high levels of training and are only justifiable to use when the volume of data is considerable and the quality of data is high.

One of the main advantages of statistical analysis is that it can be used to summarise the findings in a clear, precise and reliable way. However, not all information can be analysed quantitatively. For example, responses to an open-ended survey might provide lengthy descriptions that could be difficult to categorise without losing subtle differences in the responses. Qualitative analyses needs to be performed in these cases.

3.7.2 Qualitative Data Analysis

Qualitative data commonly includes detailed descriptions, direct quotations in response to open-ended questions, the transcript of opinions of groups, and observations of different types, *i.e.* it is mainly constituted of *text*. Qualitative analysis typically includes content analysis, analysis of case studies, and inductive analysis. All methods might produce descriptions (patterns, themes, tendencies, trends, etc.), together with interpretations and explanations of these patterns.

The analysis of qualitative data has been well documented in many publications, *e.g.* Patton (1987), Miles and Huberman (1994), and Robson (2002). In this section, only the approaches used to perform a systematic analysis of qualitative data and the use of software programs for the analysis qualitative data are explored. Further discussion on qualitative data analysis occurs in the next chapter.

Approaches for qualitative analysis. Qualitative analysis remains much closer to codified common sense than the complexities of statistical analysis of quantitative data. As such, it is more dependent on the skills of the analyst to process information in a meaningful and useful manner. Humans, as ‘natural analysts’, have deficiencies and biases corresponding to the problems that they have as observers (Robson, 2002: p459). Consequently, a systematic approach for qualitative analysis is fundamental to minimising these deficiencies. Although there is no clear and accepted single set of conventions for qualitative data analysis, there are ways in which qualitative data can be dealt with systematically (Robson, 2002: p456). For example, Drisko (2000, in Robson, 2002: p458) suggests four techniques (approaches) to qualitative analysis, namely quasi-statistical, template, editing, and immersion. *Table 3-13* summarises the key features of these techniques.

Analysis Approach	Key Features
Quasi-statistical	<ul style="list-style-type: none"> • Use word or phrase frequencies and inter-correlations as key methods of determining the relative importance of terms and concepts • Typified by content analysis
Template	<ul style="list-style-type: none"> • Key codes are determined on a priori basis (from theory or initial data) • These codes then serve as a template for data analysis • Typified by matrix analysis
Editing	<ul style="list-style-type: none"> • More interpretive and flexible than the above • No (or few) priori codes • Codes based on the researcher's interpretation • Typified with grounded theory
Immersion	<ul style="list-style-type: none"> • Least structured and most interpretive • Methods are fluid and not systematised • Difficult to reconcile with scientific approach

Table 3-13: Different techniques of qualitative analysis
(after Drisko, 2000 in Robson, 2002: p458)

Although these approaches are diverse, they have recurring features. Based on these features, Miles and Huberman (1994) describe a 'fairly classical set of analytical moves', which can be grouped into three main activities, namely (i) data reduction, (ii) data display, (iii) conclusions drawing and verification.

(i) *Data reduction.* Data reduction refers to the process of selecting, focusing, simplifying, abstracting, and transforming the data from the written notes (Weerd-Nederhof, 2001). It consists of producing a document that summarises the data collected. A single document is generated for each data source and collection mode to summarise what has been obtained. In this first step, patterns and key events are identified and labelled, in order to create categories of data. Clustering techniques are then applied to group data. According to Dey (1993), the development of a set of categories allows the data to be organised through a variety of distinctions. Data within each category can then be compared. If necessary, further distinctions can be drawn within each category to allow for a more detailed comparison of data within a set of sub-categories. Whyte (1994) and Ince (2000) have successfully applied this approach when studying the capture of user requirements for IS. The former also used clustering techniques to group data ranked by users. According to Miles and Huberman (1994), this technique is useful to extract conclusions from data. Coding/labelling data will lead to ideas of how it might be displayed, which might help to form a tentative conclusion. This process facilitates both the data manageability and data analysis. Weighting of evidence is also applied, since some data elements are stronger than

others. This facilitates the extraction of a conclusion, in a sense that greater reliance is naturally placed on the more weighted evidence.

(ii) *Data display*. Data display refers to organised, compressed assembly of information that permits conclusions drawing and action (Weerd-Nederhof, 2001). Once data have been synthesised it needs to be displayed. Maps, tables, flowcharts and organisational charts provide useful tools that help to crystallise and display complex information (Robson, 2002: p476). According to Yin (1993: p57), one of the most popular ways of presenting categorical data involves 'word tables' (or matrix 2D) in which empirical evidence is systematically arrayed but the cells are filled with words rather than numbers.

(iii) *Conclusions drawing and verification*. Conclusions drawing and verification concerns the emerging or inducing of meanings from the data and testing for their plausibility, sturdiness, and validity (Weerd-Nederhof, 2001). Conclusions need to be drawn once the data have been displayed. The researcher has to search for patterns, regularities, most weighted and frequent features, etc. The clustering techniques described above provide an important role because grouping events with similar patterns and characteristics facilitates data analysis and the subsequent drawing of conclusions. Triangulation is used to compare the collected data using different methods and sources, which allows more confidence of the events in which information from different sources converges in the same direction. Counting is also used to analyse the frequency of occurrence of events (after Miles and Huberman, 1994: p245). According to Yin (1993: p69), the most robust fact may be considered to have been established if three (or more) sources all coincide.

Verification checks are performed to assess the quality of the results. Therefore, both checking for representativeness and researcher effects are executed. To process this evaluation, the same tests presented above under the heading of quality assurance of data collection are executed. In addition, the summary of results is returned to informants (whenever possible) in order to both collect some feedback and to establish an agreement on what was produced from the data they provided.

In addition to the above methodology, the researcher referred to both experienced researchers in qualitative analysis, and published thesis where this type of analysis was conducted. Since qualitative analysis is highly dependent on the researcher's skill, this approach provided relevant guidance and advice to conduct the qualitative analysis of this research.

Use of software programmes. Software programmes can be highly useful for analysing qualitative data. These programmes can vary from simple word and Excel-processing packages to specialist software for qualitative data analysis. There are a great number of specialist software packages designed to help with qualitative analysis, *e.g.* the *NUDIST* (*Non-numerical, Unstructured Data Indexing, Searching and Theorizing*), and the *NVivo*. The specialist packages are particularly useful for the cases where large quantities of data are collected; they provide quick and easy access to data, can handle large amounts of data very quickly, and force detailed consideration of all data in the database (Robson, 2002: p462). The time and effort needed to become proficient in their use is the downside of specialist software, and so the overhead in setting up and using these packages is not always justified (Fielding, 1993). These software packages are typically of little help in the detailed examination of small amounts of data (Robson, 2002: p 463). Fielding (1993) also stresses that (i) many qualitative researchers believe that the use of specific software poses a threat to the craft skills of a long-established research tradition, and that (ii) existing specific software presume a generic theory of qualitative analysis, which largely relates to the conventional, but by no means universal, grounded theory approach. According to Stanley and Temple (1996: p167: in Robson, 2002: p463), the facilities provided in a good word-processing package will be sufficient for many researchers. In addition, access to a specific software package is often restricted to the researchers. Studies of researchers indicate that using these packages has resulted a wide range of negative experiences, especially for novice researchers (Richards, 1999: p1). Thus, within this thesis simple word and Excel-processing packages are used to analyse qualitative data.

3.8 Quality Assurance of the Research

This section stresses what needs to be done in order to make the research objective unbiased and valid, *i.e.* it explains how the quality assurance of the research was assessed. It discusses both the quality assurance of the enquiry process and of the results. Further explanation about how this quality assurance is addressed in this thesis is explained in the data analysis chapter.

3.8.1 Quality Assurance of the Enquiry Process

The quality of the enquiry process needs to be assured in order to avoid biased views in the findings (Yin, 1994: p32), and to establish trustworthiness in the research (Robson, 1995: p66). According to Yin (1994: p32; 1993: p59) and Robson (1995: p66-75), four tests are used to establish the quality of social research, namely (i) construct validity, (ii) internal validity, (iii) external validity, and (iv) reliability.

Lincoln and Guba (1985) agree that these tests are inappropriate for qualitative research, and proposes four different tests, namely credibility, transferability, dependability, and confirmability. Despite this disagreement, the former four tests will be discussed due to their importance, to understand the point about the quality assurance of the research, and because quantitative data are also used in this research. It also establishes the equivalence between both tests (whenever possible).

Construct validity. According to Yin (1994: p33-34), construct validity consists of establishing correct operational measures for the concepts being studied, and it deals with the use of instruments and measures that accurately operationalise the construct of interest in a study (Yin, 1993: p39). The relevant tactics used within this research to increase construct validity as advised by Yin (1994: p34) and Burns (2000: p476) were (i) the use of multiple sources of evidence to demonstrate convergence of data, (ii) to establish a chain of evidence that links parts together, and (iii) to have key informants reviewing the case report. These tactics were applied during the data collection phase.

Internal validity. Internal validity concerns the demonstration of a causal relationship between treatment and outcome (Robson, 1995: p69; Gill and Johnson, 1991). According to Yin (1994: p35), internal validity is a concern only for causal (or explanatory) case studies, and so is inapplicable to descriptive or exploratory case studies. Consequently, it is not applicable in this research. *Credibility* is the parallel construction to internal validity and it ensures that the subject of the enquiry is accurately identified (Robson, 1995: p403; Miles and Huberman, 1994). The tactics used to improve credibility are as follows: (Wolcott, 1990: p121-152; Burns, 2000: p476)

1. Sufficient time is allowed to understand a company's culture, test misinformation and to take as many iterative loops as required;
2. Detailed notes are taken throughout;
3. Reports are as complete and candid as possible;
4. Triangulation of data collection techniques and sources (multiple sources of evidence);
5. Feedback from colleagues and experts is sought on the presented findings.

External validity. External validity is concerned with the domain to which the findings of a study can be generalised (Yin, 1994: p33) and extrapolated beyond the immediate research sample setting. Therefore, it is closely related with the research scope. According to Robson (1995: p 404), transferability is equivalent to external validity in conventional qualitative research. He argues that in this type of research (qualitative), where a sampling methodology (probabilistic) is not used, statistical generalisation to a population is not appropriate. The responsibility in making such a generalisation should be transferred to the decision maker, and so multiple case studies are performed in order to offer a good basis for the representativeness of this research and the replication of findings. External validity is not of great importance in case study research (Burns, 2000: p476). Gill and Johnson (1991) distinguish between population validity and ecological validity. The former concerns the extent of possible generalisation from the research sample to all the population. The latter concerns describing the extent of possibility to generalise from the research environment to other environments. It also refers to the level of artificiality of the research setting to 'natural' contexts.

Reliability. Bell (1987) defines reliability as the extent to which a test or procedure produces similar results under constant conditions on all occasions, while Mehrens and Lehmann (1991) define it as the degree of consistency between two measures of the same thing. Reliability has also been considered as the possibility of replication of a study (Yin, 1994: p33) by a third party, *i.e.* it refers to the level of consistency and the possibility for other researchers to replicate the research, achieving the same findings (Gill and Johnson, 1991). This research will provide sufficient information on the methods used and on the justification for their utilisation (Robson, 1995: p 75). Dependability is analogous to reliability (Robson, 1995: p405; Miles and Huberman, 1994). Research is considered dependable if it is clear, systematic and well documented. Therefore, triangulation tactics are used to improve dependability (Burns, 2000: p475). Moreover, reporting of any possible personal bias by the investigation is always done. In addition, as recommended by Yin (1994: p37), the case studies are organised into a database in order to improve reliability.

Confirmability. Confirmability is linked to objectivity (Robson, 1995: p406). According to Robson (1995), an audit process is the best technique to provide evidence of confirmability. Therefore, a database containing all the data collected from the case studies is constructed in order to make them available to anyone wishing to their access during the research period.

3.8.2 Quality Assurance of the Research Results

The researcher generally aims to add knowledge and understanding of the world, or part of it, and so the accumulated knowledge should be applicable to a practical environment. In order to guarantee the research applicability, this knowledge needs to be tested and evaluated in a real world context and feedback from it needs to be gathered. As such, validation has a major role in every type of research by allowing the trustworthiness of the investigation to be established and to avoid biased views in the findings (or conclusions).

According to Rutman (1977), validation is first and foremost a process of applying scientific procedures to accumulate reliability and valid evidence on the manner and extent to which specific activities produce particular effects or outcomes. Flick (2002) points out that the problem of how to assess qualitative research has yet to be solved. Nevertheless, some evaluation methods have been successfully applied in different areas of research. Examples include the *NIMSAD* (*Normative Information Model-based System Analysis and Design*) (Jayaratna, 1994), the *Delphi* and nominal group technique (Pope, 1999), and expert opinion (Ayyub, 2001: chap3).

Rossi and Freeman (1993) suggest that one method of overcoming the problem of validity is for the basis upon which expert judgments are made to be described as completely as possible. If an expert makes a judgement based upon his or her own direct experiences, the extent of the experiences ought to be revealed. They also suggest than when possible, explicit references to other evaluation studies should be provided so that others can check whether the circumstances of their interventions are comparable to those of the one under judgement. Moreover, Dale (1999) suggests that systems should be developed and checked collectively with people who are potential users and who are experts on the subject. Expert opinion method has been successfully applied to evaluate similar research (e.g. Ince, 2000; Jeon, 2000; Fakun, 2000; Ford, 2001). Based on these arguments, expert opinion appears to be the most appropriate method to validate the final results of this research.

Expert Opinion. An expert can be defined as a skilful person who has much training/experience and knowledge in some special field; it is the provider of an opinion in the process of expert-opinion (Ayyub, 2001: chap 3). Expert opinion can be defined as a method of validation (or evaluation) where relevant individuals (experts) within a particular field are invited to provide opinions on a specific matter, based on their knowledge and experience. An opinion could also mean a judgment or a belief that is based on uncertain information or knowledge. An opinion is a subjective assessment, evaluation, impression, or estimation of the quality or quantity of something of interest that seems true, valid, or probable to the expert's own mind (Ayyub, 2001: chap 3). Expert opinion typically consists of presenting or testing a methodology, a system, or a tool to experts and asking for their opinion or judgement. The data gathered from the experts can be collected by conducting interviews, running questionnaires, or doing some kind of measurements (e.g. performance and time). This process is sometimes referred as a confirmatory case study (Yin, 1994).

When conducting this type of evaluation, the researcher needs to ensure that relevant information is obtained so that the systems or methodology under evaluation will have relevant advantages to address the needs of industry (Fitz-Gibbon and Morris, 1987). To fulfil this, the Delphi technique is the best known method for synthesizing expert opinions (Ayyub, 2001: chap 3). The Delphi technique offers the needed, adequate basis for expert-opinion; however, there is a need to develop guidelines on its use to ensure consistency and result reliability. The basic Delphi method consists of the following steps (Helmer, 1968 in Ayyub, 2001: chap3):

1. Selection of issues or questions and development of questionnaires;
2. Selection of experts who are most knowledgeable about issues or questions of concern;
3. Issue familiarisation of experts by providing sufficient details of the issues on the questionnaires;
4. Elicitation of experts about the issues. The experts might not know who the other respondents are.

Although expert opinion was selected as the most appropriate method to validate the final results, another strategy of validation is used before reaching final results. Whenever feasible, reports of analysis findings (from survey and individual cases studies) were sent to respondents/interviewers. The purpose of this process is not only to access the findings but also to potentially collect additional feedback. Publishing and presenting the results at conferences is an additional strategy to increase validation.

3.9 Summary of the Chapter

This chapter presented a definition of the research problem and of the research methodology. The research problem was defined by stating the research aim and objectives, which were derived from the research question that emerged from the literature review. This was followed by a description of the methodology used to collect the data required to answer the research questions. The research problem established ‘what we need to know’, and ‘why we need to know’. The methodology defined ‘from where and whom we are going to get the information’, and ‘how we will get the information’. In context with the research, this chapter reviews the research philosophies and methodologies, the research strategies, sampling strategies, and data collection methods. Table 3-14 presents the key decisions that were made regarding this review and the research.

Research Question	Enquiry Purpose	Research Strategy	Sampling Strategy	Data Collection Method(s)
Research Question 1	Descriptive	Descriptive Survey (Analytical Survey)	Probability Sampling (Non-probability Sampling)	Questionnaire Survey (Semi-structured Interviews)
Research Question 2	Exploratory	Analytical Survey	Non-probability Sampling	Semi-structured Interviews (Face-to-face + telephone)
Research Question 3	Exploratory	Qualitative Case Study	Non-probability Sampling	Semi-structured Interviews (face-to-face) Document/record analysis Questionnaire

Table 3-14: Key findings of methodology

The chapter also stresses the design methodology. It presents the steps and considerations that are followed during the design of the surveys, case studies, questionnaires, and interviews. Quantitative and qualitative data analyses are also revised. It describes the different approaches that are typically used to analyse both types of data, and it stresses the use of software programmes. In addition, the chapter presents the tests to assure the quality of the enquiry process, and the methodology to guarantee the quality of results.

Chapter IV

4 RESULTS AND DATA ANALYSIS

This Chapter aims to:

- *Present and analyse the results of enquiries*
- *Identify the enquiry findings that will support fulfilment of the research objectives*

4.1 Introduction

The previous chapter presented and justified the methodology followed for the enquiry process. The results and subsequent data analysis are provided in this chapter.

4.1.1 Chapter Objectives and Overview

This chapter presents and analyses the enquiry results. The objective is to identify the enquiry results that help answer the research questions and allow achievement of the research objectives. In order to answer the three research questions the results of five enquiries are presented (Figure 4-1).

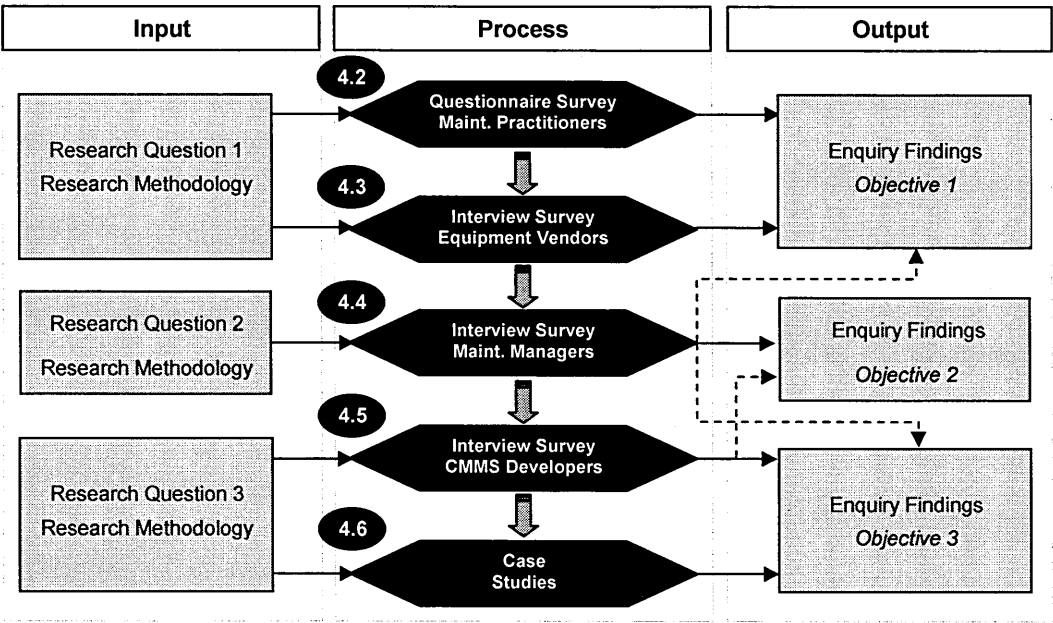


Figure 4-1: Chapter overview

For each enquiry process, the chapter presents its objectives and methodology applied before presenting the results and analysis. The results of a questionnaire survey of maintenance practitioners and an interview survey with equipment vendors are presented to answer *Research Question 1*. The results of an interview survey of maintenance managers are presented to answer *Research Question 2*. In this enquiry, data to support the answer to *Research Questions 1&3* was also collected. Results of an interview survey of CMMS developers are presented to address *Research Questions 2&3*. Finally, the results of three case studies are presented to address *Research Question 3*.

4.2 Questionnaire Survey of Maintenance Practitioners

The aim of the research is to provide evidence to answer the research questions that were stated in *Section 2.12.2*. As justified in *Section 3.4.2*, a descriptive survey is one of the most appropriate research strategies to address the first research question, which is:

“What is the current situation regarding failure records utilisation within maintenance of manufacturing systems?”

Section 3.5.3 identified a questionnaire survey as the most suitable method to collect evidence for answering this research question. This section presents the survey objectives that were established to answer the first research question, summarises the applied methodology to show how the survey was conducted, and presents the survey results and analysis.

4.2.1 Survey Objectives

This enquiry process aims to collect evidence to (i) investigate the importance of the topic and complement literature arguments, and (ii) investigate the feasibility a SDS based on failure records. This would provide arguments to decide whether or not to conduct an in-depth investigation. As such, it also can be viewed as a pilot study. The survey also aims to identify potential companies to conduct an in-depth study, and to guide the selection of a company, *e.g.* company type, size, and process type.

In order to answer the first research question and fulfil the above aim, the following objectives were defined for the survey:

1. Identify if failure records are important to assist maintenance;
2. Identify reasons for failure records collection and non-collection;
3. Identify current trends in managing failure records;
4. Assess the satisfaction and usage of current systems used to manage failure records;
5. Assess the relationship between equipment users and vendors with regard to maintenance;
6. Assess the creation of a database of failure records populated by users but managed by vendors;
7. Analyse if there is any relation between failure records collection and company type, company size, and process type.

4.2.2 Methodology Applied

Step 1: Survey Planning. The survey was initiated by defining its objectives (stated in the previous section) and the target population. Maintenance practitioners within manufacturing systems were the target population.

Step 2: Sample Selection. A probabilistic strategy within which a cluster sampling technique was applied was used to select the study sample to which the questionnaires were mailed (postal questionnaire) (Section 3.5.1). Industry typology was used to divide the population into groups, with members randomly selected from each group. Members were selected from UK and Portuguese companies. A database of contacts was formed to facilitate information handling, mail merge, and tracking of respondents. The e-mail questionnaire was posted to a maintenance newsgroup. Since the e-mail questionnaire method is relatively new, little is known about the effects of sampling bias.

Step 3: Methods Selection. A descriptive survey type was conducted to collect evidence (Section 3.4.2). Traditional mail (postal) and e-mail were the main methods used to approach respondents (Section 3.5.3); the latter was used because it is the most cost effective and quickest method of distributing a survey, and allows a worldwide survey to be carried out.

Step 4: Questionnaire Design and Testing. Two types of questionnaire forms, following the same structure, were designed, one to send by traditional mail and the other by e-mail (online-questionnaire). A cover letter was forwarded with the questionnaires. Both questionnaire forms and cover letter are presented in *Appendix B*. Questionnaires were designed following the recommendations of relevant literature (Section 3.6.3) and the opinion of a questionnaire design expert. Since this enquiry strategy is expected to produce a 'large' number of replies, close-ended questions were mainly used in order to facilitate the analysis process. Questions based on literature findings were derived. Once designed, both questionnaire forms were informally tested with colleagues and some maintenance practitioners. Results from these tests allowed the questionnaire design to be improved.

Step 5: Questionnaire Execution. The survey was executed during the academic year 2001/02. The questionnaire was sent by traditional mail to maintenance practitioners at 100 UK and 100 Portuguese companies. An on-line questionnaire was also posted to a maintenance newsgroup (*Plant Maintenance Website*). According to the newsgroup webmaster, 362 maintenance practitioners were subscribed at that time. The subscribers included consultants, academics and practitioners from all over the world, and represented a wide range of industries. The questionnaire was also used to survey maintenance managers attending a short course in Australia. It should be stressed that, in order to improve the

response rate and to meet ethical standards, pre-contact was made with most people to whom the questionnaires were sent by e-mail. In order to improve the response rate, some of the companies to which questionnaires were posted by traditional mail were initially contacted by telephone or e-mail.

Step 6: Data Collection and Analysis. The collection and analysis process consisted of first gathering and examining the questionnaires in order to discard those that failed to fulfil the acceptance requirements, *i.e.* questionnaires that were only partially completed were rejected. Approximately 1% of responses were negative, stating that the organisation did not want to participate in the survey. Approximately 2% of the returned questionnaires were dismissed because they were incomplete. Data was then manually extracted from the valid questionnaires and entered into a database for analysis. The data was analysed with the software package, *Microsoft Excel* (Section 3.7.1), and reported in both table and diagram formats in order to better fulfil the survey objectives. Due to the quantitative nature of the data and the purpose of the enquiry, a descriptive technique was used to statistically analyse the results (Section 3.7.1). This technique allows the conversion of raw data into indices that summarise datasets. Finally, a survey report summarising the results was written.

Step 7: Findings Validation. In order to validate the survey findings, a copy of the survey report was sent to most respondents and posted in the *Plant Maintenance Website* under the heading of maintenance articles. Results were also presented at a conference and published (Juliao and Greenough, 2003a).

4.2.3 Results and Analysis

The results from 111 valid responses to the descriptive survey are presented and analysed in this section. Although a worldwide survey was conducted, 86% of the respondents were based in the UK, Portugal or Australia. The responses came from a wide range of industries, with the automobile, food and mining industries being the most widely represented. Most of the respondents were maintenance managers and maintenance supervisors with extensive experience; almost half of them (45%) had collected failure records over the previous six years (Section C.1 in Appendix C).

In order to facilitate data analysis and highlight the relevance of findings, the enquiry results were clustered according to the objectives defined in Section 4.2.1. The full results of this survey are presented in Appendix C. Although some discussion is provided here, the general discussion is left for the discussion and conclusions chapter.

Objective 1: To identify if failure records are important to assist maintenance

Respondents were asked whether they collected failure records and to rate the importance of such records for assisting the maintenance function. The survey showed that 84% of the respondents collected failure records, while 55% classified failure records as very important in assisting their maintenance function (*Figure 4-2*). These results suggest that the collection of failure records is a main maintenance activity within the majority of the surveyed companies.

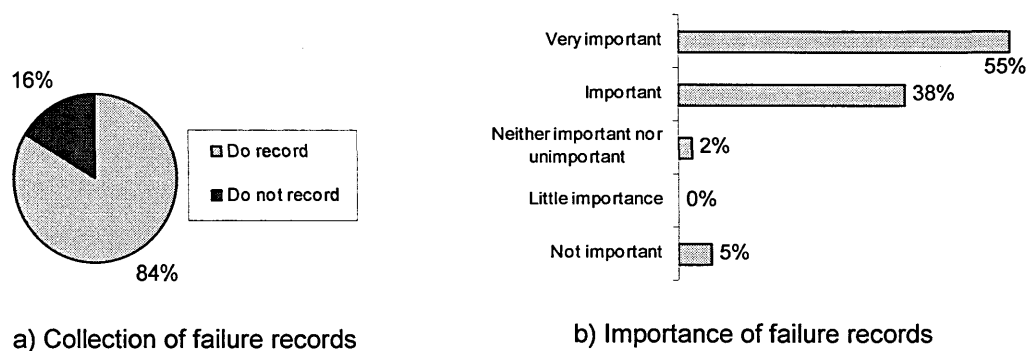


Figure 4-2: Collection and importance of failure records

Key Findings

- Collection of failure records is a significant maintenance activity within the majority of companies;
- A majority of the companies classify failure records as very important in assisting their maintenance function.

Objective 2: To identify reasons for failure records collection and non-collection

Despite a significant number of respondents claiming to collect failure records to assist failure diagnosis and repair (troubleshooting), the survey showed that assisting preventive activities was the main reason for collecting failure records. The survey results show that the main utilisation of failure records is to analyse failure modes and effects, and to assist maintenance planning and scheduling activities (*Figure 4-3*). Reliability analysis was an additional reason pointed out by some respondents for collecting failure records.

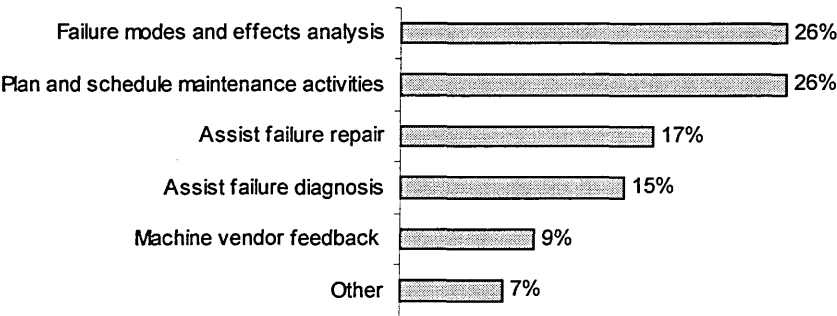


Figure 4-3: Reasons for recording failure histories

Of the eighteen respondents (16%) who claimed not to collect failure records, the inability of management systems to support failure records collection was identified as the main reason (Figure 4-4). The complexity of management systems and lack of time to do clerical work were other reasons for the non-collection of failure records.

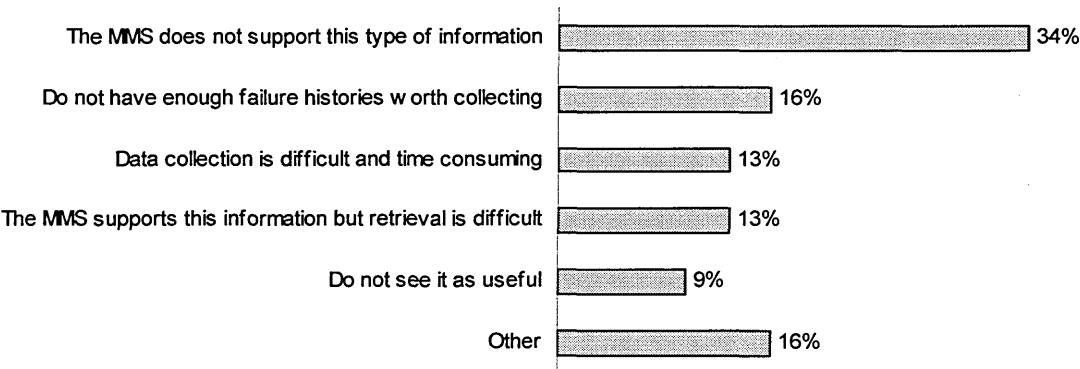


Figure 4-4: Reasons why failure history records are not being collected
(MMS – Maintenance Management Systems)

Key Findings

- Failure records are currently used more for supporting preventive activities than corrective activities;
- The use of management systems that fail to support failure records collection is the main reason for the non-collection of failure records.

Objective 3: To identify current trends in managing failure records

In order to fulfil the third objective respondents were asked about the type of system they use for failure records management, from what failure records are being collected, and about the use of a classification system to organise failure records. The survey demonstrated that there is a tendency to use computer-based systems purchased from vendors. A majority (65%) of the respondents who collect failure records use only a computer-based system to collect and store their failure records (Figure 4-5a). The number of companies that use both paper and computer-based system is significant (26%), while commercial systems (purchased from a vendor) are used more widely than self-designed systems. The survey showed that 75% of respondents used only a commercial system to manage their failure records (Figure 4-5b).

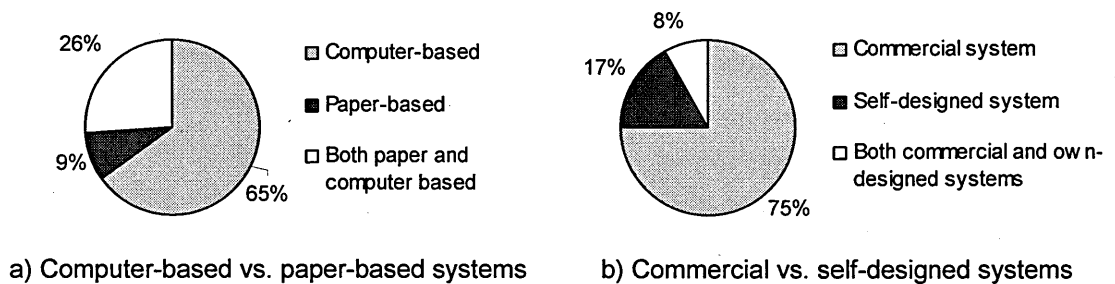


Figure 4-5: Type of system to manage failure history records

Almost half (49%) of the respondents who record failure histories appear to have no criteria to select the failures that should be recorded and so they record all failures, whether minor or major. For the remaining 51%, downtime and impact on production are the most popular types of failure for which data are collected (Figure 4-6).

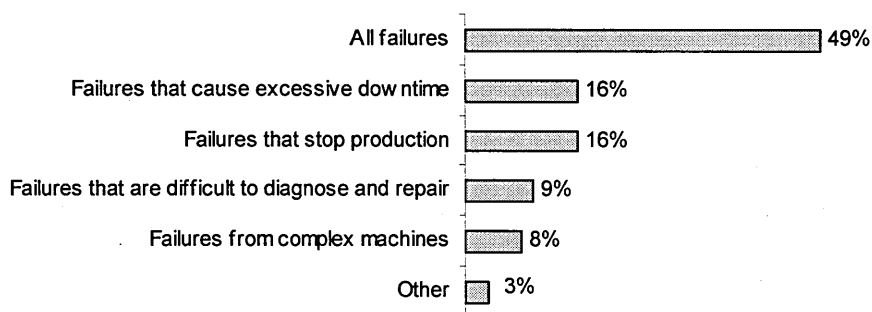


Figure 4-6: Type of failure data that are being collected

Whether they collected data on all or only some failures, 67% of respondents stated that they use a classification system to record failure histories (*Figure 4-7*).

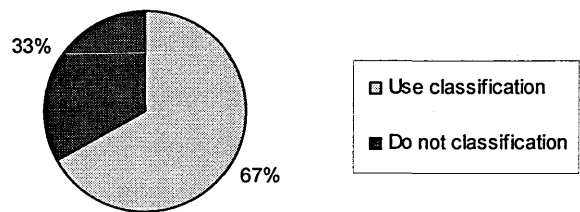


Figure 4-7: Use of a classification system to record failure histories

Key Findings

- The use of computer-based systems purchased from a vendor is the most popular approach to management of failure records. These are replacing the paper-based systems;
- Most companies do not use selection criteria for failure records collection, and collect data on all failures;
- There is a clear tendency to use a classification system to manage failure records.

Objective 4: To assess the satisfaction and usage of current systems used to manage failure records

In order to assess the satisfaction and usage of current systems used to manage failure records, respondents were asked to rate their failure data storage system for data retrieval and export. On average, respondents who collect failure records classified their storage systems as neither good nor poor for data retrieval, and as poor for data export (*Figure 4-8*).

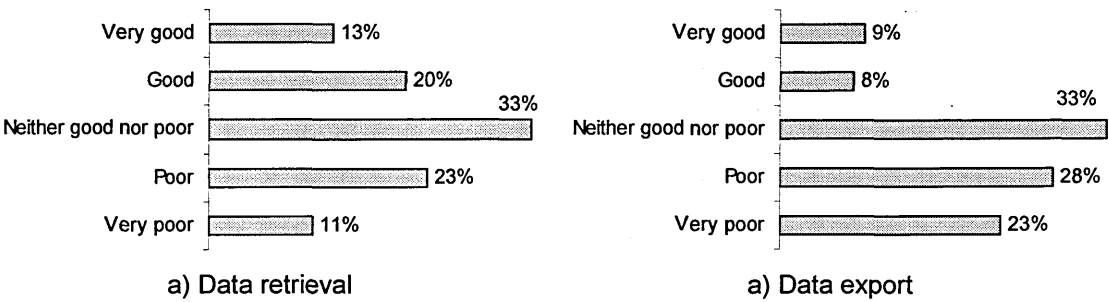


Figure 4-8: Rate of data storage system for data retrieval and data export

Respondents were also asked how often their maintainers refer to written descriptions of failure records to solve new problems. On average, respondents who collect failure records reported that their maintainers rarely refer to written descriptions of failure records to solve new problems (*Figure 4-9*).

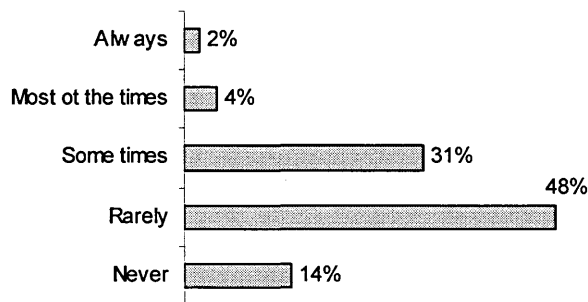


Figure 4-9: Frequency maintainers refer to written descriptions of failure records

Key Findings

- Satisfaction about failure records management system is neutral for data retrieval and negative for data export;
- Maintainers rarely refer to a written description of failure records.

Objective 5: To assess the relationship between equipment users and vendors with regard to maintenance

All respondents answered the questions regarding the relationship between machine tool users and vendors. A significant 75% of respondents reported that they exchange failure information with their machine tool vendors (*Figure 4-10a*). A majority of respondents classified the relationship with the vendor concerning assistance with machine maintenance as neither good nor poor (*Figure 4-10b*).

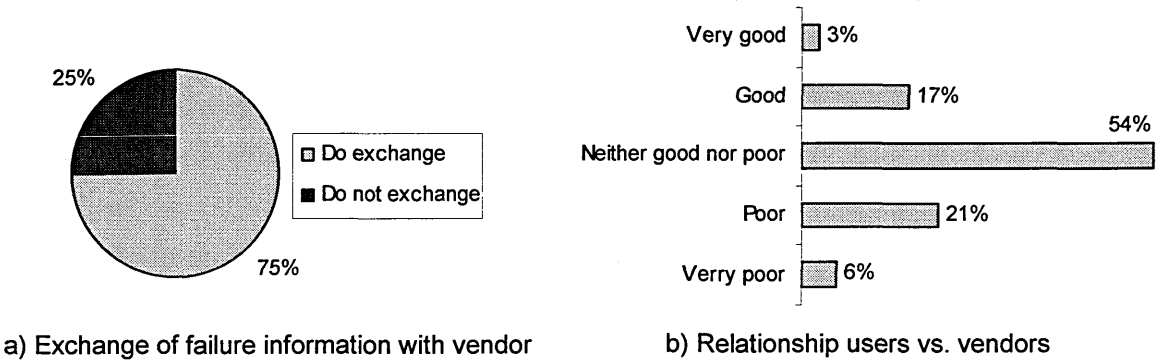


Figure 4-10: Relationship between machine tool users and vendors

Key Findings

- A clear majority of users exchange failure information with vendors;
- Users have a neutral position regarding their relationship with vendors.

Objective 6: To assess the creation of a database of failure records populated by users but managed by vendors

Respondents were asked whether they felt that a database of failure records populated by users but managed by vendors would be useful for their organisation. They were also asked if they would contribute their failure records to build such a database. All respondents answered these questions. This study found that, on average, respondents classified such databases as potentially useful for their organisation (Figure 4-11), while 85% of the respondents stated that they would contribute their failure records to build such a database.

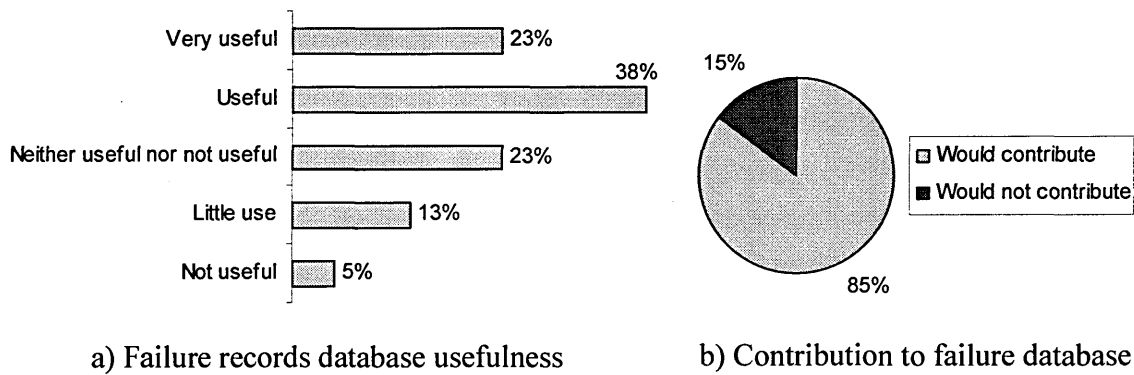


Figure 4-11: Failure database usefulness and contribution of users

Key Findings

- Maintenance practitioners classify a failure records database populated by users and managed by vendors as useful;
 - A clear majority of companies are willing to contribute their failure records to the generation of a common database.
-

Objective 7: To analyse if there is any relation between failure records collection and company type, company size, and process type

In order to fulfil the final objective and characterise respondents and their companies, respondents were asked the following questions:

- What is the total number of employees in your company?
- What is your industry type?
- What is your main manufacturing process type?

The results to these questions are presented in *Appendix D*. A visual inspection of the results did not identify any relationship between company size and the use of a paper or computer-based system to manage failure records. Analysis of the responses also provided evidence to support the idea that there is no link between the collection of failure records and the industry type, company size, or the process typology.

Key Findings

- No relationship was found between the use of paper or computer-based systems managing failure records, and the company size;
 - No relation was found between failure data collection, and company size, industry type or process typology.
-

4.3 Interview Survey of Equipment Vendors

4.3.1 Survey Objectives

The questionnaire survey from the previous section allowed presentation of the current situation regarding failure records utilisation within maintenance of manufacturing systems from the perspective of equipment users (referred as practitioners). It provided evidence to answer the first research question. The purpose of this survey is to complement the results of the questionnaire survey. Thus, the aim and objectives of both surveys are the same; but in this case from an equipment vendor’s perspective.

4.3.2 Methodology Applied

Step1: Survey Planning. The survey objectives are the same as the questionnaire survey, and the target population were equipment vendors.

Step 2: Sample Selection. The study sample was selected using a non-probabilistic strategy (Section 3.5.1) within which a dimensional sampling technique was applied (Table 3-8). A contact list of Cranfield University and Yellow Pages were used to randomly select ten equipment vendors/manufacturers from UK. These vendors sell equipment (e.g. machine tools) and provide maintenance servicing to the customers. Seven of the ten companies agreed to participate in the survey. Table 4-1 lists the companies that participated in the survey.

Company (Country)	Informant Job Title	Interview Type
Company A (UK)	Service Manager	Face-to face
Company B (UK)	Reliability manager	Face-to face
Company C (UK)	Deputy manger director & Service Manager	Face-to face
Company D (UK)	Service manager	Telephone
Company E (UK)	Reliability manager	Telephone
Company F (UK)	Service manger	Telephone
Company G (UK)	Service manger	Telephone

Table 4-1: List of interviewed equipment vendors/manufacturers

Step 3: Methods Selection. Evidence was collected using an analytical survey (Section A.4.1 in Appendix A). Interviews were used to collect evidence in this survey because they allow the collection of in-depth knowledge and the gaining of some industrial experience to establish and understand the industrial environment regarding the maintenance operation. They also permit a greater understanding of the company and allow a stronger relationship

between the researcher and companies to develop, which potentially helps to identify companies to develop future case studies. Face-to-face and telephone interview were used to approach respondents for data collection. Although it was recognised that with face-to-face interviews the ‘richness’ of communication is higher, telephone interviews were also used (*Table 4-1*) because they are cheaper and less time consuming (Gillham, 2000a). Semi-structured interviews were used to collect evidence (*Table A-2 in Appendix A*); this approach helped to focus data collection and facilitated data comparisons from the different sources of evidence. Therefore, a questionnaire similar to the questionnaire-survey was developed to follow-up the interviews.

Step 4: Questionnaire Design and Testing. The questionnaire used to guide the interviews was derived from the questionnaire applied in the postal survey. Unlike the mail-questionnaire, open-end questions were mainly used for interviewing, since they allowed more knowledge to be elicited from the experts. Some questions were also added. The questionnaire guide is presented in *Appendix B*. The questionnaire was designed following the good practice procedures presented in the previous chapter (*Section 3.6.3*).

Step 5: Interviews Execution. The interviews were conducted during the year 2002. Prior to the company visits, a cover letter was sent to informants explaining the objectives of the research and the interview. The letter indicated the people and institutions that were involved, and guaranteed the confidentiality of respondents and organisations. During the interviews, a brief introduction was given before each questionnaire module was presented to the respondents. When authorised by informants, a tape-recorder was used to facilitate later data analysis. In order to promote participation, a commitment was made to send a report of the findings to all informants. The number of interviewees and the time of interview are difficult to specify because they depended on the organisation’s availability and informant’s agenda. The researcher aimed to conduct at least ten interviews, as recommended by Whyte (1994). The interviews were designed to last a maximum of one hour.

Step 6: Data Collection and Analysis. Following the interviews, the notes were transcribed and analysed as soon as possible. Data was analysed following mainly an editing analysis approach and the analytical moves suggested by Miles and Huberman (1994). Data was clustered according to the survey objectives and analysed using *Microsoft Excel* (*Section 3.7.2*). Tables summarising results were generated. Following transcription, unclear aspects were clarified by re-contacting some interviewees.

Step 7: Findings Validation. In order to validate the survey findings, a summary report was returned to interviewees (where possible). The results were also presented at a conference (Juliao and Greenough, 2003b).

4.3.3 Results and Analysis

This section presents a summary of the interview results and analysis. As explained previously, the objectives of this survey are the same as the “questionnaire-survey” (Section 4.2.1), and the key findings are presented following the same structure.

It should be stressed that, despite all companies from the study sample providing maintenance assistance to their customers, servicing is a major activity in only five of them. Of the seven interviews, three were face-to-face and four via telephone. Five of the interviews were conducted with service managers (or equivalent) and two with reliability managers. Full results are presented in *Appendix C*.

Objective 1: To evaluate the importance of failure records to assist maintenance

The interviewees were asked if they collect failure records and to rate their importance to assist maintenance. All but one of the vendors interviewed are collecting failure records from the equipment they service, installed at the customers’ site (*Table 4-2*). Only three of them also collect failure records from customer experiences. The majority of the interviewees classify failure records as very important to assist maintenance.

Questions	Companies						
	A	B	C	D	E	F	G
Collection of failure records: from vendor servicing experiences	●	●	●	●	●	●	○
Collection of failure records: from customer's experiences	○	○	●	-	●	●	○
Importance of failure record collection	④	⑤	⑤	④	⑤	⑤	-
● - Yes; ○ - No; (-) no answer							
① = not important; ② = Little importance; ③ = Neutral; ④ = Important; ⑤ Very Important; (-) no answer							

Table 4-2: Collection and importance of failure records

Key Findings

- Collection of failure records from servicing experience is a trend among the majority of the interviewer’s vendors; it is a significant maintenance activity within the majority of companies;
- Majority of the vendors classify failure records as very important in assisting their maintenance function.

Objective 2: To identify main reasons for failure records collection and non-collection

The interviewees were asked why they collect failure records. Improving equipment reliability and providing better service to customers were the most stated reasons. Although rated lower, downtime analysis/control, and control/management of costs were other reasons stated by vendors for failure data collection.

Reasons for failure records collection	Companies						
	A	B	C	D	E	F	G
Improve equipment reliability	●	●	●	●	●	●	-
Provide better maintenance assistance	●	●	●	●	●	●	-
Analysis/control of equipment downtime	○	●	●	○	●	●	-
Costs control/management	○	●	●	●	●	●	-
Failure analysis	○	○	●	○	●	●	-
● - Yes; ○ - No; (-) no answer							

Table 4-3: Reasons for failure records collection

Some vendors also stated that they need failure records to understand how their products really perform in the field, and to compare them with competitors. Despite most vendors recognising that failure records from customer experiences would benefit equipment maintenance, 4 out of 7 vendors do not collect this information (*Table 4-2*). The main reasons were that (i) most customers do not have much data, (ii) customers are not willing to pay vendors to acquire detailed data, and (iii) failure records might suggest poor product reliability and so are omitted.

Key Findings

- Improvement of equipment reliability and maintenance servicing appear to be the most important reasons for the collection of failure records;
- Motivation and lack of data appear to be most important reasons that some vendors do not collect failure records from customers' experiences.

Objective 3: To identify current trends in managing failure records

In order to fulfil the third objective interviewees were asked about (i) the type of system they use to manage the failure records, (ii) the use of a criterion to select which failures records are collected, and (iii) the use of a classification system to organise failure records. Among vendors simultaneously using both paper and computer-based systems, was the most popular method to manage failure records (*Table 4-4*). Traditionally, paper-based systems are used to collect data and computer-based systems used to store and manage the records. Within the computer-based systems, commercial systems purchased from a software vendor are more popular.

Methods for managing failure records	Companies						
	A	B	C	D	E	F	G
Only computer-based system	○	○	○	●	○	○	-
Both paper and computer based systems	●	●	●	○	●	●	-
Purchased commercial system	●	●	●	●	●	●	-
Use of a criterion to select from which failures are records collected	○	○	●	○	○	●	-
Use of a classification systems to organise the records	○	●	●	●	●	●	-
● - Yes; ○ - No; (-) no answer							

Table 4-4: Trends managing failure records

Results also show that the use of criteria to select which failure records are collected is not common among these vendors. Most reported that they collect records from all failures. Those that use criteria claim to collect only records from which failures caused a significant downtime (more than 15 minutes). Moreover, there is a clear tendency to use a classification system to manage failure records.

Key Findings

- Tendency to simultaneously use both paper and computer-based systems to manage failure records, and to purchase computer-based systems;
- Tendency to collect data from all, and to use a classification system to organise the records.

Objective 4: To assess the satisfaction and usage of current systems used to manage failure records

In order to assess the satisfaction and usage of current systems used to manage failure records, interviewees were asked to rate their general satisfaction and utilisation rate of their system, and to indicate what they like most and least about their system. Regarding satisfaction, results indicate that vendors on average have a neutral position (Table 4-5). The majority feel their system is poorly utilised, particularly by maintainers. On average, interviewees appear happy with their system for managing and controlling costs, and mapping clients and equipment. For failure records, most of them are not happy with the storage and retrieval capabilities of their system. Some interviewees stated that a limitation of their system is the lack of a feature that allows aggregating and classifying failure information in a way that allows different records to be linked and cross-references to be established between them.

Satisfaction and usage of failure records management system	Companies						
	A	B	C	D	E	F	G
Overall satisfaction	④	③	③	②	③	②	-
General utilisation rate	③	②	③	②	②	②	-
Maintainers utilisation rate	②	①	②	②	①	①	-
Good to manage and control costs	●	●	●	○	●	○	-
Good to map clients and equipment	●	●	○	○	●	○	-
Poor storage and retrieval capabilities	○	●	○	●	●	●	-
① = very poor; ② = poor; ③ = Neutral; ④ = good; ⑤ Very good ● - Yes; ○ - No; (-) no answer							

Table 4-5: Satisfaction and usage of failure records management system

Key Findings

- Although neutral regarding the overall satisfaction about their management system, vendors classify the system utilisation rate as poor; particularly the utilisation by maintainers;
- Despite being good for managing and controlling costs, and mapping clients and equipment, management systems were classified as poor by most vendors regarding their capabilities to store and retrieve failure information;
- Aggregation of failure information is a common limitation of vendor's management systems.

Objective 5: To assess the relationship between machine users and vendors with regard to maintenance

In order to assess the relationship between equipment users and vendors regarding maintenance, interviewees were asked (i) to rate their relationship with their customers, (ii) if they exchange failure information with customers, (ii) to indicate what type of support information they provide to their customers, and (iii) to characterise customer participation on support documentation development. A majority of interviewees classified their relationship with their customers as very good, and stated that they exchange failure information with their customers (Table 4-6). All interviewees provide equipment manuals to their customers, and most of them also provide troubleshooting manuals. Regarding the development of support documentation, only half of those who provide a troubleshooting manual to their customers reported that they consider customer experiences when developing these manuals.

Relationship users vs. vendors	Companies						
	A	B	C	D	E	F	G
Relationship rate	⑤	⑤	⑤	④	⑤	④	⑤
Exchange of failure information with customers	○	●	●	●	●	●	○
Provide equipment manuals	●	●	●	●	●	●	●
Provide troubleshooting manuals	○	●	●	●	●	●	○
Consider customer's experiences on troubleshooting manuals development	○	○	●	○	●	●	○
Single troubleshooting manual per equipment type	○	●	●	●	○	●	○
① = very poor; ② = poor; ③ = Neutral; ④ = good; ⑤ Very good ● - Yes; ○ - No; (-) no answer							

Table 4-6: Relationship between users and vendors

Key Findings

- The majority of vendors exchange failure information with their customers, and classify the relationship with customers as very good;
- There is a trend to provide maintenance support information to equipment customers in the form of equipment and troubleshooting manuals;
- Considering customer experiences when developing troubleshooting manuals is not a trend for all vendors;
- Vendors tend to develop a single troubleshooting manual per equipment type.

Objective 6: To assess the creation of a database of failure records populated by users but vendor managed

Vendors were asked (i) whether they felt that such a database would be useful for their organisation, and (ii) if they would contribute their data to build such a database. A majority of interviewees think that such database would benefit their organisation (*Table 4-7*). Furthermore, all of them stated that they are willing to contribute their failure records to derive such a database. However, those for whom servicing is a major activity, concerns regarding sharing of failure information were expressed. These companies were concerned about losing customers and so did not want to provide troubleshooting records directly to them. Regarding reliability data, they are also sensitive to show information that might indicate low performance of their equipment. However, they were motivated to develop a stand-alone database that would allow the establishment cross-references between all maintenance support documentation, and to promote acquisition of part of the tacit knowledge of maintenance technicians.

Vendors also expressed that the feedback from their customers, regarding failure experiences, is important for them to better understand how their equipment perform in field. This would allow them to improve the reliability of their equipment, and produce better troubleshooting manuals.

Failure database populated by users and vendor managed	Companies						
	A	B	C	D	E	F	G
Benefit for your organisation	④	④	④	③	④	③	③
Contribute their data	⊙	●	⊙	⊙	⊙	⊙	●
① = nor useful; ② = little use; ③ = Neutral; ④ = useful; ⑤ Very useful ● = contribute; ⊙ = contribute with restriction							

Table 4-7: Failure database usefulness and contribution of vendors

Key Findings

- The majority of vendors think that a global database of failure records populated by users but vendor managed would benefit their organisation;
- A global failure records database would increase customer feedback, which would contribute for the improvement of both equipment reliability and troubleshooting manuals;
- Vendors for whom servicing is a major activity showed serious concerns about sharing their data with customers; they prefer to develop a stand-alone database.

4.4 Interview Survey of Maintenance Managers

This section presents the results of interviews conducted with maintenance managers (or equivalent position). It presents the enquiry objectives before briefly describing the applied methodology. Collecting evidence to answer the second research question is the main purpose of the enquiry (*Section 2.11.2*). The objective is to identify the reasons why current information systems (CMMS and documentation systems) do not effectively support troubleshooting, as literature suggests (*Section 2.10*). In order to identify if the main results from the questionnaire survey and interviews converge, it also aims to identify the current situation regarding failure records utilisation. It also aims to identify potential companies in which to conduct case studies.

The literature review suggests that current Information Systems (IS) fail to effectively support troubleshooting (*Section 2.10*). It also shows that downtime can be reduced if troubleshooting is performed effectively and efficiently. As such, a new approach to reduce troubleshooting time based on efficient management of failure records and technical documentation (maintenance documentation) was proposed (*Section 2.9.3*). Consequently, the importance here is to verify if current IS are in fact failing to effectively support troubleshooting. Understandably, it may be that resistance to change could occur as a result of replacing an already familiar operation with that of a newer system of procedure with an unknown level of success. Thus, the aim of this enquiry process is to establish an industrial perspective, based on maintenance managers' view, to verify the need (or lack of one) for a new approach/research to help reduce troubleshooting time.

4.4.1 Survey Objectives

In order to fulfil the above requirements, the objectives established for the survey of maintenance managers were to:

1. Identify the utilisation rate and the degree of satisfaction with CMMS and documentation systems in troubleshooting assistance;
2. Identify the causes, effects, and suggestions of problems with CMMS and documentation systems when supporting troubleshooting;
3. Evaluate end-user involvement in CMMS and documentation systems development;
4. Evaluate the importance of failure records for assisting maintenance.

4.4.2 Methodology Applied

The methodology followed in this enquiry process is similar to the one used for the interview survey of equipment vendors and so this section only highlights the key differences between them (*Table 4-8*). The interviews were mainly conducted during the academic year 2002/03. Of the nine interviews, seven were conducted with manufacturing companies and two with service companies, the majority of which are UK based (*Table 4-9*). The majority of interviewees were either maintenance managers or equivalent.

Steps	Description
<i>Survey Planning</i>	Survey objectives: stated in previous section Target population: maintenance managers within manufacturing systems
<i>Sample Selection</i>	Strategy: non-probabilistic (<i>Section 3.5.1</i>) Technique: Dimensional sampling (<i>Table 3-8</i>) Source: Contacts list of Cranfield University and of Portuguese Maintenance Association Study sample: presented in <i>Table 4-9</i>
<i>Methods Selection</i>	Enquiry strategy: analytical survey (<i>Section 3.4.2</i>) Method: Semi-structured interviews (<i>Table A-2 in Appendix A</i>). Technique to approach respondents: face-to-face
<i>Questionnaire Design and Testing</i>	Similar to previous enquiries (<i>Sections 4.2.2</i>) Questions based on literature findings were derived for the interview guide Interview guide presented in <i>Appendix B</i>
<i>Interviews Execution Data Collection and Analysis Findings Validation</i>	Similar to the survey of equipment vendors

Table 4-8: Key feature of methodology

Company (Country)	Industry (Sector)	Informant Job Title	Interview Type
Company A (UK)	Automobile (Engine plant)	Maintenance manager	Face-to-face
Company B (UK)	Automobile (Engine plant)	Maintenance manager	Face-to-face
Company C (UK)	Automobile (Assembly plant)	Reliability Engineer	Face-to-face
Company D (Portugal)	Automobile (Assembly plant)	Maintenance manager	Face-to face
Company E (UK)	Automotive (Parts manufacturer)	Maintenance manager	Face-to face
Company F (UK)	Precision Engineering	Operations manager	Face-to face
Company G (UK)	Servicing	Reliability engineer	Face-to face
Company H (Portugal)	Servicing	Site manager	Face-to face
Company I (Portugal)	Paper Mill	Maintenance manager	Face-to face

Table 4-9: List of interviewed maintenance managers

4.4.3 Result and Analysis

This section presents the results and analysis of the interviews with maintenance managers. The full results extracted from the interview transcriptions are presented in *Section C.3 (Appendix C)*. The following results and key findings are presented according to the objectives of the survey.

4.4.3.1 Utilisation rate and the degree of satisfaction

Objective 1: Identify the utilisation rate and the degree of satisfaction of CMMS and documentation systems in troubleshooting assistance

In order to fulfil *Objective 1* of the survey, interviewees were asked to rate utilisation (*Question 1*) and overall satisfaction (*Question 2*) of both their CMMS and documentation in troubleshooting support. Regarding utilisation, interviewees were asked to distinguish the utilisation by both maintenance supervisors/engineers and by maintenance technicians/shop-floor. The questionnaire guide of interviewees is presented in *Appendix B*. Utilisation and satisfaction in this case relates to the interviewee's personal feelings about the usage by their maintenance staff and about their expectations. *Table 4-10* presents the main results of *Question 1* and *Question 2*.

Issues of Q1 & Q2		Companies								
		A	B	C	D	E	F	G	H	I
I1	[Q1] Utilisation by maintenance supervisors/engineers									
	Maintenance information system	4	3	4	4	3	4	4	3	4
	Maintenance documentation	3	2	4	3	2	3	-	2	3
I2	[Q1] Utilisation by maintenance technicians/shop-floor									
	Maintenance information system	3	3	3	3	2	2	3	2	2
	Maintenance documentation	2	2	3	2	2	2	-	2	3
I3	[Q2] Overall satisfaction									
	Maintenance information system	3	2	3	3	2	2	3	2	2
	Maintenance documentation	3	3	4	3	2	3	-	3	4
I1; I2	1 = Never; 2 = Rarely; 3 = Sometimes; 4 = Often; 5 = Always; (-) = do not know or no answer									
I3	1 = very low; 2 = low; 3 = medium; 4 = high; 5 = very high; (-) = do not know or no answer									

Table 4-10: Utilisation and satisfaction of information systems in troubleshooting assistance

Key Findings

- The majority of interviewees reported that their company maintenance supervisors/engineers *often* refer to their CMMS and *sometimes* to documentation to assist troubleshooting;
 - The majority of interviewees reported that their maintenance technicians/shop-floor *rarely* refer to both CMMS and documentation to assist troubleshooting;
 - Overall CMMS tend to be used more to assist troubleshooting than maintenance support documentation;
 - For the time and money invested in systems and documentation, higher utilisation was expected by most of the interviewees;
 - The majority of interviewees appear unhappy about their CMMS assisting troubleshooting and classify as low their level of satisfaction;
 - On average, interviewees classified as medium their level of satisfaction for documentation assisting troubleshooting;
 - Overall, interviewees are less happy with their CMMS than the documentation regarding troubleshooting assistance.
-

It is important to stress that most interviewees expressed high levels of satisfaction with their CMMS when considering planning PM activities, inventory and resources control, and administrative tasks.

4.4.3.2 Causes, effects and suggestions of problems with current information systems when supporting troubleshooting

Objective 2: Identify the causes, effects, and suggestions of problems with CMMS and documentation systems when supporting troubleshooting

Interviewees were asked to indicate the causes and effects of problems they experienced with their CMMS and documentation system when used to support troubleshooting (*Question 3*). They were also asked to provide suggestions to improve those problems (*Question 4*). The suggestions aim to generate the requirements for a new approach to improve both CMMS and documentation when supporting troubleshooting.

In order to cluster data analysis and create categories, data from the transcriptions were summarised and the following key issues (events) identified:

1. Use of CMMS to support troubleshooting;
2. Aggregation of maintenance documentation;
3. Content of maintenance documentation;
4. Acquisition of failure information;
5. Management of failure information;

Data elements were then compared within each category and results displayed in tables, since they allow the empirical evidence to be organised, compressed, and synthesised in a systematic way. The tables that show the results are presented according to the defined categories in *Appendix C*. It is important to stress that the data presented in these tables is still raw data. The results of the first level analysis of each of these tables are described below. These descriptions represent what was perceived from the interviews and are presented as close as possible to the way they were reported. A distilled and structured analysis of these results is presented in the following sections.

Issue 1: Use of CMMS to support troubleshooting

Despite recognising that CMMS are an important tool to collect and manage work and information flow, most interviewees stated that current CMMS are not being designed to provide direct support to troubleshooting. As such, regarding troubleshooting support, users are generally unhappy with the systems currently in place. Most interviewees claimed that it is difficult to access and manipulate specific information to support troubleshooting using their CMMS. Thus, getting the right information to support troubleshooting is either intangible or time consuming. A common feeling among interviewees is that their CMMS is more oriented to assist accounting, administrative, and preventive activities. Most interviewees suggested that new features should be added to current CMMS that make them more self-oriented to support troubleshooting and easy to use by maintenance technicians.

Interviewees also reported that maintenance technicians found their CMMS too complex and not user friendly. Consequently, providing too little training de-motivates technicians because they need to spend more time to understand the system than to retrieve information. This complexity inhibits technicians from referring to CMMS to support troubleshooting. As such, technicians tend to use their own experience and skills to solve problems rather than referring to CMMS. It was suggested that CMMS need to be designed that make them easier to use and with a shorter learning curve.

Regarding the support of troubleshooting, it was reported that end-user expectations are not being met by CMMS because IT experts who develop them rarely have sufficient maintenance expertise and fail to efficiently collect user requirements. Most interviewees reported that there is a lack of contact between developers and end-users. It was suggested that meeting specific needs end-user requirements should be integrated in the new CMMS development, *i.e.* end-users should have more interaction during CMMS development. It was also suggested that this participation should be only at a level that end-users can understand.

In order to reduce CMMS drawbacks, three out of nine companies developed their own failure database dedicated to assisting troubleshooting by collecting and managing failure records; the database complemented their CMMS. In these three companies failure data is collected through a paper-based system, which is then introduced into a computer-based system to be managed. It was also found that each company found its own way to classify their records.

Issue 2: Aggregation of maintenance documentation

The lack of aggregation of documentation that can be used to support troubleshooting was another issue presented by the interviewees. It was reported that documentation is usually physically dispersed to various locations and was of different document types. These documents are rarely based near the workplace because they tend to be paper-based, which made them difficult to move. The above problems cause access difficulties, which decreases the technician's motivation to use documentation to support troubleshooting. As a result, technicians only refer to documentation to support the troubleshooting of problems they fail to solve, of too specific problems, and of problems of which they have no previous experience. It was claimed that this potentially causes a decrease in troubleshooting quality because problems are solved by guessing, repair procedures are missed, only failure symptoms are fixed (not their causes), safety procedures that are not considered, etc.

Most interviewees claimed that the paper-based nature of most documents is one of the causes for the lack of documentation aggregation. Their paper-based nature makes it difficult to establish cross-references between documents and pieces of information. Moreover, it makes updates more difficult to do and to distribute. It was reported that the diversity of formats and documents where support information for troubleshooting can be found also limited aggregation. Interviewees also reported that the aggregation of documentation is limited because their CMMS do not provide an efficient way of

integrating and linking the different type of documents that simplifies their utilisation for troubleshooting.

It was suggested that making all documentation digital would improve aggregation and their utilisation for supporting troubleshooting. This would allow all documents to be put into a single computerised database that would facilitate the distribution of updated information to where it is needed. It would also facilitate access to information by allowing cross-references to be established between different documents and specific information contained in the documents.

Issue 3: Content of maintenance documentation

For the purpose of this analysis about documentation, a distinction is made between maintenance manuals, failure records, and operation/equipment manuals.

Most interviewees classified the maintenance manuals (traditionally provided by equipment vendors) as useful to support troubleshooting. They also reported some limitations, including: (i) often only include a limited number of standard failures of the equipment, (ii) do not consider the operational conditions of the equipment, (iii) do not include the field experiences, and (iv) frequently instruct users to contact the vendor for guidance on troubleshooting.

Interviewees reported that collecting failure records is a way of dealing with the limitations of the maintenance manuals. In addition to standard failures, failure records also take into account the context in which equipment operates and might include maintenance technician's experiences. However, most interviewees reported that their maintenance technicians often fail to refer to their failure records because of (i) difficulties accessing information, and (ii) specific information about troubleshooting is often missing. The former reason is discussed later in this section. Regarding the causes for the latter reason, some interviewees indicated that their failure records forms were not initially designed to collect failure information to support troubleshooting. Moreover, the description of the work experiences in troubleshooting and elimination of failures are commonly missing in the failure records because technicians have a "*fear*" of sharing their knowledge. Some interviewees also claimed that the lack of a structured process that guides the collection of past failures is a cause for the missing information.

Generally, interviewees suggested optimising the content of failure records because the information they contain enhances a better understanding of the nature of equipment failures. This information is also potentially more self-oriented to support troubleshooting and is more intuitive to use than other types of documentation, *e.g.* technical manuals. One

statement was “*experience is an important element of maintenance technician’s competencies in finding the reason for an accurate malfunction*”. Encouraging maintenance technicians to collect experiences of past failures and identifying a strategy to reduce the fear of sharing their knowledge was suggested. Some believed that collecting these experiences facilitates knowledge transfer from experienced technicians to novices and less experienced technicians. It also provides guidance on troubleshooting, avoids solving problems by “guessing”, and increases self-confidence, particularly of novices often afraid of failing.

Regarding other documents, *e.g.* operations manuals and equipment manuals, it was reported that generally they are useful for supporting troubleshooting. However, they tend to be too complex and not too intuitive for maintenance technicians to use. According to the interviewees, maintenance technicians generally find it time consuming and tedious to search for failure information in these documents. It was indicated that these documents are too complex to use because they are not designed exclusively to support troubleshooting. Most interviewees suggested that reversing this trend would be highly useful for troubleshooting support to link/integrate all information of documentation in a single system.

Issue 4: Acquisition of failure information

The lack of failure records and the unclear/missing information were the main problems reported by the interviewees. They often claim that they are not aware how much data needs to be collected, what level of detail is needed, and what the best method to capture field data is.

Generally, interviewees reported that the acquisition of failure information is time consuming and expensive, and is probably the main reason for the lack of failure records. Work pressure and motivation of maintenance technicians were also pointed out as causes for the lack of failure records. It was reported that work pressure limits the time for technicians to do clerical work. Moreover, results indicate that maintenance technicians are traditionally not motivated to collect data because they commonly (i) do not know exactly why they are collecting data and how they will benefit from it, and (i) do not refer to records to support troubleshooting.

Although work pressure and motivation was also associated with the problem of unclear/missing information, other causes were identified for this problem. Detailed forms tend to be used to collect failure information, which commonly result in incomplete reports where many fields are not completed. Although tick-boxes tend to be used to speed up data

collection, it was claimed that this process provides less accurate information. Conversely, written descriptions imply more analysis work. It was also identified that unclear/missing information tends to increase if people who were not directly involved in the problem solving process report failures. Unclear/missing information also made it difficult both to assign the best person and resources to do the job.

Some interviewees reported that the experiential knowledge that is acquired by technicians with experience and training is an important piece of information that is commonly missed in the records. It was stated that, in general, technicians fail to provide clear and sufficient information about problems they experienced. The main causes for this problem were (i) this type of knowledge is unstructured and intuitive, and so difficult to represent, (ii) technicians' lack of motivation and time, and (iii) technicians' fear of losing their jobs as a result of sharing their knowledge.

In order to reduce some of the above problems, it was suggested that:

- Data collection forms and procedures should be improved;
- Data collection forms should be made as simple as possible;
- Requested information should be minimised to the strictly necessary;
- A reporting procedure that facilitates failure identification, speeds response to problems, and could be standardised for most failures should be provided;
- Collection systems should be designed so that it distinguishes clearly data for each purpose (e.g. PM activities, accounting, and troubleshooting);
- A database rather than paper-based forms should be used for data collection;
- Technicians should not be asked for information they are unlikely to have, and to seek data that will be used and from those directly linked to the job;
- Data be provided by maintenance technicians (e.g. troubleshooting information) should be kept separate from that by engineers (e.g. reliability data), i.e. identify domains of expertise;
- Motivation for data collection would increase if technicians are told why they are collecting data and how they will benefit from it, and
- Since failure records are probably the best way to collect experiential knowledge, a strategy should be found to motivate technicians to record their experiences in reports.

Issue 5: Management of failure information

The management of failure information that can be used to support troubleshooting was another issue stressed by interviewees. This discussion mainly focused upon the management of failure records, *i.e.* information concerning previous failures. Most interviewees claimed that their failure records are not aggregated or classified in a way that facilitates the retrieval and use of failure information to support troubleshooting; particularly by maintenance technicians. Results suggest that most classification and coding systems of interviewees are not creating meaningful results. The majority of the interviewees reported that “*miscellaneous*” failures or “*failure not listed*” are the categories where more failures are recorded.

Results also suggest that failure records tend to be classified using only equipment attributes, *i.e.* failure records are assigned with an equipment code, which are then associated with a repair code. However, this equipment code classification make it difficult to relate similar failures from different equipment types, and to extract specific information from equipment with an extensive number of records. It was also stated that too many records are pulled out when the equipment code is introduced, and when maintenance technicians receive too much information they begin to ignore it. Regarding access to failure records, some interviewees characterised this type of classification as inflexible and limited. Although attempts were made to develop a system to classify and code failure information (to be used to support troubleshooting), most respondents claimed that no efficient way has been found. “*How to classify and organise failure information?*” appears to be the main question. This difficulty of handling failure records was identified as one of the reasons for the feeling that more data is being collected than used. It was also reported that the difficulties retrieving failure information from records leads to a lack of use of failure information in troubleshooting support.

All interviewees recognised that the development of an improved system to classify failure records would be useful for achieving a better decision-making environment for problem solving; it would also make failure troubleshooting more efficient. Most interviewees suggested the development of a classification system that integrates both equipment and failure attributes. It is believed that adding failure attributes to the classification system would facilitate the management of failure records, particularly the retrieval. This would facilitate cross-references between different records, finding records from a particular equipment type, and classifying similar failures from different equipment. It was also suggested that using failure attributes that reflect what maintenance technicians see, hear and feel when failures occur would make the classification system more intuitive to use by technicians.

Most of the interviewees also reported that failures that are poorly described make difficult the correct identification of failure records. Failure descriptions tend to be reported through a free form text, allowing each person to describe failures in their own way, using different syntax and nomenclature. Using verbiage in failure description complicates the management of failure records because they are more difficult to identify, sort, and manipulate. It was reported that the inconsistent terminology used in failure descriptions decreases the quality of the information. This process limits the identification of failure records and so some interviewees suggested classifying/coding the failure descriptions using pre-defined categories to facilitate the identification and retrieval of records. A suggestion was made to create a taxonomy to organise the failure description and develop a relational structure to guide its reporting. To facilitate the identification and retrieval of failure records, some interviewees suggested that failure description keywords could be used to initiate a search browser.

The paper-based nature of most of the failure records and documentation in general was also identified as a problem regarding the management of failure information. Results show that difficulties managing paper-based documents are making companies move towards electronic documentation, despite most companies managing their electronic documents as paper-based documents. The electronic documents are simply placed into folders without links or cross-references to facilitate retrieval.

It was reported that most maintenance technicians are experienced field personnel that have great technical experience but little IT experience, *i.e.* computer skills and database knowledge. This lack of IT skills causes problems retrieving failure information to support troubleshooting.

4.4.3.3 End-user involvement in CMMS and documentation systems development

Objective 3: Evaluate end-user involvement in CMMS and documentation systems development

Interviewees were asked to characterise the end-user involvement in the development phase of CMMS and documentation systems. This section presents the main findings from the analysis of the interview results. *Appendix C* presents a table with the results extracted from interview transcriptions.

Interviewees generally reported that the level of involvement (or participation) of end-users in CMMS is either low or non-existent. The reasons for this are that CMMS are commonly purchased from vendors, which, with a few exceptions, do not collect end-user

requirements; some found it difficult to arrange the right timing for developers and end-users to meet and discuss system development. It was also suggested that managers are those who eventually have some involvement in CMMS development. Regarding external documentation, *i.e.* documentation that usually comes with equipment, the above is also valid. Conversely, it was reported that there is involvement of end-users in the development of internal documentation. However, in this latter case engineers/supervisors rather than maintenance technicians tend to get involved.

The non-collection of end-user requirements by developers and/or the non-involvement of end-users in systems development is viewed as a primary reason for the lack of functionality of a system. It is also identified as a reason for the low utilisation rate of CMMS and documentation. Most interviewees believe that maintenance technicians would be more enthusiastic about using the system if they were directly involved in its development. It was suggested that end-users should have more interaction in systems development, and their participation should be encouraged and allowed.

Using an *ad hoc* approach to collect end-user requirements was identified as another problem. The absence of a structured process to collect and analyse end-user requirements is a cause of the low involvement in systems development, and so some interviewees suggested the definition of a structured process to guide the collection and analysis of end-user requirements that specify the stages to gather and analyse data. It was also suggested that, although questionnaires might be used, brainstorming sessions are probably the most suitable method to collect end-user requirements.

4.4.3.4 Importance of failure records for assisting maintenance

Objective 4: Evaluate the importance of failure records for assisting maintenance

In order to identify if the main results from the questionnaire survey and interviews converge, informants were asked to answer a set of questions about failure records utilisation (*Appendix B*). *Table 4-11* presents a summary of the results.

All interviewees stated that they collected failure records from their equipment, while a majority classified failure records as very important for assisting maintenance. Although all interviewees stated that they use computer-based systems to manage their failure records, the majority reported using paper-based systems to complement them. Paper-based systems were mainly used to collect data from the field. It was also found that the majority of interviewees exchange failure records with equipment vendors and classify the relationship with their vendor(s) as good. Regarding a vendor-managed database of failure records, a

majority classified it as potentially useful, but only two respondents reported that they would contribute their data to generate such a database. Servicing companies answered ‘no’ to contributing their data to a database, although they agreed to contribute if restrictions were put in place.

Questions		Companies								
		A	B	C	D	E	F	G	H	I
Q6	Collect failure records	Y	Y	Y	Y	Y	Y	Y	Y	Y
Q7	Importance of failure records to assist maintenance	5	4	5	5	3	4	-	5	5
Q9	Type of system to manage failure records	B	B	B	B	C	C	C	B	B
Q10	System self-designed or purchased from vendor	B	B	B	B	V	V	V	B	S
Q11	Relationship with vendor	5	4	4	4	-	4	-	3	4
Q12	Exchange failure information with vendor	Y	Y	Y	Y	-	Y	-	Y	Y
Q13	Failure database populate by users and vendor managed	4	4	5	4	3	4	3	4	4
Q14	Contribute failure records	Y	Y	Y	Y	Y	Y	N	N	Y
Q6; Q12; Q14	(Y) = yes; (N) = no; (-) = do not know or no answer									
Q7	1 = not important; 2 = little importance; 3 = neutral; 4 = important; 5 = very important									
Q9	(C) = only computer; (P) = only paper; (B) = both computer and paper									
Q10	(S) = self designed; (V) = purchased from vendor (B) = both systems									
Q11	1 = very poor; 2 = poor; 3 = neutral; 4 = good; 5 = very good									
Q13	1 = not useful; 2 = little use; 3 = neutral; 4 = useful; 5 = very useful									

Table 4-11: Importance of failure records for assist maintenance

4.5 Interviews with CMMS Developers

This section presents the results and subsequent data analysis of the CMMS developers' survey. Similar to previous sections, it first presents the enquiry objectives before briefly describing the applied methodology. Collecting evidence to mainly support the answers to both the second and third research questions is the purpose of this enquiry (*Section 3.2.2*). That is, it investigates the argument that current CMMS fail to effectively support troubleshooting (as suggested by literature), and examines ways of improving the use of CMMS for troubleshooting.

4.5.1 Survey Objectives

In order to fulfil the above aim, the objectives established for the survey of CMMS developers were to identify:

1. Whether CMMS are being designed to support maintenance technicians during troubleshooting.
2. Types of failure information used to support troubleshooting that is recordable by CMMS.
3. Failure attributes used by CMMS to classify failures records.
4. Purposes of the failure records classification.

4.5.2 Methodology Applied

The survey was planned by defining its objectives and the target population. The survey objectives were stated in the previous section, while CMMS developers within manufacturing systems are the target population. The sample considered in this survey consists of nine interviewees representing UK-based CMMS companies. *Table 4-12* presents the list of the surveyed companies and information about the informant job title and the interview type. In order to preserve confidentiality, the real names of the companies are omitted. Of the nine interviews, five were conducted by phone and four face-to-face. This sample was selected using a non-probabilistic strategy (*Section 3.5.1*), and a dimensional sampling technique (*Table 3-8*). Ten CMMS developers were selected to be interviewed by phone. This selection was based on the results of a world wide survey conducted by the “*Plant Maintenance Resource Centre*” in the year 2000 (Dunn, 2000), which presents a ranking of the most common CMMS. Only five of the ten companies were willing to be interviewed. The four face-to-face interviews were conducted at selected

companies that attended a maintenance exhibition (MAINTEC 2002) in Birmingham, UK. This selection was based on the popularity of their products and on the availability of informants to conduct an interview.

CMMS Developers

Name	Informant Job Title	Interview Type
CMMS A	Regional general manager	Telephone
CMMS B	Sales & marketing	Telephone
CMMS C	IT Consultant	Telephone
CMMS D	Account manager	Telephone
CMMS E	IT Engineer	Telephone
CMMS F	IT Consultant	Face-to-face
CMMS G	IT Manager	Face-to-face
CMMS H	IT Engineer	Face-to-face
CMMS I	Sales & marketing	Face-to-face

Table 4-12: List of interviewed CMMS developers

Semi-structured interviews were the main data collection method used in this survey. In order to support these interviews, and to achieve the stated objectives, a questionnaire guide based on literature was derived. The questions are presented in *APPENDIX B*. A glossary of terms was used to explain the meaning of the specific nomenclature used in the questionnaire. The methodology followed for execution of the interviews, data collection, analysis, and validation was the same as for the previous enquiries (see *Section 4.3.2*).

4.5.3 Results and Analysis

The results and analysis are presented sequentially according to the survey objectives presented in *Section 4.5.1*. The results presented in the grey area of the tables are from face-to-face interviews. Key findings are presented at certain points in this section; these are used in the next chapter as part of a broad analysis and discussion.

Objective 1: Identify whether CMMS are being designed to support maintenance technicians during troubleshooting.

All the respondents reported that their system could be used to support troubleshooting. However, a majority (five out of nine) recognised that direct support to troubleshooting is not a main function of their system, the main reason being that developers typically identify the user’s requirements through meetings with managers who traditionally emphasise aspects such as cost control, spares and materials management, maintenance scheduling and planning, and preventive activities.

Objective 2: Identify types of failure information used to support troubleshooting that is recordable by CMMS.

The interviewees were asked to select failure information types (repair data) from a given list, identified from literature, that can be used to support troubleshooting and considered in their system. They were also asked to indicate other failure information types that were not listed but are recordable by their system. *Table 4-13* shows the results obtained from the nine interviews.

(2) Types of failure information recorded by CMMS		CMMS								
		A	B	C	D	E	F	G	H	I
a	Brief description of the repair action taken (< 5 words)	●	●	○	●	●	○	●	○	○
b	Detailed description of the repair action taken (> 5 words)	●	●	●	●	●	●	●	●	●
c	Identification of who repaired (e.g. owner, manufacture, contractor)	○	●	○	●	●	●	●	○	●
d	Craftspeople trade identification (e.g. mechanic, electrician)	●	●	●	●	●	●	●	●	●
e	Repair location (e.g. on site, repair shop)	●	●	●	●	●	●	●	●	●
f	Spare parts used	●	●	●	●	●	●	●	●	●
g	Special tools used	●	○	○	○	●	○	●	○	○
h	Description of the failure via free text (e.g. location, symptoms)	●	●	●	●	●	●	●	●	●
i	Description of the failure diagnosis via free text	●	-	○	○	●	○	●	○	○
j	Repair recommendations	●	○	○	●	●	○	+	+	+
k	Description of the operating conditions (when the failure occurred)	●	●	●	●	●	○	●	○	●
l	Description of eventual machine tool changes	●	-	○	●	●	○	●	○	●
m	Setting of the standards for the good working conditions	●	-	○	●	●	○	●	○	○
● - Yes; ○ - No; (-) no answer										
+ - possible to be indicated in the observations field										

Table 4-13: Types of failure information recorded by CMMS

In addition to the above, some interviewees indicated that their system also can record the following types of information:

Type of failure information	Nr. of CMMS the record
Repair duration	9
Step-by step repair actions	2
Risk assessment	1
Materials needed	9
Repair actions that were not successful	1

Key Findings

- Most types of failure information that are commonly used to support troubleshooting are recordable by the CMMS considered in the survey.
- The types of failure information that are more recordable by the CMMS surveyed, and that may be used to support troubleshooting, are as follows:

Recordable by all (100%)	Recordable by majority (<100% – 50%)
<ul style="list-style-type: none"> - Detailed description of the repair action taken - Craftspeople trade identification - Spare parts used - Description of the failure via free text - Repair location - Materials needed - Repair duration 	<ul style="list-style-type: none"> - Brief description of the repair action taken - Identification of who repaired - Description of the operating conditions - Description of eventual machine tool changes - Setting of the standards for the good working conditions

- The types of failure information that are less recordable by the CMMS surveyed, but which might be needed to support troubleshooting, are as follows:

Recordable by minority (<50% - 25%)	Rarely used (<25%)
<ul style="list-style-type: none"> - Special tools used - Description of the failure diagnosis - Step-by-step repair actions - Repair recommendations 	<ul style="list-style-type: none"> - Repair actions that were not successful - Risk assessment

Objective 3: Identify failure attributes used by CMMS to classify failures records

The interviewees were asked to identify the failure attributes considered in their CMMS and that can be used to classify failure records. The interviewees were asked to identify failure attributes from a given list (identified from literature), and to indicate other attributes that are not listed but considered in their system. Table 4-14 presents the results.

(4) Failure attributes that can be used to classify failure records		CMMS								
		A	B	C	D	E	F	G	H	I
Location of the failure: identify where the failure is located										
a	Equipment location - geographic location of the equip. in the factory	●	●	●	●	●	●	●	●	●
b	Equipment identification - characterises the type of equipment	●	●	●	●	●	●	●	●	●
c	Failure location at the equipment level	●	●	●	●	●	●	●	●	●
d	Failure location at the component level	●	○	○	●	●	○	○	●	○
Characteristics of failure: failure attributes that identify each failure										
e	Failure symptoms described at the equipment level	●	○	○	○	●	○	○	●	○
f	Failure symptoms described at the component level	●	○	○	○	●	○	○	●	○
g	Nature of the symptoms (e.g. progressive or temporary symptom)	●	-	○	○	●	○	○	○	○
h	Combination of symptoms (describe more than one symptom)	●	○	○	○	●	○	○	○	○
i	Failure cause - brief description	●	●	●	●	●	●	●	●	●
j	Combination of causes - describe more than one cause	●	○	○	○	●	○	○	○	○
k	Failure nature (e.g. mechanical failure, electrical failure, etc)	●	●	●	●	●	●	●	●	●
l	Failure discovered (e.g. during installation, service, inspection, etc.)	●	-	●	○	●	○	○	●	●
m	Failure reason (e.g. unscheduled or scheduled intervention)	●	○	●	○	●	●	○	●	●
● - Yes; ○ - No; (-) no answer										

Table 4-14: Failure attributes used to classify failure records

In addition to the above failure attributes, some interviewees indicated that their system also considers the following attributes to classify failure records:

Failure attributes	Nr. of CMMS that consider it
Work order number	6
Failure effects	4
Identification of equipment manufacturer	7
Failure consequences	2
Failure criticality	5
Method of observation	2
MTBF and MTTR	4

Key Findings

- The failure attributes that are most ‘considered’ by the CMMS surveyed to classify failure records are as follows:

‘Considered’ by all (100%)	‘Considered’ by majority (<100% – 50%)
<ul style="list-style-type: none">- Equipment location- Equipment identification- Failure location at equipment level- Failure cause- Failure nature	<ul style="list-style-type: none">- Failure discovery- Failure reason- Work order number- Failure criticality- Identification of equipment manufacturer

- The failure attributes that are less ‘considered’ by the CMMS surveyed to classify failure records are as follows:

‘Considered’ by minority (<50% - 25%)	Rarely ‘Considered’ (<25%)
<ul style="list-style-type: none">- Failure location at component level- Failure symptoms at the component level- MTBF and MTTR- Failure effects- Failure symptoms – equipment level	<ul style="list-style-type: none">- Failure consequences- Method of observation- Nature of the symptom- Combination of symptoms- Combination of causes

Objective 4: Identify purposes of the failure records classification

Following identification of the failure attributes that can be used in their CMMS to classify failure records the interviewees were asked to indicate the purposes of that classification. Analysis of the survey results enabled the identification of a list of purposes that were classified into more or less common according to the responses of the interviewees.

More common	Less common
<ul style="list-style-type: none">- Management of spare parts and inventory control- Costs management- Management of preventive activities; planning and scheduling- Perform failure and reliability analysis	<ul style="list-style-type: none">- Highlight trends- Identify critical failures- Support troubleshooting- Optimise total productive maintenance

Key Findings

- The main purposes of the failure records classification from the surveyed CMMS are: (i) management of spare parts and inventory control, (ii) cost management, and (iii) preventive activities.
- Supporting troubleshooting is not a main purpose of the failure records classification of the surveyed CMMS.

It was not possible to identify a relationship between the failure attributes used to classify the failure records and the purpose of the classification system. The survey sample is too small to identify such a relationship. Also, the identification of this relationship was not an objective of the survey.

Additional Findings from survey

- Most interviewees claimed that it is difficult to gain access to the users that they want at the right time to be involved in the development of new systems.
 - Some interviewees suggested that questionnaires are more efficient for collecting user requirements. However, it was generally assumed that *brainstorming* sessions would probably be more effective for collecting the correct requirements, since users are often unclear of their requirements. Nevertheless, time was identified as a main problem in collecting user requirements, and *brainstorms* are time consuming.
-

4.6 Case Studies

As described and justified in the previous chapter (*Section 3.4.2*), case study is the most appropriate strategy to address the third research question. This research question aims to identify recommendations/requirements to develop a Support Documentation System that will provide better aid to maintenance personnel during troubleshooting.

Moreover, previous surveys showed that end-user recommendation needed to be collected to make both CMMS and documentation more efficient to support troubleshooting. In addition, according to Gillham (2000a; p2) the naturalistic style of case study research is particularly appropriate to study human phenomena.

The aim is to identify a framework of recommendations to develop a system to classify documentation. This system will be the basis for the development of a SDS to assist maintenance technicians during troubleshooting, which may be integrated into a CMMS. The specific nomenclature (or terms) presented in this section are defined in *Appendix E*.

4.6.1 Case Study Objectives

In order to fulfil the above aim the following objectives were defined as follows:

1. Identify the goals and requirements of the maintenance personnel regarding the use of documentation to support troubleshooting;
2. Identify and classify repair data that can be used to support troubleshooting;
3. Identify and rank attributes to characterise and classify failure records;
4. Identify how equipment identification data is being classified.

The above objectives were also defined considering the methodology to guide the development of a classification system suggested by Ball (1970).

4.6.2 Methodology Applied

While much discussion and justification concerning the case study methodology employed in this research was made previously (*Section A.4.2* of *Appendix A* and *Section 3.6.2*), here it deals with the operational issues relating to the field work, *i.e.* the case study process applied in the research. Each step of this process is introduced in the context of the research.

Step 1: Case study planning. Case study planning involved taking the research questions and objectives, and defining the aim of the case study (stated above). Once the aim was established, the case study objectives and target population were defined. The case study objectives were stated in the previous section and the target population are medium/large size companies within manufacturing systems, which have vast experience of maintenance. The medium/large size companies were chosen because they have a relatively large number of maintenance staff, which enables the exploration of patterns concerning the maintenance function.

Step 2: Sample Selection. Sample selection involves selecting the cases (or companies). In this thesis, cases were selected following a non-probability sampling strategy (*Section 3.5.1*), *i.e.* cases that replicate or extend ‘theory’ by filling conceptual categories are selected. Regarding the number of cases, there are practical difficulties that limit the number of cases that can be studied at one time (*e.g.* Yin, 1994; Eisenhardt, 1989). Moreover, it is difficult to judge the right number of cases. Eisehnardt (1989) argues that despite not existing an ideal number of cases, a number between 4 and 10 usually work well; although, he also stresses the import role of single-case research. According to Yin (1994), if two or more cases are shown to support the same theory, replication may be claimed. Considering the above, and the time constraints of the research, only three cases were conducted (*Table 4-15*).

	Company A	Company B	Company C	Σ
Initial Interview of maintenance manger/supervisor	yes	yes	yes	3
Interviews of maintenance personnel				
Maintenance technicians	no	5	4	9
Maintenance engineers	4*	1	1	6
Failure records analysis - number analysed	115	100	50	275
Work requests	50	50	50	150
Maintenance information systems analysis	yes	yes	yes	

* - it was conducted a group interview with the four engineers of this company

Table 4-15: Case study description

Regarding the selection of companies, due to the difficulties in gaining access and the limitations of resources, random selection from a population was not possible. Therefore, semi-purposive (or semi-opportunistic) sampling was used to select the companies in which to carry out the cases; that is, the companies were chosen as an outcome of their accessibility. Moreover, the choice of the companies was also semi-strategic in that these types of companies were selected for their likelihood of replicating or extending the

emergent arguments. In other words, there is much in common among these companies even though they produce different products. In addition, the three cases were conducted in order to allow triangulation of results and assess the quality of the collected data and assess aggregation.

Step 3: Methods Selection. During the company visits data were collected mainly through three sources: semi-structured interviews, document/records analysis and questionnaires (Section 3.5.3). These multiple methods are used for data triangulation (Patton, 1987), and to enhance the internal validity of the data (Yin, 1994) (Section 3.8).

Step 4: Case Study Design. A single-case design was used to conduct the three cases (see Yin, 1994; p39). The case study design consisted of establishing a protocol of procedures, which in this research essentially comprises:

1. A research overview: brief presentation of the research;
2. Some field procedures: list of procedures to conduct the field work;
3. A questionnaire guide: to guide the interviews;
4. Questionnaire: to complement interviews.

A questionnaire was derived to complement the interviews of maintenance technicians on issues concerning the use of failure information to support troubleshooting. The purposes of this questionnaire are (i) harness information captured from interviews, and (ii) help quantify the interpretation of collected data by other sources. The enquiry instruments employed in the cases studies are presented in *Appendix B*.

Step 5: Case Study Execution. Case study execution mainly involved carrying out the company visits and performing the case protocol. All the empirical work of the cases was conducted at plant level. This work involved several (4 to 6 visits) visits to each company, which were made during the academic year 2003/2004. Each first visit consisted of an interview with a maintenance manager/supervisor to get an overview of the company, to plan following visits and activities, to do initial presentations to the maintenance staff, and to be introduced to the maintenance management systems. Following visits consisted mainly of interviews with maintenance staff, who are directly involved in troubleshooting, and analysis of documentation/records and CMMS. One group interview was conducted at company A, while all others involved individual interviews. During interviews a brief presentation of the research was initially given. A copy of the questionnaire guide was also given to interviewees so they could have a fair idea what the conversation was about before starting, and they could refer back to the questions without asking for them to be repeated. Moreover, extra questions were asked based on the working background of the individual

and to according the follow up of the interview. During interviews, whenever possible a tape recorder was used. The interview process also involved a questionnaire that informants were asked to complete once the interview was concluded. Other researchers, such as Hanson (1980) and Ince (2000) have successfully used the combination of interview and questionnaire. Regarding the records analysis, it was randomly selected, according to availability, a set of 50 to 155 records, and analysed according to the objectives of the cases study.

Step 6 & 7: Data Collection & Analysis & Findings Validation. Regarding data collection, analysis and finding validation same procedures of previous enquiries were followed.

The potential limitation of this research strategy will be assessed and discussed in the following chapter, as it is considered to be more appropriate to review these limitations as part of the wider limitations of this study at the end of the thesis.

4.6.3 Company Backgrounds

The empirical work of this research includes the study of three companies. This section provides a brief description of the companies. In order to preserve the identity of the companies, their real name is omitted.

Company A: Machine Tool & Servicing Company

Company A is a machine tool UK-based company that offers advanced CNC machine tools from some of the worlds leading producers. Some examples of these machines include: CNC lathe, multi-axis turning centre, a high speed horizontal machining centre, and flexible manufacturing cells. The company also manufactures some of their own machines. In addition to selling machines, this company provides maintenance servicing to their customers. They claim themselves to be a machine tool company that is proud of its record on service and back-up. They provide maintenance service all over the UK and overseas. The maintenance service, consisting of a team of six maintenance engineers, is mainly provided at the customer's site. Some maintenance services are also done at the company's site by a technical team. The company has a service support desk led by a service manager who receives the service requests from customers either by phone or by fax. Depending on the complexity of the problem, the service manager might provide either the actions to be taken to solve the problem or assigns a service engineer to do the job at the customer's site.

Company B: Pulp & Paper Company

Company B is a pulp and paper company based in Portugal. The company consists of two paper mills and one pulp mill that work simultaneously in a continuous process. This company is one of the most efficient pulp and paper production units in Europe. It guarantees an annual volume of production and processing of fine uncoated papers of some 750 thousand tonnes, and represents the biggest mill site in Europe for uncoated woodfree paper. The company efficiency is mainly due to a strong investment in advanced technology, in operations management, and in human resources. The company has 850 employees who have a high level of education and specialist training. The maintenance is mainly assured by both their internal maintenance department and an outsourcing company. Their maintenance department consists of approximately 160 employees, of which about 20% are engineers. Since downtime is a main concern for the company, investments in maintenance have been considerably high. Their strategy for optimising maintenance is based on (i) highly trained staff, (ii) the implementation of TPM (total productive maintenance) and RCM (reliability centred maintenance), (iii) the implementation of preventive activities, and (iv) a self-developed CMMS.

Company C: Manufacturer & Assembly Automobile Company

Company C is a manufacturing and assembly automobile company based in Portugal and is part of a multinational French enterprise. This company has about 1280 employees and produces more than 200 vehicles per day on a non-stop process (works on three shifts). The company manufactures the car body and does all the car assembly. The factory is divided into three sectors: car-body manufacturing, painting, and assembly. The maintenance of the three sectors is assured by a single maintenance department, which is divided in two main sections, maintenance engineering, and maintenance operations. The maintenance department consists of about 60 employees, of which 14 are engineers. Despite many preventive activities (e.g. planning, scheduling, and inspections) are implemented, corrective maintenance in this company represents about 40% of all maintenance work.

4.6.4 Results & Analysis: Goals and requirements of maintenance personnel

The aim of this section is the collection of data to fulfil *objective 1* of the case study. The purpose of this objective is to identify the goals and requirements of maintenance personnel regarding the use of documentation to support troubleshooting.

Since major differences were not found between the three companies, the results are presented together. Particular differences are referred to when appropriate.

Lack of time and missing data. Nearly all the interviewees reported that documentation, particularly failure records, is important to making their job more efficient. Most interviewees stated that they rarely refer to documents to support troubleshooting. Generally, it was claimed that they do not have time to look for support information, and it is usually missing when they look for it in the records.

Interview results show that, in general, maintenance technicians do not expect to have to wait too long in order to get the information they need, from either computers or files. They expressed that daily work pressure together with difficulties accessing information turn down the chances of using documentation. Many reported that workload is greater than capacity. A typical comment was; “*if we hardly have time to do our job, where will we get time to look for and read records*”. It was also reported that failure records tend to include all types of failure data to support every maintenance activity (e.g. PM, CM, accounting). Thus, troubleshooting-related information loses visibility due to the large amount of failure information contained in the records. This overload of information and lack of visibility motivates technicians for not using or for ignoring failure records to support troubleshooting.

At the three companies, maintenance technicians are the main people in charge of reporting failure data, particularly troubleshooting data. Most interviewees expressed the view that they do not like to do this clerical work. Lack of motivation and time were the main factors for the above problem. A common thought between technicians is: “*we are trained to fix equipment and keeping the plant running, not to do clerical work*”. It was understood from the interviews that technicians seem prepared to make compromises if their job is assured and if they can achieve benefits from reported data. It was generally understood that technicians are not motivated to report failure data because they do not see how they benefit from it. Some interviewees showed that they fear sharing their knowledge through a reporting system because they are afraid of being sacked once it is transferred to others. It was observed that some of the interviewees keep in their file cabinets their own archives of

failure records. Moreover, some interviewees reported that they would be motivated to reporting failure data if they were given sort of compensation or reward, *e.g.* money, career development. Some interviewees claimed that when they report a solution for a problem, their name/photo should be referenced. It was also reported that, generally, the forms used to collect failure data are too extensive and complex, which do not encourage collection. In addition, it was reported that failure records tend to be kept only for the most frequent and complex equipment failures, and/or failure that can cause high downtime.

Key findings:

- Maintenance documentation systems need to provide a speedy and productive means of retrieving information to support troubleshooting;
 - Some sort of reward is needed to motivate maintenance technicians to report and share their experiences;
 - Forms used to collect failure data need to be easy and quick to complete;
 - Failures that are frequent, complex or cause high downtime are those for which failure records tend to be kept.
-

Failure experiences vs. troubleshooting. Many of the interviewees assumed they occasionally missed steps during troubleshooting. They also reported that many failures they face had been efficiently solved before, and that if they could access these past-experiences, the chances of missing troubleshooting steps would be lower. However, it was expressed that they do not have an efficient way to identify and retrieve the knowledge of past-experiences where it is next needed. At two of the surveyed companies, troubleshooting manuals provided by equipment vendors are being used to support troubleshooting. Interviewees from these companies classified the troubleshooting manuals as a very good tool to guide them during troubleshooting. However, it was claimed that these manuals are normally only available for a few pieces of equipment, and only address failures foreseen by its designers. On the other hand, interviewees reported that most failures that occur in practice are not included in these manuals. In order to address this issue, a few interviewees created their own troubleshooting guide, which is mainly a collection of experiences of failure troubleshooting that each maintainer records in order to recall later. Others edited the troubleshooting manuals supplied by developers and introduced changes/updates. However, it was observed that both edited manuals and/or private records are in the possession of individuals and not shared with the other

technicians. It was understood that many technicians are afraid of sharing their knowledge. Only a few technicians expressed that are willing to share their experiences. However, in this last case, technicians claimed they needed a system that allows them to exchange experiences. Moreover, at one of the companies, the maintenance manager created a paper-based simplified form (single-page) to report daily failure experiences, where only troubleshooting-related information is reported.

Interview results also suggest that maintenance technicians who are less experienced and/or work pressure is high, tend to treat the symptoms of the problem rather than addressing its root cause, and tend to rely on hunches and intuition to solve problems. Moreover, there were situations where technicians felt threatened by situations where they do not have the skills or experience to solve problems. Most interviewees reported that more training is needed to make troubleshooting more efficient. It was also reported that the development of a systematic approach for failure troubleshooting would be a solution. However, it was expressed that such approach will succeed only if it is established as a norm or a formal procedure. In addition, it should include textual instructions, pictures/illustrations, diagrams, and eventually videos, which should be linked.

Interview results also show that, generally, technicians have the tendency to push failure troubleshooting in the direction of his/her pre-conceived conclusions, which tends to generate conflicting situations when different technicians have different opinions. This seems more evident between senior technicians with more experience. However, both seniors and novices, when given written instructions, such as documents or manuals tend to follow them.

From interviews, it was also perceived that failure experiences, accumulated with practical doing, are remembered by maintenance technicians mainly through (i) sensuously conceivable attributes of the experience, (ii) some empirical coded work rules, and (iii) visual images. Moreover, work experiences are passed on as hints and perceptions, *e.g.* “*if you see this ..., if you hear that ..., than do this and do that*”. It was also claimed that failure experiences in troubleshooting and elimination of faults is rarely documented.

Key findings:

- Maintenance technicians felt that accessing failure experiences to guide troubleshooting would make the repair process more efficient. However, these experiences are rarely documented;
 - The structure used in the troubleshooting manuals is a good reference to guide the way failure experiences need to be reported;
 - Although some interviewees expressed the need for an approach that motivates the collection and communication of failure experiences, most of them show concerns sharing their failure experiences;
 - A systematic approach for failure troubleshooting needs to be developed and established as a formal procedure;
 - The SDS should include textual instructions, pictures/illustration, diagrams, and eventually videos, which should be linked;
 - Written instructions appear to be easily followed by maintenance technicians than instructions given by maintenance staff;
 - The use of sensuously conceivable attributes of the failure experiences and some empirical coded work rules appears a good approach to classify troubleshooting-related documents.
-

Managing failure information. At the three surveyed companies, most maintenance documents are paper-based. The majority of the interviewees preferred to use paper-based systems rather than computer-based systems to collect/report failure data. However, computer-based systems are preferred for managing and retrieving documents/information. Many interviewees reported that they are used to operating computers, most often in their homes.

It was reported that documents filed into cabinets have limited distribution; as such, they are rarely where needed. Many documents get lost or are misfiled once they are taken out from the cabinets. Moreover, most interviewees reported that they rarely have the most up-to-date documents. In addition, it was reported that with paper-based documents instant access is nearly impossible. Instant access is also limited because information is often spread through different documents, and information in the source document is not searchable. It was reported that different kinds of data, at different sources, bearing on the same issue, sometimes yield contradictory results. It was also reported that when digital

documents are used, they are just piled into folders, which is not any better than having paper.

Regarding data acquisition, most interviewees suggested the use of a single-page reporting form, which needs to be easy-to-use. It was also suggested that most data fields should be pre-defined/classified in order to use tick-boxes and speed reporting. *Table 4-16* presents some examples given by the interviewees to pre-define data. Moreover, it was suggested that descriptive fields should be reduced to the fields where repair actions and additional comments are described. It was also reported that the equipment identification (tag number) and the failure description (free-form field) are the data types that are most often used to characterise/describe each failure, and to later identify the failure reports. It was suggested that failure description should be structured or even coded to standardise reporting. This procedure would limited “personalise” descriptions, which might suggest multiple interpretations.

Data class	Description	Examples
Equipment identification	Complete identification and characterisation of the equipment that failed.	Equipment location; Manufacturer/Maker; Equipment classification; Serial nr.
Maintenance reason	Identification of the maintenance cause/s	Equipment failure; Scheduled maintenance Replacement; Inspection
Type of maintenance	Type of maintenance activity	Planned / Unplanned; Preventive maintenance; Corrective maintenance
Action code	Actions taken to rectify breakdown or otherwise	Adjust; Align; Clean; Repair; Lubricate; Reset
Operating status	Operating condition of equipment/operation during the intervention	Equipment running; Equipment not running Production stoppage; Production running
Failure causes	Reason for failure or cause of breakdown	Hydraulic; Pneumatic; Lubrication; leakage; wear; Mechanic; Electrical
Failure effect	Description of what the failure cause to operation	Downtime, Repair time
Part code	Code of parts used for repairing	-

Table 4-16: Examples of classification of repair data

Some of the interviewees also reported that it is important to implement a verification procedure to validate data that is reported. It was reported that different technicians often take different approaches to the same problem, and so it is necessary that some sort of supervision is made in order to identify best approaches.

Regarding the retrieval of failure records, it was claimed the paper-based nature of most documents limits instant access. It was suggested the development of a single document database, which they could browse using equipment and failure attributes. Some interviewees suggested the use of a pre-defined list of attributes that they could choose to browse the database; others, referred to the use of *Keywords* to search the database. It was also expressed that it is important that the database have the capacity to relate failure reports of different equipments, because despite being different they may have similar repair modes. It is important to stress here that at the surveyed companies failure codes are being used. However, it was identified that these codes mainly illustrate the reason(s) why assets fail, and are traditionally being used to get statistics about equipment failures and/or breakdowns. As such, they are not most useful for maintenance technicians to identify and retrieve failure records for troubleshooting support.

Key findings:

- Maintenance technicians prefer to use a paper-based system rather than computerised to report failure data;
 - Maintenance technicians suggest the use of a single-page reporting form to collect data, which needs to be easy-to-use and quick to fill;
 - To speed reporting maintenance technicians suggest the use of pre-defined fields to allow tick-boxes to be used;
 - Maintenance technicians felt that documentation would be more efficiently managed through a computerised system;
 - The failure description field of reporting forms should be structured to standardise reporting and facilitate the identification of failure records;
 - A verification procedure needs to be implemented to validate reported data;
 - Documentation should be pulled together into a searchable single database;
 - A browse system based on pre-defined list of attributes or keywords needs to be implemented to facilitate the retrieval of failure information.
-

Systematic approach for failure troubleshooting. According to what was expressed by most interviewees, a systematic approach for failure troubleshooting should include five main steps. These are as follows:

1. *Identification of the failure:* Complete and accurate identification of the equipment that failed, and physical location of the fault on the equipment. Identify equipment parts that failed;
2. *Identification of symptoms:* List of symptoms that are commonly detected by vision, sound, touch or smell; signals or indications that show that there is a deviation from the expected level of performance. Look for simultaneous symptoms and be as detailed as possible;
3. *Failure diagnosis:* Investigate and relate the failures with symptoms in order to identify possible causes;
4. *Repair action:* Take actions to solve the failure. Whenever possible, address the elimination of failure causes and implement preventive actions to prevent failure recurring;
5. *Testing & validation:* Test the equipment after repair actions in order to validate the repair.

Classification of failure information. Results also identified that maintenance information is mainly classified into three main categories:

- (i) *Equipment data:* plant numbering system, equipment name, manufacturer, location, serial number, model, etc.
- (ii) *Failure data:* failure identification data, failure date, failure time, etc.
- (iii) *Maintenance data:* repair actions, maintenance date, maintenance category, maintenance resources, maintenance time, etc.

These categories will be discussed in the following sections.

4.6.5 Results & Analysis: Repair data to support troubleshooting

This section presents the results and analysis of data collected from three case studies, which aim to fulfil *objective 3* of case studies. The purpose of this objective is to identify and classify repair data that can be used to support troubleshooting. The data presented here were mainly collected through a questionnaire that was given to maintenance technicians, and through analysis of the companies' records. Maintenance technicians here are those that are directly engaged in failure troubleshooting.

Questionnaire Results

The interviewees were asked at the end of interviews to answer a questionnaire about the management of failure information. They were first asked to rate types of repair data from troubleshooting experiences that can be used to support troubleshooting (*i.e.* failure diagnosis and repair). A sample of the questionnaire that was used is provided in *Section B.7.2* (in *Appendix B*). In order to facilitate data analysis, repair data was grouped into three categories: (i) repair actions data, (ii) data regarding resources, and (iii) general repair data. According to these categories, *Figure 4-12* presents the average of results from all three companies. The raw data are presented in *Section C.4.2* (in *Appendix C*).

The analysis of the average results by company showed that there are not major differences in the results between the three companies (*see Section C.4.1*). As such, the data from the three companies were integrated for analysis.

According to the interviewees, the description of the actions that were taken to repair failures, and the repair recommendations are the most important repair actions data to support troubleshooting. Results also indicate that the interviewees prefer brief descriptions rather than detailed descriptions of the repair actions. Moreover, a significant majority classified the description of repair actions in a *step-by-step* way as very important to assist troubleshooting. However, results indicate that the repair actions that were not successful and the repair duration are not important repair data to support troubleshooting.

The interviewees rated as the most important repair resources to support troubleshooting (i) the work trade identification (*e.g.* mechanic, electrician), (ii) the number of staff that participated in the repair, and (iii) the spare parts and special tools needed for the repair. Regarding the identification of who performed the job (*e.g.* contractor, manufacturer, internal-job) and the repair location (*e.g.* on site, repair shop), results suggest that they are not viewed by maintenance technicians as relevant to support troubleshooting.

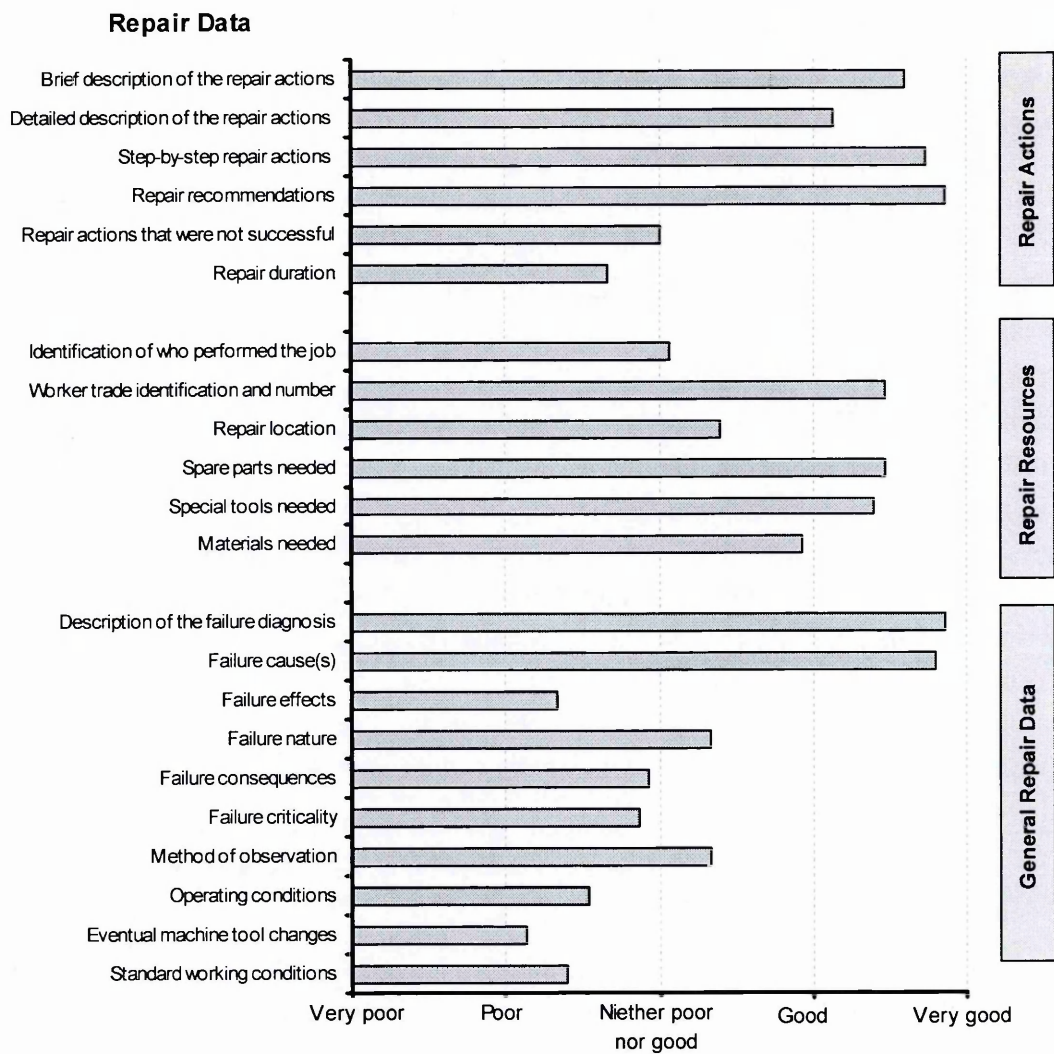


Figure 4-12: Repair data: average results of all the three companies (questionnaire)

The majority of the interviewees rated both the description of the failure diagnosis and failure causes as very good to support troubleshooting. From all other general repair data that was asked to rate, only the failure nature (e.g. mechanical failure, electrical failure) and the method of observation (method used to detect the failure) had a positive rating.

Results of records analysis

A sample of failure records from the three companies were also analysed in order to establish a triangulation of results with previous enquiries. Failure records here are any form of report where experiences of failure troubleshooting are recorded (not exclusive), *e.g.* service reports, work orders, failure reports. This study consisted of analysing the failure records to identify what types of repair data are being recorded by maintenance technicians. Data was mainly collected from the fields that describe the repair actions and from specific fields of each of the forms. For each company, the percentage of occurrence of each type of repair data was calculated. *Figure 4-13* presents the results obtained for each company and the average results of all three companies. The raw data is presented in *Section C.4.2*.

The collection forms used by the three companies to collect failure data have a free-text field to describe the repair actions (see *Section C.4.2*). The records analysis shows that, overall, nearly all analysed records (98%) include a description of the repair actions. It also demonstrates that these descriptions tend to be detailed. Indicating the repair actions in a brief or *step-by-step* way is rarely done (see *Figure 4-13*).

Still regarding the repair actions data, results show that the repair duration (in terms of time), the action type (or type of maintenance), and the cause of maintenance (*e.g.* equipment failure, replacement) are commonly recorded at the three companies. On the other hand, the indication of the repair actions that were not successful, and the repair recommendations are rarely recorded at the three companies; particularly the former, only 2% of all analysed records include repair actions that were not successful.

The most frequent repair resources indicated in all records are (i) the worker trade identification, and (ii) the spare parts needed. From all other repair resources, only the materials needed for the repair have a significant representativeness, 40% of all records include this type of data. Results also show that both the indication of the number of workers and special tools needed for the repair are rarely recorded. Moreover, no records were found with the indication of who performed the job (*e.g.* manufacturer, contractor) at the three companies. Regarding the repair location, it is only representative at *Company A* (62%) and *Company B* (37%). It should be stressed here that the collection forms of these two companies have a dedicated field for this type of data. At *Company A* repairs can be taken in-house or at customer's site, and at *Company B* repairs may be performed at one of their three workshops or on-site.

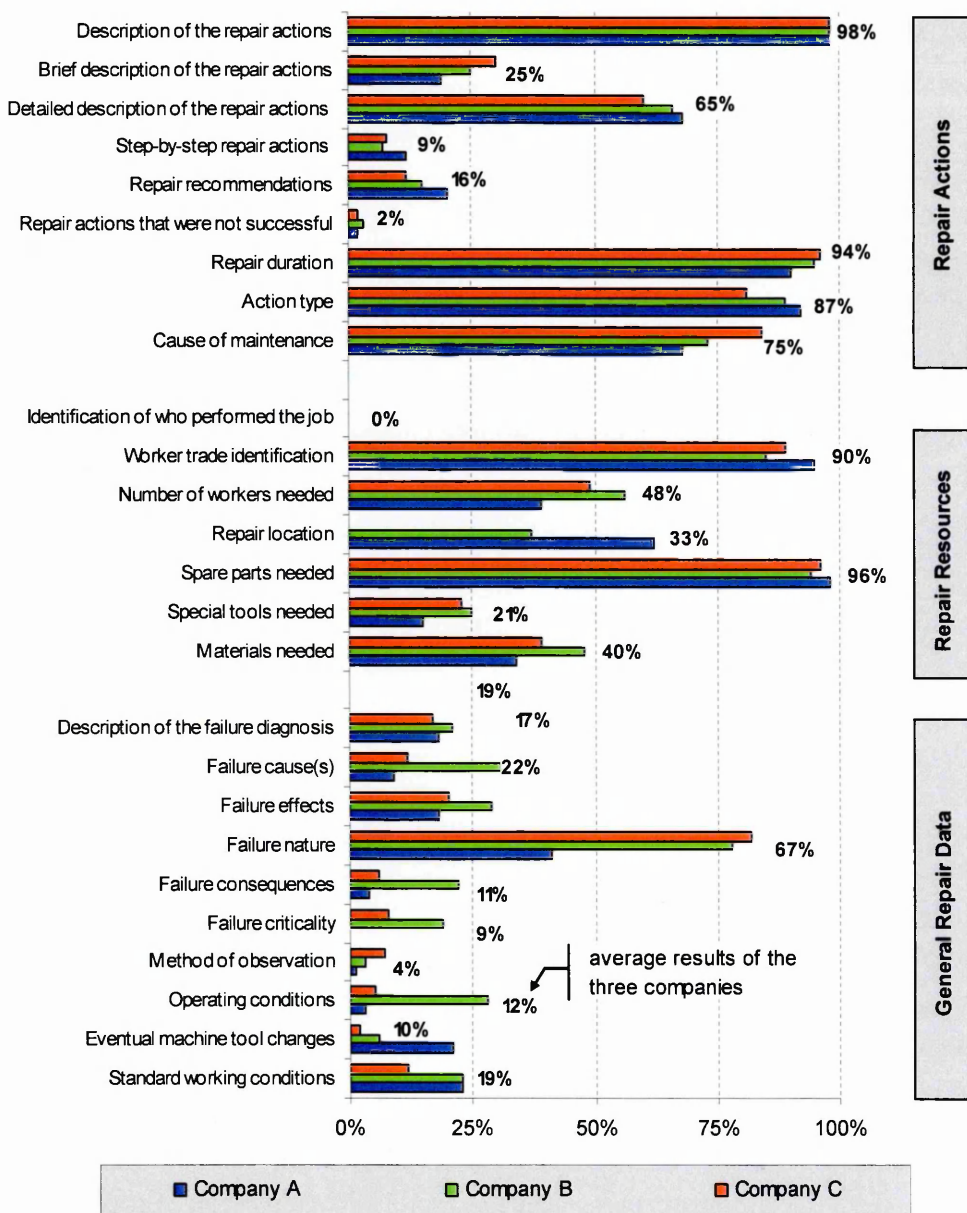


Figure 4-13: Repair data: average results by company (records analysis)

Regarding the category of *general repair data*, the failure nature is the most frequent type of data included in the records of the three companies; 67% of all analysed records have indication of this type of data. All the rest repair data considered in the analysis are in general rarely recorded. It is important to stress here that only *Company B* collects data for reliability and failure analysis, which justifies the higher percentages of records on failure causes, effects, consequences and criticality. Moreover, this collection is only done for specific equipment of the company.

4.6.6 Results & Analysis: Attributes to characterise and classify failure records

The results presented in this section aim to achieve *Objective 3* of the case studies. The aim is to identify and rank failure attributes, which are to be used to characterise and classify failure records. The classification has the purpose of facilitating maintainers' access to failure records and related documentation, which are to be used to support troubleshooting. As in the previous section, the data presented here were collected through a questionnaire that was given to maintenance technicians and by analysis of company records. In order to facilitate analysis, attributes were classified into three groups, (i) equipment identification and failure location attributes, (ii) failure description attributes, and (iii) general attributes. The definition of these classes and particular attributes are presented in *Section B.7.1*.

Questionnaire results

Figure 4-14 presents the average results of the three companies. The raw data and results by companies are presented in *Section C.4 (Appendix C)*.

The average results of the three companies show that respondents classify both equipment identification and failure location as very good attributes to classify failure records. Although with a small difference, results also show that respondents find equipment identification (tag number that characterises the equipment) a more important attribute than the equipment location (geographic location of the equipment). Regarding the failure location, results indicate clearly that respondents prefer the indication of the failure location at a lower equipment level to which failures can be isolated, *i.e.* the failure source, than the failure location at equipment level.

The attributes regarding failure description (*i.e.* description of what the failure exhibit and caused) were highly rated by respondents. Results show that respondents rated more highly the indication of the failure symptoms at the equipment level than at a lower equipment level. Moreover, results suggest that the symptoms should have the indication of their nature, *i.e.* indication of an adjective, adverb, or noun that helps understanding the symptoms, *e.g.* progressive noise, temporary vibration, and high temperature. The rating of the combination of symptoms also suggests that respondents find relevant the indication of more than one symptom, when known. The failure effect attribute is among the most rated attributes classified by the respondents. This suggests that the indication of the consequences of the failure in terms of the operation is an important attribute to classify the failure records. Examples of failure effects are: '*Motor X stopped*', '*Machine A has less*

output'. Regarding the category of general attributes, they are generally poorly rated. Only the failure nature (e.g. mechanical failure, electrical failure) and the failure reason (or causes of maintenance) have a significant rating.

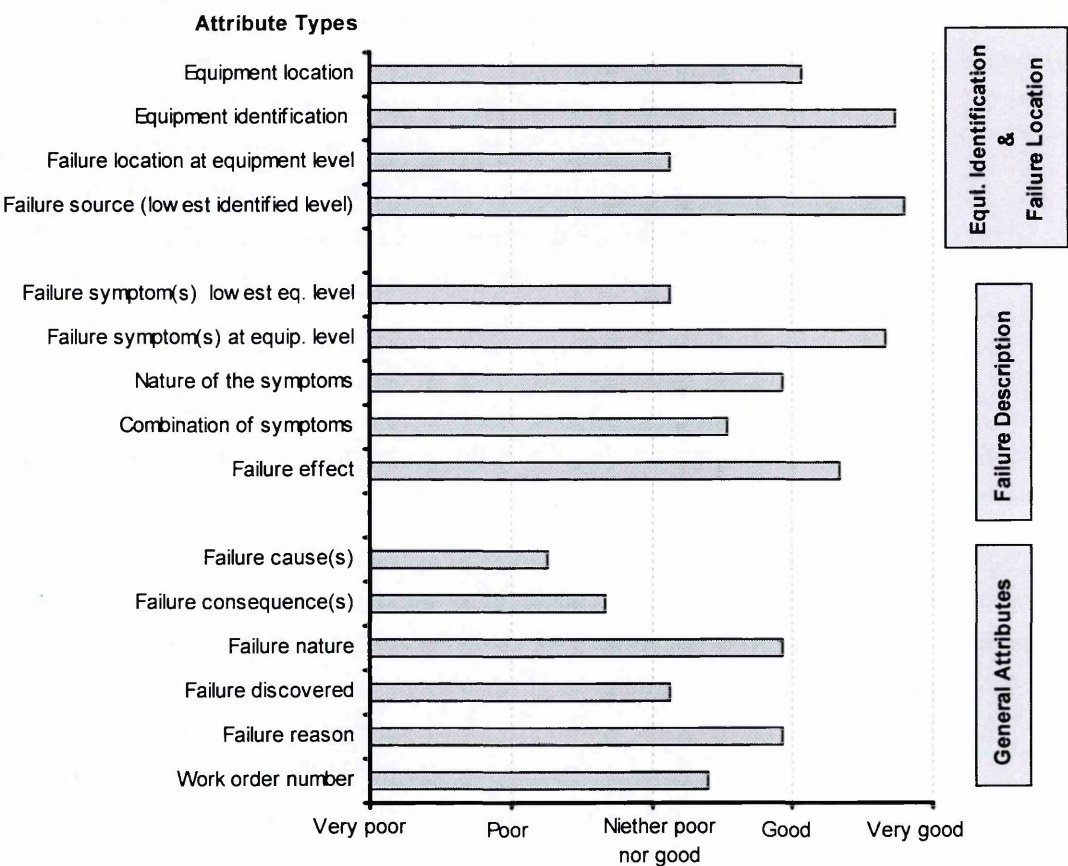


Figure 4-14: Failure attributes: average results of all the three companies (questionnaire)

To summarise, the questionnaire results indicate that the most important attributes to characterise and classify failure records are (i) the equipment identification, (ii) the failure source, (iii) the failure symptoms at equipment level with the indication of their nature, and (iv) the failure effect.

Results of records analysis

Failure records and CMMS were also analysed at the three companies. The CMMS were analysed to identify attributes that are being used by current systems to characterise and classify failure records. The failure records were analysed to identify types of attributes that are being recorded, and that potentially can be used to classify failure records. In this latter analysis, the fields used to identify the failure records and the fields used to describe the failures were analysed. All raw data are presented in *Appendix C*.

The CMMS analysis showed that the attributes most used to classify failure records are the (i) equipment location, (ii) the equipment identification, and (iii) the work order. At *Company A* customer *ID* is also used to classify the failure records. It was also found that none of the three companies use their classification system to identify records to support troubleshooting. The classification systems are mainly being used for cost control, administrative purposes, and to assist preventive activities.

Figure 4-15 presents the results of the failure records analysis according to the categories previously defined. Results show that nearly all analysed records include (i) equipment location, (ii) equipment identification, and (iii) failure location at equipment level. It is important to stress here that the three companies use specific fields to collect data regarding the equipment location and identification. Regarding failure location, records rarely include the indication of the failure source, *i.e.* the location of the failure at the lower equipment level to which failure can be isolated. Moreover, the analysed records do not have a dedicated field for the failure location. The indication of the failure location is reported in the form-free field where failures are described.

Regarding the attributes under the class of failure description, only *Company B* has a specific field to collect the failure symptoms at equipment level. All other attributes within this class are being recorded at the failure description field.

Results show that the most frequent failure description attributes being recorded are (i) the failure symptoms at equipment level and the failure effect. Overall, 73% of records have the indication of the failure symptoms, of which 62% are indicated at the equipment level, and 11% at the lowest identifiable equipment level. The indication of the failure effect was found in 74% of the analysed records. Regarding the way failure symptoms are being recorded, results show that there is a trend to use the symptom nature to help describe symptoms. On the other hand, indicating the combination of symptoms is less common (see *Figure 4-16*).

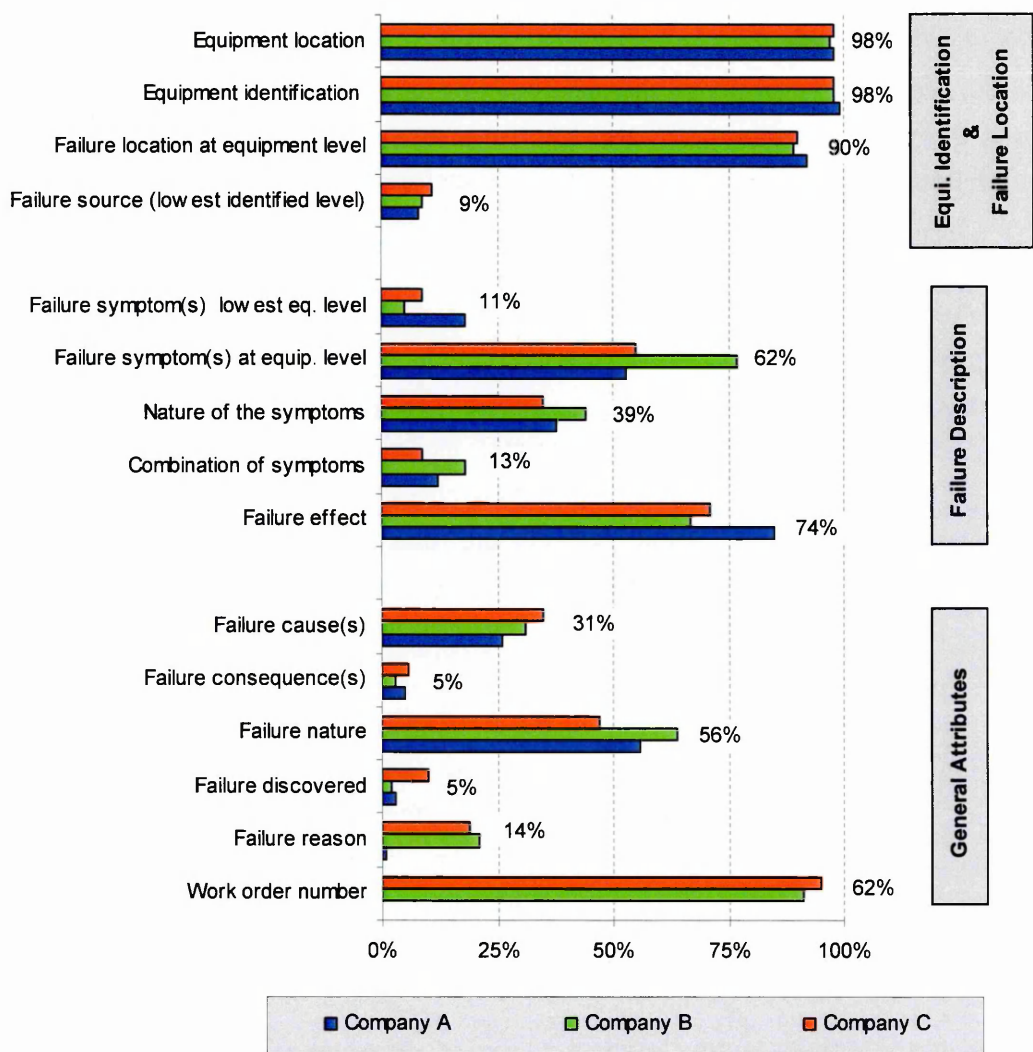


Figure 4-15: Failure attributes: average results of all the three companies (records analysis)

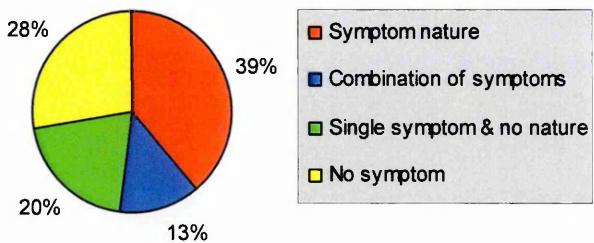


Figure 4-16: Failure symptoms reported in failure records (average values)

Regarding the general attributes, the failure nature and the work order are the attributes that are recorded more frequently. From all other attributes only failure causes have some representativeness (31%).

4.6.7 Results & Analysis: Equipment identification data

The purpose of this section is to fulfil *Objective 4* of case studies, *i.e.* identify how equipment identification data is being classified. In order to achieve this objective records and CMMS at the three companies were analysed.

This analysis was performed because it is expected that similar equipment might have similar failure modes, therefore similar failure repair actions. Consequently, it is important that equipment taxonomy allows the maintainers to compare failure records of particular equipment type with others installed in other areas, sites, or even companies. It is assumed that it is also important to compare failure records from same class unit (*e.g.* compressor) but of different type, *i.e.* physically different but provide a similar function (*e.g.* piston and radial). As such, it is important to identify how equipment identification data is being classified to access if it is possible to define the above relationships.

According to BS ISO 14224 (1999) the data that allow equipment identification can be divided into the following subcategories: (i) equipment location, (ii) equipment classification, (iii) equipment unit hierarchy, (iv) equipment unit data, and (v) manufacturer's data. Although this standard has been developed for oils and gas industries, it has been applied in other areas. Some successful CMMS, such as MAXIMO and IMMPOWER, follow this standard to structure the equipment hierarchy and enable the effective collection of maintenance data. *Figure 4-17* presents the organisational structure of equipment from the three companies.

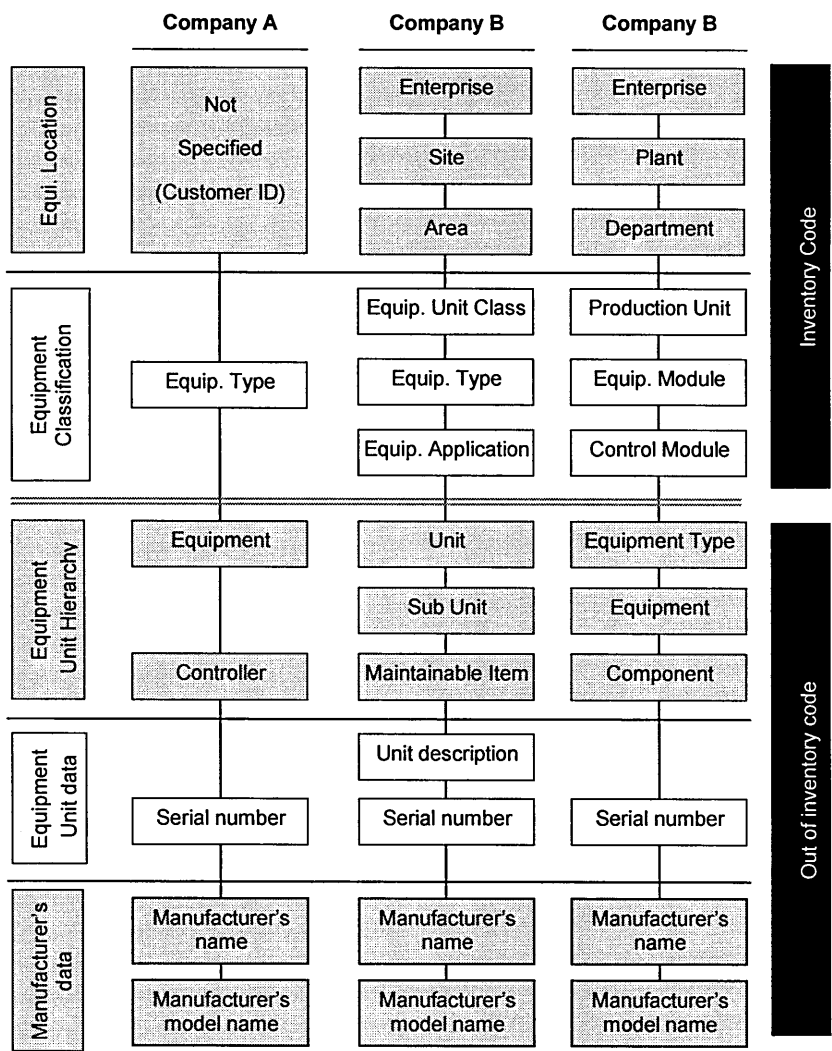


Figure 4-17: Organisational structure of equipment data

4.7 Summary of the Chapter

The chapter describes and presents the results of five enquiries carried out to answer the research questions and to fulfil the research objectives. It presents the results of a questionnaire survey of maintenance practitioners and an interview survey of equipment vendors. The data collected from these enquiries contributed to the achievement of *Objective 1*, i.e. for the characterisation of the current situation regarding failure records utilisation within maintenance. In order to identify the reasons why current information systems do not effectively support troubleshooting, the chapter presents the results of an interview survey of maintenance managers and of CMMS developers. The results of the above enquiries helped to conclude that management of documentation needs to improved to support maintenance technicians during troubleshooting, and that further research in this issue needs to be conducted. Thus, the chapter also presents results of three case studies that contribute to the identification of key features for the development of a Support Documentation System that will best assist maintenance technicians during troubleshooting.

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Chapter V

5 DISCUSSION AND CONCLUSIONS

This chapter presents:

- *The discussion of the research objectives*
- *The conclusions about the research findings*
- *The contribution to knowledge*

5.1 Introduction

5.1.1 Chapter Objectives and Overview

The objective of this chapter is to discuss and conclude the findings of the research presented in this thesis. The chapter discusses the enquiry findings of each research objective, and relates findings to previous research and theory. It then presents the conclusions drawn form the research findings, and the limitations of the research. The chapter concludes by presenting the contribution to knowledge and the main elements for future research (Figure 5-1).

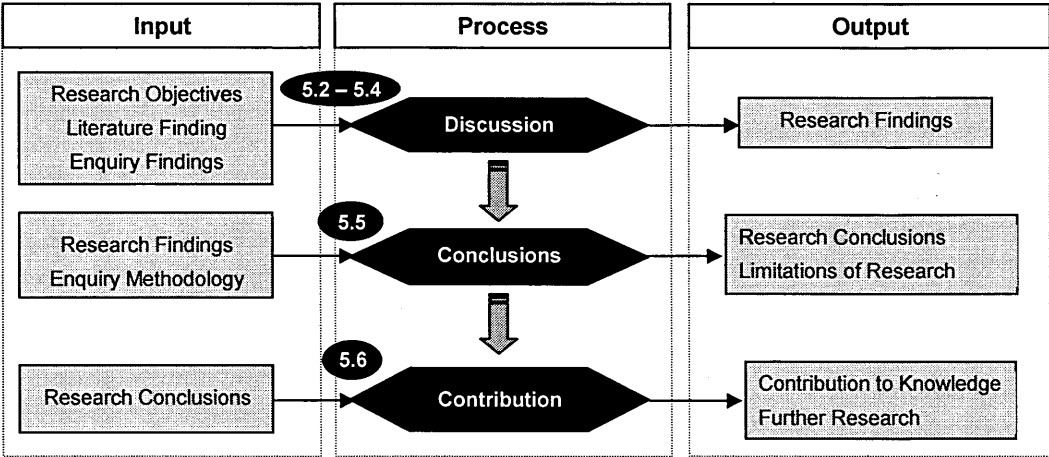


Figure 5-1: Chapter overview

5.1.2 Research Problem and Objectives

Supported by literature, the research proposes the development of a Support Documentation System (SDS) that will improve troubleshooting. It suggests that if maintenance practitioners could easily access support documentation, particularly failure records, both failure diagnosis and repair would be performed more effectively.

During troubleshooting technicians may refer to support documentation to assist their job. Using the proposed system, once a failure and its symptom are identified, technicians can search for support documentation using the attributes that resulted from that identification (Figure 5-2). The retrieved documentation can then be used to support the failure diagnosis and repair, and eventually any tests for the validation of the repair.

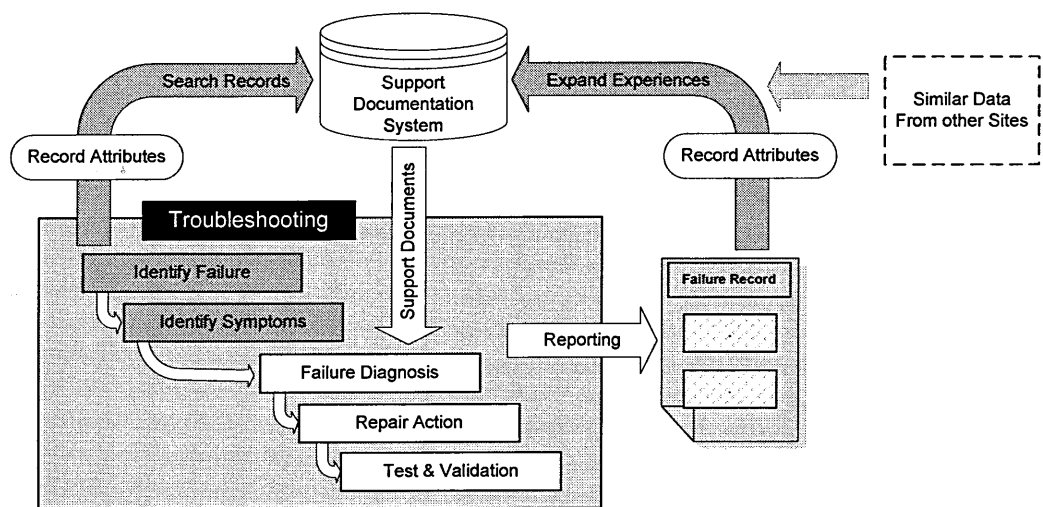


Figure 5-2: Approach to improve troubleshooting

This research explores the conceptual design of a Support Documentation System (SDS) that will best assist maintenance personnel during failure troubleshooting. The aim is to identify key features for its development. This aim led to the definition of the following three objectives:

- Objective 1:** Assess the feasibility of a SDS based on failure records to assist maintenance personnel during troubleshooting.
- Objective 2:** Identify reasons why current maintenance information systems (CMMS and documentation systems) do not effectively support troubleshooting.
- Objective 3:** Identify key features for the design of a proposed SDS that will best assist maintenance technicians during troubleshooting.

Literature indicates that these objectives were not addressed by previous research, and so their fulfilment will represent a contribution to knowledge.

5.2 Discussion of the Research Objectives

This section discusses each of the three research objectives. It presents the main enquiry findings, compares them with literature, and presents the researcher opinion, *i.e. what was found in the 'real world', what does literature say, and what is my opinion?* The main goal is the generation of new knowledge within the research issues.

5.2.1 SDS Feasibility

In order to judge the feasibility of the proposed SDS, a number of indicators collected through the survey of maintenance practitioners and equipment vendors are discussed. *Table 5-1* presents the main findings for each indicator.

- SDS development depends on the availability of failure records. This research has shown that equipment failure records play a critical role in the efficiency of maintenance, and their collection is common practice for maintenance practitioners and equipment vendors alike; most companies tend to collect data on all failures without clearly defined criteria. Although it is recognised that failure records are important to guide the execution of corrective jobs, the primary reason for their collection is not the support of troubleshooting. Records are generally collected to control maintenance activities and support PM. As such, although failure records are available, they are not being used to support troubleshooting.
- To effectively develop a SDS, documents need to be computerised. This research shows that, although a significant number of users still use paper-based systems, the use of computer-based systems to manage failure records is becoming more popular. However, since technicians rarely refer to the IS to support their activity, it appears that current systems are not orientated to support troubleshooting. Moreover, the research shows that despite the trend to use classification and coding systems to help managing failure records, users are not happy about their results. Overall, this part of the research identified a trend to use computer-based systems, and that the management of failure records needs to be improved if they are to be successfully used by technicians during troubleshooting.

Indicators		Main Findings
Importance & Availability	Res.	<ul style="list-style-type: none"> • Failure records are very important to assist maintenance (for both equipment users and vendors) • Nearly all surveyed maintenance practitioners and a majority of equipment vendors collect failure records
	Literat.	<ul style="list-style-type: none"> • Failure records play a critical role in the efficiency of maintenance (e.g. Dhillon, 2003) • Failure records are important to guide the execution of corrective jobs (e.g. Kelly, 1997a; Labib, 1998a)
Use Utilisation	Research	<ul style="list-style-type: none"> • Maintenance practitioners: supporting PM, control, and administrative activities are the primary reasons of using failure records • Equipment vendors: failure records mainly used to improve equipment reliability, and servicing • Maintenance technicians rarely refer to documented failure records
	Literature	<ul style="list-style-type: none"> • PM has attracted greater attention than CM in both industry and research (e.g. Finch and Gilbert, 1986) • Current CMMS are generally more orientated to support PM and administrative activities than to CM (e.g. Cato and Mobley, 1999) • Technicians rarely used CMMS (e.g. Swanson, 1997a; O'Hanlon, 2003)
Management	Research	<ul style="list-style-type: none"> • Although computer-based systems purchased from a vendor is the most popular approach to management of failure records, the combined use of paper and computer-based systems is still significant • Classification systems tend to be used to help managing failure records • Regarding the CMMS capabilities to store and retrieve failure records the level of satisfaction is not high
	Lit.	<ul style="list-style-type: none"> • Increasing tendency to use computer-based systems to manage failure records (e.g. Cato and Mobley, 1999) • Paper-base systems are becoming less used (e.g. Wireman, 1994; Kelly, 1997a)
Collection	Research	<ul style="list-style-type: none"> • Most companies tend to collect data on all failures without clearly defined criteria • The use of management systems that fail to effectively support failure records collection is a main reason for its non-collection (among maintenance practitioners)
Relationship User vs. Vendor	Research	<ul style="list-style-type: none"> • A majority of equipment users and vendors do exchange failure information between each other • Although equipment vendors classified their relationship with users as very good, users had a neutral position regarding this relationship • There is a trend among vendors to provide maintenance support information to customers in the form of equipment or troubleshooting manuals. However, there is no tendency among vendors to consider customers' experiences during the development of troubleshooting manuals
Global Database of Failure Records	Research	<ul style="list-style-type: none"> • A clear majority of maintenance practitioners are willing to contribute their failure records to a global database populated by different users and managed by the equipment vendor. However, vendors have serious concerns about sharing their data with customers; they prefer a standalone database • Both users and vendors classified the global database as potentially useful • Vendors feel that such a database would increase customer feedback, which would allow them to improve the reliability of their equipment and the quality of their troubleshooting manuals. Troubleshooting manuals would also be more dynamic and close to user's needs if vendors receive more feedback from users

Table 5-1: Feasibility indicators - main findings

- An aim of SDS is to promote the communication of failure records, and so accessibility is important if a global database of failure records populated by users and managed by equipment vendors is possible. The research findings support this by highlighting that the relationship between equipment users and vendors' regarding the exchange of

failure information is relatively good. Both equipment users and vendors recognise the usefulness of a global database for their organisation. However, despite the perceived benefit of using a global database, some equipment vendors highlighted their concerns about sharing their failure experiences with users. For example, some vendors preferred the development of a standalone database. Nonetheless, the research findings suggest that if a strategy to improve the feedback of failure experiences to equipment vendors could be found, vendors would be able to produce better quality troubleshooting manuals to distribute to their equipment users. The proposed SDS is potentially a good basis for the development of such a strategy.

- As this research shows, there is no relationship between industry type, size, process typology, and the collection, use, and management of failure records, meaning that SDS could be applied to a diverse number of companies.

5.2.2 Reasons for Information Systems Failure

This section discusses why current information systems (CMMS and documentation systems) do not effectively support troubleshooting. The main findings discussed here summarise interviews taken with maintenance managers, CMMS developers, and literature findings. *Tables 5-2 to 5-4* present the main research and literature findings.

- **Utilisation & Satisfaction.** Although used by supervisors and engineers, maintenance technicians rarely use CMMS to support troubleshooting. A main factor constraining the technician's utilisation is that direct troubleshooting support is not a main feature of CMMS. Moreover, the complexity of these systems makes failure information difficult to access. These difficulties, combined with workload pressure, lead to low utilisation by technicians. The lack of aggregation of documentation is another problem that affects utilisation during troubleshooting. It is claimed that documents are rarely available where most needed, usually dispersed through different locations and frequently out-dated. Cross-referencing between documents and information is also difficult to establish. Due to this misuse, maintenance personnel are generally unhappy with CMMS regarding troubleshooting support. The use of electronic documents managed through a relational database could solve most of the above problems; this could be integrated in the CMMS or used as a standalone database. The lack of an effective classification system for the documents is one of the constraints to development of such a system.

Issue		Main Findings
Use of CMMS – Troubleshooting	Research	<ol style="list-style-type: none"> 1. Maintenance managers claim to be unhappy with their CMMS for troubleshooting support 2. Provide direct support to troubleshooting is not a main function of CMMS (from CMMS survey). 3. Although maintenance supervisors and engineers often refer to CMMS to support troubleshooting technicians rarely refer to these systems 4. Although troubleshooting information is included in most systems, it is generally not linked or related; as so accessing troubleshooting information is time consuming 5. CMMS need to be more self-orientated to support troubleshooting, and easier to use by technicians. 6. End-user requirements should be considered during CMMS design
	Literature	<ul style="list-style-type: none"> • CMMS are primarily designed for planning and scheduling (e.g. Wireman)
Documents Aggregation	Research	<ol style="list-style-type: none"> 1. Documents tend to be in various locations, generally distant from the position where the troubleshooting activity takes place. Troubleshooting data disperse through different documents, and frequently out-dated 2. Paper-based nature of most documents appears to be one of the main causes of the above problem 3. Time and effort needed to access information to support troubleshooting decreases technicians' motivation to use documentation. By not referring to support documentation quality of troubleshooting might decrease
	Literature	<ul style="list-style-type: none"> • Using paper-based documents portability is limited, cross-references between documents and information are difficult to establish, and updates are more difficult to do and to distribute (e.g. Ventura, 1988; Lewis, 2004) • Referring to support documentation can make troubleshooting more efficient (e.g. Kelly, 1997a). • Electronic documents can solve most of the problems associated with paper (e.g. Ventura, 1988; Lewis, 2004)
Contents of Documentation	Research	<ol style="list-style-type: none"> 1. Although troubleshooting manuals are found useful to support troubleshooting, they only include a limited number of standard failures, do not consider field experiences, and there information is too 'static' 2. Although technical manuals can be used to support troubleshooting, they are not designed to support troubleshooting, as so they tend to be difficult to use by technicians to support there activity 3. Collecting failure records is a way of dealing with the limitations of the above manuals. They take into account the context in which equipment operates, and are more intuitive and self-oriented to support troubleshooting.
	Literature	<ul style="list-style-type: none"> • Authors such as Bennet and Jenney (1980); Higgins <i>et al.</i> (2002) support the first two findings • Failure records provide useful information to guide the execution of future corrective jobs, <i>i.e.</i> failure diagnosis and problem solving (e.g. Kelly, 1997a; Labib, 1998a) • By using failure records, solutions for repetitive equipment failures do not have to be looked at over and over again (e.g. Biase <i>et al.</i> 2001)

Table 5-2: CMMS use, documents aggregation and contents – main findings

- **Contents of documentation.** Documentation content affects the use of documentation in troubleshooting. It is claimed that troubleshooting manuals are commonly limited to a reduced number of standard failures perceived by equipment designers. They neither consider the conditions in which the equipment operates, nor include field experiences. They are also found to be too static, *i.e.* produced from design and are rarely revised. Traditionally, technical manuals tend to contain too much information that is unrelated to troubleshooting, reducing their usefulness to technicians. A solution to overcome the above problems is the collection of failure records oriented to support troubleshooting,

which include field experiences. They can also provide useful information to guide the execution of corrective jobs, and standardise solutions for repetitive jobs that need to be looked at repeatedly. However, the research identified that there is a lack of failure records, and that written descriptions of work experiences about failure troubleshooting are often missing in failure records.

- **Acquisition of failure information.** The research suggests that current systems are not fulfilling practitioner expectations regarding the collection of troubleshooting-related data. It shows that the work pressure combined with deficient collection methods inhibit the acquisition of failure records. Moreover, troubleshooting information is typically unstructured and difficult to communicate, and so difficult to report. Most collection forms need to be re-designed to orient contents for troubleshooting and provide the means for quick data entry. A strategy that encourages maintenance technicians to report their failure experiences and reduce their fear of sharing their knowledge also needs to be developed.
- **Management of failure records.** The research findings show that that current CMMS are not managing failure records in a way that facilitates the retrieval of troubleshooting-related information. The research indicates that the inefficiency of current failure records classification is a primary cause of the above problem. It suggests that this inefficiency is mainly because (i) only equipment attributes are used to classify records, and (ii) there are deficiencies in the way failures are described in the failure records. The former limits the relation of troubleshooting-related information from different equipment, and is not too accurate when the number of records is extensive. Regarding the latter, failure records are difficult to identify and classify because failures tend to be described in the failure records through a free-form field. For the reasons expressed previously, the above problems increase when paper-based documents are used. Although current failure records classification does not particularly suit troubleshooting, it needs to be understood that they have not been designed for this purpose. Their purpose is mainly management of spare parts, costs, and PM activities. In order to achieve a better decision-making environment for problem solving, and make troubleshooting more efficient, the way failure records are being managed needs to be improved.

Issue		Main Findings
Acquisition of Failure Information	Research	<ol style="list-style-type: none"> 1. Current CMMS and documents used for data acquisition are not fulfilling some user expectations 2. Lack of failure records, unclear/missing data, lack of time to report failures and the low motivation of technicians to report failure experiences are among main problems 3. Data collection is time consuming and expensive. Technicians commonly do not have much time to report failures because of their workload 4. Motivation for data collection would be increased if technicians are told why they are collecting data and how they will benefit from it 5. Troubleshooting-related information tends to be missing because technicians fear sharing their knowledge; they are afraid of losing their jobs
	Literature	<ul style="list-style-type: none"> • Acquisition of data through CMMS is generally difficult (e.g. Cato and Mobley, 1999; Kelly, 1997a: p174). • Work pressure inhibits collection of failure records (e.g. Hipkin, 2001) • The usual objection to comprehensive data collection is the cost (e.g. Sherwin, 2003) • Quality of information is improved when managers explain to technicians why data collection is necessary (e.g. Hipkin, 2001) • Maintenance technicians do not share their knowledge easily (e.g. Tobin, 2001; Davenport, 1994) • Collection methods should enable quick data entry and its format should be logical and consistent (e.g. Levitt, 1996: p169) • The expert's knowledge tends to be tacit, which is characterised for being unstructured and so difficult to represent and to communicate (e.g. Davenport and Prusak, 1998; Sternberg and Horvath, 1999)
Management of Failure Records	Research	<ol style="list-style-type: none"> 1. Current CMMS are not managing failure records in a way that facilitates the retrieval of information to support troubleshooting 2. Within CMMS the retrieval of troubleshooting information is not a main purpose of their failure record classification (from CMMS survey) 3. Users are not happy with the current equipment-code based system; as so they suggest that the way failure records are classified should be improved, for example, integrating equipment attributes with failure attributes 4. The use of failure attributes would facilitate to establish cross-references between failure records of different equipment types that have similar failure modes. Moreover, failure attributes reflect better what technicians see, hear and feel, as so it would make retrieval more intuitive 5. In order to facilitate the identification and classification of failure records, failure descriptions should be reported in a structured way. Currently failures tend to be reported through a free-form field, as so each person describes each failure in their own way, using jargon and their own nomenclature 6. Information retrieval is also facilitated if companies leave the paper-based failure records toward electronic documents

Table 5-3: Failure records acquisition and management – main findings

- **End-user involvement in systems development.** Although it is recognised that the involvement of end-users in CMMS and documentation development would increase their functionality and motivation to use, end-users do not get involved, nor are their requirements often collected. Finding the right time for end-users and developers to meet, and the lack of an efficient method to collect requirements appear to be the primary causes of the above problem. Questionnaires appear to be the most suitable method for collecting end-user opinions.

Issue		Main Findings
End-user Involvement	Research	<ol style="list-style-type: none"> 1. The level of involvement, or participation, of end-users in MIS development is either low or none 2. CMMS designers rarely collect end-user requirements 3. Maintenance technicians would be more enthusiastic about using a system if they were directly involved in its development 4. Both maintenance managers and vendors feel that finding the right time suitable for both to meet for discussing systems design, and the lack of and efficient method to collect user requirements are the problems 5. Questionnaires appear to be more efficient for collecting user requirements. However, it is generally assumed that <i>brainstorming</i> sessions would probably be more effective for collecting the correct requirements, since users are often unclear of their requirements. Nevertheless, time was identified as a main problem in collecting user requirements, and <i>brainstorms</i> are time consuming.
	Literature	<ul style="list-style-type: none"> • Gathering functional requirements, e.g. user and technology requirements, typically comprises the first phase of a IS development (e.g. Shenoy and Bhadury, 1998: p97) • CMMS are often a poor fit to maintenance requirements because the generalists and IT experts that design them usually do not have sufficient experience of maintenance (e.g. Herbaty, 1990; Mulcahy, 1999) • Designing a proper MIS requires the designers to have an adequate understanding of the maintenance functions (e.g. Raouf <i>et al.</i> 1992) • Technicians are interested in becoming involved and managers should provide opportunities and structures for their involvement (e.g. Cooke, 2003) • Other researches also suggest the use of questionnaires (e.g. Greenough, 2004)

Table 5-4: End-user involvement in system’s design

5.2.3 Key Features for SDS Development

This section discusses the third research objective, which aims to identify key features for the development of a proposed SDS. For the purpose of this discussion, findings from the three case studies are considered and compared with literature. Findings from the survey of maintenance managers and CMMS developers are also discussed.

5.2.3.1 End-user Requirements

This section presents the end-user (maintenance technicians and managers) requirements for the development of a SDS. The research shows that the success of a SDS depends on its usability at two levels: (i) data collection, and (ii) information access and retrieval. Table 5-5 presents the main research and literature findings. Findings from the survey of maintenance managers previously presented are also considered for the purpose of this discussion.

Issue		Main Findings
Data Collection	Research	<ol style="list-style-type: none"> 1. Failure information needs to be easy and quick to collect 2. Difficulties collecting data and technician's concerns over sharing their experiences are among the main reasons for the lack of documented failure experiences (also reported by managers) 3. Technicians expect some sort of reward to motivate them to report and share their knowledge 4. Technicians expressed the need for a structure way or formal procedure for the collection of troubleshooting-related information 5. Data collection forms should contain both structured and free-form sections 6. Failure description field, traditionally free-format, should be structured to standardise reporting and facilitate the identification of records (also reported by managers) 7. Although technicians prefer computer-based systems to manage documentation, they also prefer paper-based systems to report data 8. Failure information should be reported in the way troubleshooting is conducted. The structure used in the troubleshooting manuals is a good reference to guide the way failure experiences need to be reported
	Literature	<ul style="list-style-type: none"> • When designing report forms one should look for simplicity, clarity and flexibility, and eliminate the need for memorising codes (e.g. Dhillon, 1999) • Literature findings presented in <i>Table 5-3</i>
Information Access & Retrieval	Research	<ol style="list-style-type: none"> 1. A SDS needs to provide speedy and productive means of retrieving information to support troubleshooting 2. A SDS needs to provide the means for documentation to be available next to the work place, <i>i.e.</i> where it is most needed 3. A SDS system should have some sort of browsing system based on a pre-defined list of attributes or key words to facilitate the retrieval of failure information 4. A SDS should contain troubleshooting-related documents, and provide the means to integrate and link textual instructions, pictures/illustrations, diagrams, and eventually videos, <i>i.e.</i> allow establishing cross-references between different document types, and records of different equipments
	Literature	<ul style="list-style-type: none"> • Technicians spend a significant amount time in searching for information rather than troubleshooting (e.g. Greenough <i>et al</i>, 2001; Ventura, 1988) • The most popular place for storing records (paper-based) is in everyone's offices (Webster <i>et al</i>. 1999)

Table 5-5: System requirements – main findings

- Data collection requirements.** The research shows that the SDS needs to provide the means for easy and quick data collection, and promote failure records collection. The collection forms need to be designed in a logical way and with a consistent format. These forms should include structured sections to ensure that important and standard information is collected, and to promote quick reporting. Although, free-form sections need to minimised, they should be included to ensure that unforeseen and detailed information is collected. Describing the failure diagnosis and the repair actions are examples where free-form sections might be applied. Contrary to what is commonly done, the failure description field needs to be structured to standardise the way failures are described, so their later identification will be easier. The SDS needs to include information that is troubleshooting-related and intuitive to use. It should include failure records and technical documents, such as pictures, diagrams, sketches, and videos.

- **Information access & retrieval requirements.** The research shows that the SDS needs to provide the means for information to be available next to the work place, and to be easily retrievable. It should allow cross-references to be established between different type of records, and records of different equipment. It also should allow the user to use a pre-defined list of equipment and failure attributes to search for records.

5.2.3.2 Contents of Records

Although it was identified that technicians would like information other than failure records to be included in the SDS, this research only investigated the contents of failure records that can be used to support troubleshooting, referred to as repair data. In order to simplify data collection and make reporting of troubleshooting-related data more efficient this research identified the most important repair data types to include in the failure records. The findings from a survey of CMMS developers and case studies are considered for the following discussion. *Table 5-6* presents the main findings.

- **Repair actions.** Although detailed repair action descriptions are more common, a brief and systematic description of the repair action appears to be more appropriate for technicians. The tendency for reporting detailed descriptions might be due to the fact that CMMS format their reports in this manner, and that an expert's knowledge tends to be tacit and difficult to communicate and report. Regarding the repair recommendations, although technicians classify them as very good, the absence of a dedicated field in the CMMS means they are rarely recorded. The unsuccessful repair actions are rarely recorded and not well rated by technicians, which might be because technicians would not be happy to expose their mistakes. Although commonly recorded, the repair duration is not seen by technicians as important to support troubleshooting. The finding about the action type and the cause of maintenance are not conclusive because they were not considered when surveying the technicians.
- **Repair resources.** The most important repair resources to support troubleshooting identified by this research are the work trade identification and number, the spare parts and specials tools needed for the job. Special tools are rarely recorded because only a minority of CMMS consider this type of data. The materials used for the job are considered by technicians to be fairly important to record, and frequently recorded, as so might be included in records as well. Although the repair location (*e.g.* on site, repair shop) is also classified as good, it might not be applicable to every company.

- General repair data.** This research has shown that both failure diagnosis and failure cause descriptions are very important to support troubleshooting. However, diagnosis descriptions are rarely included in the failure records, which could be due to a minority of CMMS only considering this data type. The failure causes are also rarely recorded. Although both the failure nature (*e.g.* mechanical failure, electrical failure) and methods by which failures are observed are considered fairly important to record, only the nature of failure is included in a significant majority of the records. All other data types, *e.g.* failure effects, failure consequences, and failure criticality, were poorly rated. Feedback results also indicated that the latter last data types are commonly collected for failure and reliability analysis.

Repair Data	Technicians Classification	Recording Frequency	CMMS Recordable
Repair Actions			
Brief description of the repair actions	Very good	25%	Majority
Detailed description of the repair actions	Good	65%	All
Step-by-step repair actions	Very good	9%	Minority
Repair recommendations	Very good	16%	Minority
Repair actions that were not successful	Neutral	2%	Rarely
Repair duration	Poor	94%	All
Action type	-	87%	-
Cause of maintenance	-	75%	-
Repair resources			
Identification of who performed the job	Neutral	0%	Majority
Worker trade identification	Very good	90%	All
Number of workers needed		48%	-
Repair location	Good	33%	All
Spare parts needed	Very good	96%	All
Special tools needed	Very good	21%	Minority
Materials needed	Good	40%	All
General Repair Data			
Description of the failure diagnosis	Very good	19%	Minority
Failure cause(s)	Very good	17%	-
Failure effects	Poor	22%	-
Failure nature	Good	67%	-
Failure consequences	Neutral	11%	-
Failure criticality	Neutral	9%	-
Method of observation	Good	4%	-
Operating conditions	Poor	12%	Majority
Eventual machine tool changes	Poor	10%	Majority
Standard working conditions	Poor	19%	Majority

Table 5-6: Contents of records – main findings

5.2.3.3 Record Attributes

The research showed that a main requirement of end-users for the use of support documentation is that it should be quickly retrieved. Both the identification and classification of failure records are key issues to fulfil the above requirements. The record attributes identified by this research have two objectives. First, provide a structure to guide the way failures are described in the failure records, which would facilitate the reporting and the later identification of records. Second, provide a structure to guide the definition of each record's metafile, which would be used to classify the failure records. *Table 5-7* presents the ranking of these records attributes identified by the research. The equipment identification attributes are discussed below.

Attributes	Technicians Classification	Frequency in Records	CMMS Recordable
Equipment Identification & Failure Location			
Equipment location	Good	98%	All
Equipment identification	Very Good	98%	All
Failure location at equipment level	Neutral	90%	All
Failure source (lowest identified level)	Very Good	9%	Minority
Failure Description			
Failure symptom(s) lowest equipment level	Neutral	11%	Minority
Failure symptom(s) at equip. level	Very Good	62%	Minority
Nature of the symptoms	Good	39%	Rarely
Combination of symptoms	Good	13%	Rarely
Failure effect	Very Good	74%	Minority
General Attributes			
Failure cause(s)	Poor	31%	All
Failure consequence(s)	Poor	5%	Rarely
Failure nature	Good	56%	All
Failure discovered	Neutral	5%	Majority
Failure reason	Good	14%	Majority
Work order number	Neutral	62%	Majority

Table 5-7: Attributes of records – main findings

- **Equipment identification & failure location attributes.** The research showed that equipment identification and failure source (the lowest equipment level to which the failure can be isolated) are among the most important attributes. However, it is the failure location at equipment level that tends to be recorded, rather than the failure source. This might be because only a minority of CMMS consider the failure source. The literature also suggests that the failure source is an important attribute to consider within the troubleshooting process (*e.g.* Moss, 1985). The equipment location is considered by technicians to be fairly important to record, frequently recorded, and highly considered by all the surveyed CMMS. This latter attribute is considered below.
- **Failure description attributes.** Within this category, the research shows that the failure symptoms at the equipment level and the failure effect are the most important attributes. The use of this type of attributes make the system more intuitive to use by technicians because they reflect what maintenance technicians see, hear, and feel when failures occur. None of the analysed records has a dedicated field for the attributes referred to in this category. Thus, when stated that an attribute is recorded, it means that is indicated in the failure description field (free-form). The research also shows that the symptoms should have the indication of their nature, *i.e.* the indication of an adjective or adverb that helps in understanding the symptom itself, and that multiple symptoms should be indicated, if known. Although the failure effect attribute is only considered by a minority of CMMS, it is considered by technicians to be fairly important to record, and frequently included in the records. This suggests that the indication of the consequences of the failure in terms of the operation is also an important attribute to classify the failure records.
- **General attributes.** Although most of the attributes within this category are commonly related to preventive activities, *e.g.* failure and reliability analysis, they were also subject to analysis in order to assess their importance for the classification of failure records. The failure nature and failure reason might be used to identify and classify failure records. Although considered in most CMMS, the research shows that no other attributes within this category are relevant.

5.2.3.4 Equipment Identification Attributes

This research also investigated how equipment identification data is commonly classified. The equipment taxonomy at the surveyed companies was analysed and compared with existing standards. This was conducted because maintenance managers claimed to be unhappy with the equipment-based system used to classify failure records.

The availability of consistent data, made possible by the creation of enterprise-wide standards for classifying equipment is the foundation for any CMMS. This level of standardisation can be achieved only by implementing equipment taxonomy. Thus, traditionally every manufacturing company would have implemented a particular taxonomy to classify their equipment assets into an ordered system of family groups with consistent names. The exact form of the plant number code will vary from industry to industry, but the basic principle to be applied should always remain the same (Corder, 1976; p28). Several organisations, such as the *American Petroleum Institute*, the *British Standards Institution*, and the *International Organisation for Standardisation* have been working to create standards for equipment taxonomy.

A number of standards or guide systems have been developed to support companies to implement their equipment taxonomy. For example, BS ISO 14224 (1999), BS EN 61512 (1999), ISA S88.01 (1995), and KKS (used on Danish and German power companies). The three surveyed companies have used the BS and ISA standards to guide the development of their equipment taxonomy.

The equipment code comprises two main types of data, namely the geographic equipment location and the equipment classification. Equipment is also identified by a classification scheme, where purpose and task are the main characteristics. *Figure 5-3* provides an example of an equipment code. Assigning failure records with only this type of code limits the comparison and correlation of troubleshooting-related information. For example, between the same the equipment at different sites, same type of equipment but applied in different applications, or different equipment within same class. Thus, in order to improve the classification of failure records, the equipment attribute classes should be independently used, and not as a single code comprising the all classes.

Equipment can also be identified by other attributes that are not typically included in the equipment code. These attributes are commonly grouped in the following categories: (i) equipment unit hierarchy, (ii) equipment unit data, and (iii) manufacturer's data. The equipment unit hierarchy indicates the organisational framework that reflects the relationship between the equipment unit and sub-units. The highest level is the equipment unit class.

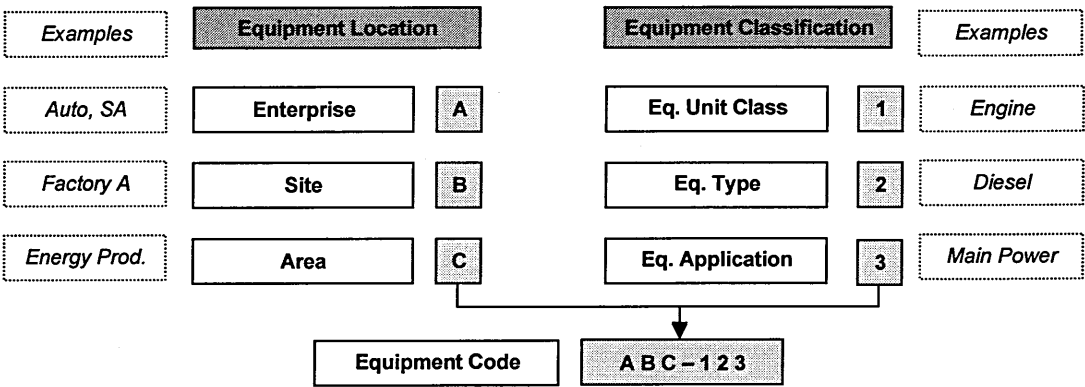


Figure 5-3: Example of an equipment code

The number of levels for subdivision will depend on the complexity of the equipment. Figure 5-4 illustrates and presents an example of the equipment unit hierarchy. This equipment attribute class is particularly important for locating the failure. As previously discussed, the failure source is one of the most important attributes to classify and identify failure records.

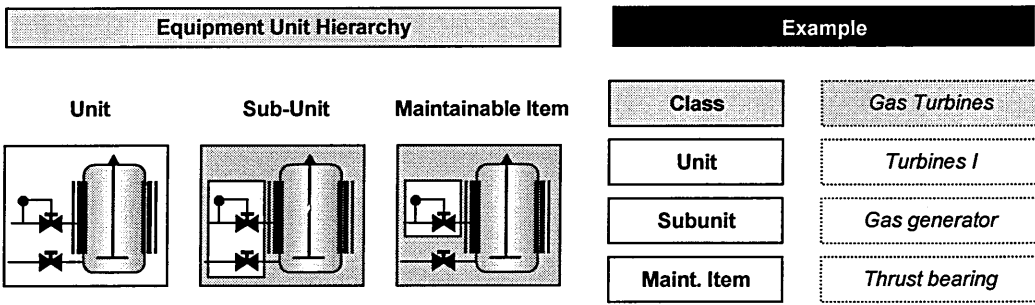


Figure 5-4: Example of equipment unit hierarchy

The equipment unit data represents data that is intrinsic to the equipment, e.g. its description, serial number, and accessories. Neither the maintenance managers nor the technicians reported that any attribute within this class would be important to classify and identify the failure records. Manufacturer's data is another attribute class that contributes to equipment identification. The manufacturer's name and the manufacturer's model name are examples of attributes within this class. Maintenance mangers state that these two attributes are important to classify/identify failure records. These attributes are important to communicate to the manufacturer problems that require technical analysis and recommendations. According to equipment vendors, this feedback is important for them to study field equipment failures, to investigate those failures and suggest preventive and corrective actions, and to improve equipment reliability.

5.2.3.5 Records Format, Supporting Tools, and Standards

Since none of the companies where the case studies were conducted use a computerised document system, it was not possible to draw any conclusion from the performance of such systems. This research revised some these tools and similar applications that can be used to support the proposed SDS.

- Supporting Tools.** Considering the end-user requirements and the features the integrated *Database Management Systems* (DBMS) and the *Electronic Document Management Systems* (EDMS), it can be suggested that this integrated solution might be a good approach for designing the proposed SDS (see *Appendix G*). Many leading vendors of document management applications such as *FileNet* and *Documentum* have taken this approach. Another bolt-on approach that might be used is the *Industrial Hypermedia Task Support Systems* because technicians suggested that records other than text documents should be included in the system, such as pictures, diagrams, and videos. Most of the end-user requirements match the features of the industrial TSS (*Table G-1* in *Appendix G*), while previous work in industrial TSS show that this technology has been successfully applied to resolve similar problems to the one in this research (*Table G-3* in *Appendix G*).
- Format.** For the records management function to be effective, records should be kept in formats that enhance their utility. This research did not conduct an in-depth investigation about the records format. Nevertheless, it identified that Portable Document Format (PDF) is being frequently used with the surveyed companies. According to other researchers, PDF is now a common document format within manufacturing (e.g. Greenough, 2004). In addition, even in other areas, this format appears to be assuming a primary role when compared with other formats such as HTML or the Rich Text Format. For example, governments are adopting PDF as a standard format (McKinley, 1997). The current available features of PDF also allow expansion of the navigation capabilities (McKinley, 1997). In addition, the tool to read this format (Acrobat Reader) is available free. However, PDF presents several disadvantages that might affect its utilisation, e.g. the difficulty to modify or edit contents, and lack of re-use and multiple views of contents (Lee *et al.* 2002). Thus, further research needs to be conducted to assess the best format for the documents.
- Standards.** This research also identified some standards that might be used to support the development of documentation systems are: BS ISO 15489-1, (2001), BS PD ISO/TR 15489-2, (2001), BS EN 82045-1, (2001), BS EN 61355, (1997), BS ISO 2709, (1996), and BS ISO 14224, (1999).

5.3 Research Conclusions

This section presents the conclusions drawn out from the research.

5.3.1 System Feasibility

- The first premise underlying the development of the proposed SDS is that failure records are available. It is acknowledged that some authors argue that failures are not supposed to happen in the first place, and so data collection is not needed (*e.g.* Moubray, 1999). However, within this thesis, it is assumed that failures do occur and data collection is needed, as argued by others (*e.g.* Sherwin, 2000). This research shows that the collection of failure records is a common practice within maintenance of manufacturing systems, and that they play a critical role in the efficiency of maintenance. It also shows a tendency for companies collecting data on all failures without clearly defined criteria, which supports the argument for failure records collection.
- The second premise is that failure records need to be computerised. The research shows that although a significant number of users still use paper-based systems, the use of computer-based systems to manage failure records are becoming more popular.
- The third premise is that current systems (CMMS and documentation) are failing to effectively support troubleshooting. The research has identified that maintenance personnel are in general unhappy with CMMS regarding troubleshooting support. It shows that these systems are complex to use by technicians, typically do not establish cross-references between different troubleshooting-related documents, and do not manage failure records in a way that facilitates the retrieval of troubleshooting-related information. The inefficiency of current failure classification is the primary cause for the retrieval problem. It also demonstrates that technical manuals are not effectively supporting troubleshooting, and that the collection of failure records is a solution to overcome this. However, the lack of motivation for data collection and deficiencies of current collection forms affect the availability of troubleshooting-related information. In order to achieve a better decision-making environment for problem solving, and make troubleshooting more effective, the way failure records are being collected and managed needs to be improved.

- The fourth premise is that troubleshooting quality and speed are improved by effective access to documentation, particularly failure records. The research shows that troubleshooting is improved if documentation accessibility and retrieval are facilitated. It shows that by fulfilling these two requirements technicians would refer more often to troubleshooting-related information. As such, troubleshooting quality is improved because technicians would minimise problems solved by guessing, repair procedures missed, failures where only symptoms are fixed, and safety procedures not considered. Troubleshooting speed is potentially increased because maintenance crews would spend less time determining a solution to the problems when starting from ‘scratch’.
- **Global database of failure records.** An aim of the SDS is to promote the communication of failure records. Accessibility therefore is important if a global database of failure records populated by users and managed by equipment vendors can be derived. Although the benefits for users and vendors are evident, the research findings suggest that development of such a database is currently not feasible. First, equipment vendors show concerns sharing directly with customers their failure experiences, particular for those having service contracts with customers. Second, technicians do not share their knowledge easily. However, it is acknowledge that the evidence collected in this research is insufficient to draw a supported conclusion.

5.3.2 Key Features for the Development of a SDS

This section presents a set of recommendations determined by the research regarding the development of the proposed SDS.

5.3.2.1 User Requirements for the Development of a SDS

- **Data collection.** The research shows that the proposed SDS needs to provide the means for easy data collection and promote failure records collection. The forms used for data collection should be simple, have a consistent format, and be logical to complete. In order to speed up data collection the maximum number of fields should be structured. Fields to describe diagnosis, repair actions, and observations should be free-form to assure the collection of unforeseen data. Collection forms should include a structured field to describe failures in a standardised way to facilitate the identification of failure records. The form-free field to report repair action might be semi-structured with subsections that reflect the way troubleshooting is conducted. Besides failure records and technical documentation, the system should include pictures, diagrams, sketches, and eventually videos.

- **Information access & retrieval.** The research shows that the SDS needs to provide a speedy and productive means of retrieving troubleshooting information, and the means for information to be available next to the work place. The speed might be provided by developing a search system based on pre-defined equipment and failure attributes to characterise and classify failure records. Productivity might be achieved by allowing cross-references to be established between different types of records, and records of different equipment.

5.3.2.2 Contents of Records

In order to improve failure data collection, and assure relevant troubleshooting-related data is collected, the research investigated the importance of the different repair data types for troubleshooting. *Figure 5-5* presents a summary of the main findings.

	Important to Include	May be Included	Not Important to Include
Repair Actions	<div>Brief and systematic description of repair actions</div> <div>Repair recommendations</div>	<div>Action type</div> <div>Cause of maintenance</div> <div>Repair actions not successful</div>	<div>Repair duration</div>
Repair Resources	<div>Work trade Identification and number</div> <div>Needed spare parts & special tools</div>	<div>Indication of who performed the job</div> <div>Repair location</div> <div>Materials needed</div>	
General Repair Data	<div>Failure diagnosis description</div> <div>Failure cause(s)</div>	<div>Failure Nature</div> <div>Method of observation</div> <div>Failure consequences</div> <div>Failure criticality</div>	<div>Failure effects</div> <div>Operating conditions</div> <div>Eventual machine tool changes</div> <div>Standard working conditions</div>

Figure 5-5: Selection of repair data to include in failure records

The main findings identified by this research regarding the contents of records are as follows:

- *Table 5-8* presents the most important repair data to be included in the failure records and the way it should be reported.

Data Type	Field Type
• Brief and systematic description the repair actions	Free-form
• Descriptions of repair recommendation	Free-form
• Work trade identification (needed for the job)	Structured
• Number of workers (needed for the job)	Structured
• Indication of the spare parts (needed for the job)	Structured
• Indication of special tools (needed for the job)	Structured
• Description of the failure diagnosis	Free-form
• Description of the failure causes	Structured

Table 5-8: Repair data vs. field type

- The results about the action type and the cause of maintenance are not conclusive.
- Description of repair actions should include any testing performed.
- Regarding the indication of who performed the job (*e.g.* contractor, manufacturer), it was assessed that it is only significant for companies that often refer to contactors or manufactures for servicing. Similarly, it was verified that the indication of the repair location (*e.g.* on site, repair shop) is only significant when the size of the company justifies it, *e.g.* multi-plants and multi-workshops.
- For reporting to be logical and concise, the repair data should be reported in a way that resembles the troubleshooting steps. The troubleshooting manuals are a good source to guide design of the collection form.
- In order to improve the record’s contents, the motivation of those reporting data, usually technicians, needs to be increased. Motivation is increased if technicians are told why data is being collected and how they will benefit from it. The participation on design of collection forms also increases their motivation. In addition, technicians will be more motivated for reporting their experiences if they receive some sort of reward.
- Although technical documentation is found less important than failure records to support troubleshooting, it can provide useful assistance in some cases. Thus, technical documents should be included in the SDS whenever relevant. These documents should be linked to the respective failure record.

5.3.2.3 Record Attributes

This research identified and classified a set of record attributes that aim to structure the way failures are described in the records and to provide guidance to develop a classification scheme to classify failure records. *Figure 5-6* presents a summary of the main findings.

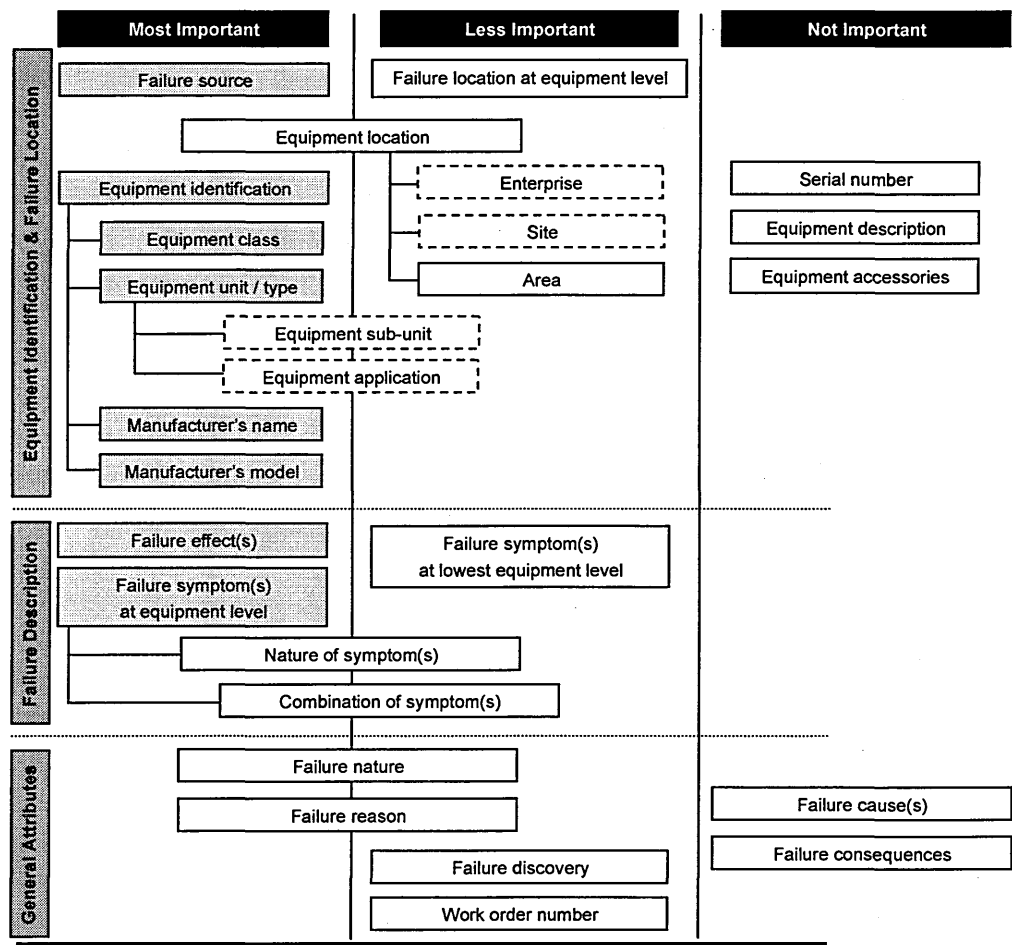


Figure 5-6: Ranking of records attributes

The main findings identified by this research regarding records attributes are as follows:

- The research identified that the most important attributes to characterise and identify failure records are as follows:
 - *Equipment identification*: identification of the equipment that failed
 - *Failure source*: lowest equipment level to which the failure can be isolated
 - *Manufacturer's name & manufacturer's model name*
 - *Failure effects*: consequence of a failure in terms of operation
 - *Failure symptoms at equipment level*: brief description of what the failure exhibited.
- The equipment location might also be considered. The indication of the enterprise and the site are only important for organisations with multiple enterprises and/or multiple sites.
- The failure nature and the failure reason might also be considered. However, since they are not among the most highly rated attributes, it is suggested that each company should decide on their use.
- Equipment identification attributes should be independently used, and should include the equipment class and the equipment unit (or type). Depending on the complexity of the equipment, it might also include the equipment sub-unit and the equipment application.
- The indication of failure symptoms should include the characterisation of their nature, i.e. the indication of an adjective or adverb that helps in understanding the symptom itself. Multiple symptoms should also be indicated if they are known.
- All the attributes adopted by each organisation should be reported in a structured way through dedicated fields, i.e. a set of pre-defined attribute values needs to be provided, from which one will choose the most appropriate. In case a particular value is not listed, a way of reporting it should be provided. When new values are reported, they need to be validated before added to the pre-defined list.

5.3.2.4 *Records Format, Supporting Tools and Standards*

Conducting an in-depth investigation about the format, supporting tools and standards was not a main purpose of this research. However, the research suggests the following:

- Integrating EDMS and DBMS, and using industrial hypermedia TSS technologies might be a good approach for system design.
- The system design might be supported by the following standards: BS ISO 15489-1, (2001), BS PD ISO/TR 15489-2, (2001), BS EN 82045-1, (2001), BS EN 61355, (1997), BS ISO 2709, (1996), and BS ISO 14224, (1999).

5.4 Limitations of Research

This section discusses the limitations of the research. Most of these limitations were a result of the methodology chosen. Thus, this section presents the author's reflections on the methodology used.

A great part of this research is qualitative and, despite the effort to avoid bias to support opinions, analytical judgements are explicitly assumed as subjective. Although there is an element of subjectivity in analysing data, the researcher tried to be as objective as possible in his conclusions.

A drawback of the research is that it did not allow sufficient time and opportunity to collect more evidence to produce conclusions based on the largest possible sample, *i.e.* case companies. However, in this research universality was not directly sought, as the purpose of it was to use case studies to explore, understand and answer a particular research question. Additionally, although this research provides a view from a cross section of industries, due to time constraints it does not provide a thorough view of each sector's requirements.

It is also acknowledged that there are a number of methodology strategies and collection methods that could have been reviewed and applied. The limited time and resources available meant that it was not feasible to test them all. However, as justified in *Chapter 3*, the research applied for this thesis was considered the most robust and reliable with regard to the requirements.

It is also acknowledged that a discrepancy between what people say and what they actually do might exist; they may not be lying, they may simply be inaccurate. Crosscheck views with different interviewees and with other sources, such as written documents, were made to avoid one-sided views. It should also be stressed that *what is accessible is what is researchable*, *i.e.* some kind of information and people are more accessible than others.

The above limitations are acknowledged but they do not detract from the significance of the findings. In fact, the findings of this research support the choice and use of this research methodology.

5.5 Contribution to Knowledge

The research presented in this thesis has improved the understanding of the use of documentation in the support of industrial failure troubleshooting. It has made two primary contributions to the body of knowledge.

- First, supported by literature the research proposed the development of a Support Documentation System (SDS) that will improve troubleshooting. However, in order to assess the feasibility of this system, the research identified that there is little evidence about failure records management and the performance of current systems supporting troubleshooting. This research has provided the evidence that demonstrates the feasibility of such a system and confirms the importance of failure records for maintenance. The research has also supported the findings from literature that current systems are failing to effectively support troubleshooting.
- Second, the first part of this research showed that failure records are available, but the existent systems are not managing them in a manner that are effectively used by maintenance personnel supporting troubleshooting. Based on an exploratory investigation, this research has established a set of key features that would promote a new design of SDS that will improve this situation. The research found that the provision of truly useful documents and the ability to provide a fast and productive means to collect and retrieve troubleshooting information are among the primary goals of end-users. In view of this, the research identified the type of documents/records and the type of troubleshooting data that such a system should include. It also identified the most relevant record attribute classes, which contributes toward the establishment of a formal structured description of equipment failures. This formal structure provides system designers with a systematic way to guide the storage and retrieval of documentation/records.

5.6 Recommendations for Further Research

In the course of addressing the research questions, other questions arise require further investigation. The following are recommendations for future research:

- The first recommendation, and probably the most obvious, is to design a pilot model of the proposed SDS to test the pre-design recommendation proposed in this thesis.
- Based on literature the research gives suggestions about the tools and technologies to develop the SDS. It is recommended that empirical evidence be collected to assess them. Regarding the document format, an in-depth investigation about its selection is also recommended.
- The research identified that maintenance technicians have particular ‘characteristics’ and motivations, and so it is suggested that they are carefully studied to effectively design the user interface of the SDS.
- Investigate the replication of the empirical results, within the same scope or within a reduced scope, to strengthen and enhance the validation of the research findings. In this thesis, a case study methodology was used to explore the pre-design recommendation; a positivist survey to generalise the findings is suggested.
- Investigate the integration of the SDS in CMMS.
- This research does not provide sufficient evidence to support the development of a global database of failure records populated by equipment users and vendor managed. Despite considering the potential benefits of it for both parties, further investigation on the collaborative creation of such database is suggested.
- This research identified that verification procedures need to be implemented to validate reported data, and so it is suggested that these procedures are investigated.
- This research identified that maintenance technicians are not motivated to share their knowledge ‘freely’ and to do clerical work. An investigation of these issues might bring a new contribution for maintenance knowledge management.
- It is also suggested to investigate the applicability of the findings of this research into other maintenance activities other than troubleshooting, *e.g.* PM activities.

*“Ah, but this is not the end. It is not even the beginning of the end.
But it may well be the end of the beginning”*

Winston Churchill (Speech after the Battle of El Alamein, 1942)

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Appendix A

A. METHODOLOGY BACKGROUND

A.1.1 Basic Concepts

Ontology and epistemology. Ontology and epistemology are two of the most central concepts in research methodology. Ontology refers to the claims or assumptions that a particular approach to a social enquiry makes about the nature of social reality (Blaikie, 1993). It makes claims about what exists, what it looks like, what units make it up, and how these units interact with each other. Epistemology refers to the claims or assumptions made about the ways in which it is possible to gain knowledge of reality, whatever it is understood to be. It presents a view and a justification for what can be regarded as knowledge – what can be known, and what criteria such knowledge must satisfy in order to be called knowledge rather than beliefs. (Blaikie, 1993).

Method and methodology. Method and methodology are two related concepts that must also be distinguished since they are often wrongly used in an interchangeable way. Methods of research are the actual techniques, instruments, or procedures used to gather and analyse data related to the research questions, *e.g.* questionnaire and interview techniques (Blaikie, 1993). Methodology of research is the analysis of how research should or does proceed. It is a set of principles, practices, and rules used by those who work in a discipline or engage in an enquiry that, in a particular situation, have to be reduced to a unique method suitable for that situation (Checkland, 1994: p161; Davis, 1999a). Moreover, it is a process of enquiry, not a method to produce a predetermined result (Bignell, 1991) that aims to ensure nothing is overlooked in the process of solving a complex problem (such as developing a complex information system). It also provides the means for the investigator to develop a plan for gathering, analysing, and using data about a phenomenon.

A.2 Research Philosophy: *positivism and interpretivism*

Positivism. Other terms that describe the positivism approach include positivist, hypothetico-deductive and experimental (Henwood and Pidgeon, 1993: p14-32). Positivism entails an ontology of an ordered universe made up of atomistic, discrete and observed events (Blaikie, 1993). In its epistemology, knowledge is seen to be derived from sensory experience by means of experimental or comparative analysis, and concepts and generalisations are shorthand summaries of particular observations. This is, positivism generally assumes that reality is objectively given, single, tangible, fragmented and can be described by measurable properties that are independent of the observer (researcher) and his or her instruments (Lincoln and Guba; 1985; Myers, (1997). Positivist studies generally attempt to test theory, in an attempt to increase the predictive understanding of phenomena, and where real causes can be defined. It also has a particular successful association with the physical and natural sciences.

In the context of the social sciences it is traditionally assumed that the social world consists of a number of truths or facts that can be uncovered through observation and experimentation. This forms the basis for many people's ideas of science, a process of discovery of reality, of providing causal explanations for events or behaviours that occur in the world around us. The existence of laws of physics is a good example and indeed the traditional approach has its roots in the natural sciences. With IS research, positivism is only applicable if there is evidence of formal propositions, quantifiable measures of variables, hypothesis testing, and the drawing of inferences about a phenomenon from the sample to a stated population (Orlikowski and Baroudi, 1991: p5)

Interpretivism. As with positivism, interpretivism is also labelled using different terms – constructivism, anti-positivist, contextual, and interpretative are some examples (Henwood and Pidgeon, 1993: p14-32). Interpretivism entails an ontology in which social reality is regarded as the product of process by which social actors negotiate the meanings for actions and situations. It contends that only through the subjective interpretation of and intervention in reality can that reality be fully understood. In its epistemology, knowledge is seen to be derived from everyday concepts and meanings (Blaikie, 1993). It attempts to understand phenomena through the meanings that people assign to them and interpretive methods of research. Within interpretivism, realities are multiple, constructed and holistic (Lincoln and Guba, 1985). Opposite to positivism, it is assumed that individuals play an active role in constructing knowledge, *i.e.* the relationship between the researcher and the researched is interactive and inseparable. The study of phenomena in their natural environment is the key to the interpretative research, together with the acknowledgement that scientists cannot avoid affecting those phenomena they study. Moreover, it does not predefine dependent and independent variables, but focuses on the full complexity of human sense making as the situation emerges (Kaplan and Maxwell, 1994).

A.3 Quantitative and Qualitative Methodologies: strengths and weaknesses

A.3.1 Quantitative Methodology

Strengths. According to Burns (2000) the quantitative approach has a number of strengths. First, it has control and precision, which are achieved through the sampling and design of experiments and through quantitative and reliable measurements. Second, the systematic manipulation of a variable can be shown to have a direct causal effect on another when other variables have been controlled. Third, hypotheses are tested through deduction, with the use of quantitative data permitting statistical analysis.

Weaknesses. The quantitative approach is not the most suitable approach to apply in social situations because its objectivity does not allow the subjectivity of the social action of reality to be taken into account (Robson, 2002). According to Burns (2000), it also fails to take account of people's unique ability to interpret their experiences, construct their own meanings, and act on these, which leads to the assumption that facts are true and the same for all people all the time. Robson (2002) states that quantitative research restricts experience in two ways: first by directing research to what is perceived by the senses; second by employing only standardised tools, based on quantifiable data, to test hypotheses. Burns (2000) argues that there is a lack of flexibility with this approach because the criteria considered appropriate for the research are not necessarily appropriate for work that rests on different assumptions, uses different methods, and appeals to different forms of understanding. Robson (2002) states that the overemphasis that positivity places on quantitative measurement is wrong and unjustifiable, for it cannot capture the real meaning of social behaviour.

A.3.2 Qualitative Methodology

Strengths. According to Bryman (2001), the main advantage of the qualitative approach is that contact with participants is possible at various levels in a manner more likely to provide a depth, as well as breadth, to accounts of events. This approach is well suited for locating the meanings people place on events and for connecting these meanings to the social world around them (Miles and Huberman, 1994). Eisner (1979) describes this approach as being highly relevant because it is concerned with processes rather than consequences, wholeness rather than independent variables, and meanings rather than behavioural statistics. This view is supported by Flick (2002), who argues that researchers are increasingly confronting new contexts and perspectives. Avison *et al.*, (1999) point out that a particular strength of qualitative methods is their value in explaining what goes on in organisations.

Weaknesses. According to Shaw (1999), applying the standards of reliability and validity needed for evaluation is a limitation of qualitative approaches. Parlett (1976) argues that the intimacy between participant and observer affects the results. On the other hand, the observer needs to gain some confidence with the participant in order to retrieve quality information. The promise of anonymity, which often serves as the basis for trust, together with the requirements of authenticity, also makes the task of the researcher difficult. Another weakness of this approach is that the researcher needs to spend a considerable amount of time in the research setting in order to examine the interactions, reactions and activities of subjects. In addition, the results of qualitative studies may not be generalisable

to a large population because the sample group is usual small and the subjects are commonly not chosen randomly (Hancock, 2002).

A.4 Research Strategies

This section presents the key features of the research strategies that are traditionally used within social research. According to Robson (1995: p42), these main research strategies are experiment, survey, and case study. Action research is also introduced due to its relevance and utilisation within social research. The aim of this section is to identify the strengths and weaknesses of the strategies, and to explain how they operate in order to justify the choices adopted for this research.

A.4.1 Survey Strategy

A survey consists of the collection of standardised information by asking a set of pre-formulated questions in a predetermined sequence in a structured questionnaire to a sample of individuals drawn to be representative of a defined population (Hutton, 1990). Information is usually, but not necessarily, collected by means of personal or telephone interviews and mailed questionnaires (Totten *et al.* 1999).

Depending on the enquiry purpose, surveys can be applied in different ways (Gill and Johnson, 1991). They can be used purely for data gathering, for hypothesis/theory testing, or for the estimation of relationships between variables (Thomas, 1996). *Table A-1* characterises the two main types of surveys, namely the descriptive and the analytical surveys. This table allows one to select the appropriate type of survey based on the purpose of the enquiry and on the features of the survey.

The advantage of the survey is that it can elicit information from a respondent that covers a long period of time in a few minutes, and, with comparable information for a number of respondents, can go beyond description to looking for patterns in data (Burns, 2000). A key weakness of the survey is that it is difficult to realise insights relating to the causes of or processes involved in the phenomena measured. There are also several sources of bias, such as the possibility of the self-selecting nature of respondents, the point in time when the survey is conducted, and in the researcher him/herself through the design of the survey itself (Alreck and Settle, 1985).

	Descriptive Survey	Analytical Survey
Type	<ul style="list-style-type: none"> • Quantitative survey • Enumerative, census-type 	<ul style="list-style-type: none"> • Qualitative survey • Relational type
Purpose	<ul style="list-style-type: none"> • Exploratory • Make inference to the population from which the sample was drawn • Not designed to explain or show casual relationships between variables 	<ul style="list-style-type: none"> • Explanatory • Establish cause and effect relationships • Explore the associations between particular variables
Key issues	<ul style="list-style-type: none"> • Representative sampling of population • Standardised way data collection, measurement and analysis • Large populations • Portray accurately the characteristics of particular individuals, situations, etc. 	<ul style="list-style-type: none"> • Control is crucial • Less orientated towards representativeness • Towards finding associations and explanations • Test theories and/or hypothesis about relationships between variables
Questions Type	<ul style="list-style-type: none"> • 'how many', 'how often' • Tendency for close-questions 	<ul style="list-style-type: none"> • 'why', 'what goes with' • Tendency for open-questions

*Table A-1: Characteristics of survey types
(after Oppenheim, 1992: Chp2-3; Thomas, 1995; Burns, 2000: p566)*

A.4.2 Case Study Strategy

A case study is a research strategy (Eisenhardt, 1989) or an empirical enquiry (Yin, 1994) that investigates a contemporary phenomenon within its real-life context (Robson, 1995:p 52; Benbasat *et al.* 1897); when the boundaries between phenomenon and context are not clearly evident (Yin, 1994); and in which multi sources of evidence are used (Yin, 1994; Robson, 1995: p52). It is characterised by the development of detailed, intensive knowledge about a single or small number of cases (Robson, 1995: p40). Case studies also involve an attempt to describe relationships that exist in reality. This reality can be captured in greater detail by an observer-researcher, with the analysis of more variables than is typically possible in experimental and survey research. Case study knowledge is traditionally gathered by collecting evidence through methods such as documentation, archival records, interviews, direct observation, participant observation, and physical artefacts (Yin, 1994: p80). As such, depending on the methods that are used, case studies can involve only qualitative data, only quantitative data, or both types. As demonstrated in following section, the combination of data types can be highly synergistic. Finally, case studies can be used to accomplish various aims, e.g. (i) to provide description, (ii) to test a theory, (iii) to generate a theory, and (iv) to explore a phenomenon (Eisenhardt, 1989).

Similar to surveys, depending on the purpose of the research, different forms of case studies can be conducted, namely exploratory, explanatory, and descriptive (Robson, 1995). Case studies can be designed according to different types in order to fulfil the particular

requirements of each enquiry proposed. *Figure A-1* presents two different taxonomies of case study types.

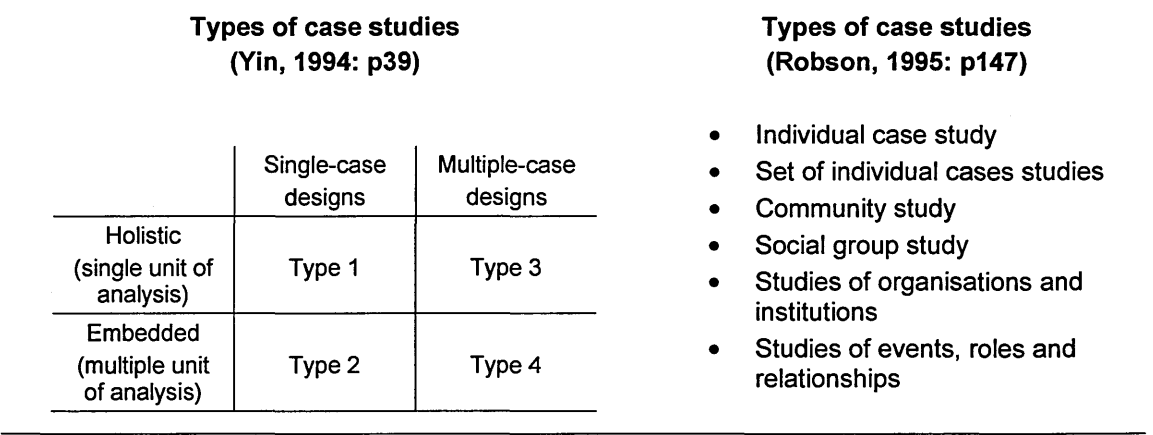


Figure A-1: Types of case studies

Despite their extensive application in research, there are some general criticisms of case studies. One argument is that case studies are often sloppy investigations where equivocal evidence or biased views influence the direction of findings and conclusions (Yin, 1994). However, bias can reduce the quality of any research, and case study quality and reliability can be high if the case is carried out following a stringent methodology (Yin, 1994). Case studies can be considered weak because they are typically restricted to a single organisation (or small number), and results are difficult to generalise because it is difficult to find similar cases with similar data that can be analysed in a statistically meaningful way. Here, Yin (1994: p39) refers to four types of designs for case studies, where they can be constructed in a way that generalisation can be increased. An additional weakness commonly referred to with case study is its representation, namely that is too long and cannot be readily analysed. Yin (1994) counters that it is a question of the presentation format and structure and that cases can be described in an acceptable length.

A.4.3 Experiment Strategy

The experiment strategy is characterised by enabling the researcher to systematically test theories and hypotheses. It permits precise relationships to be identified between a small number of variables by measuring the effects of manipulating one variable on another variable though hypothesis testing (Gill and Johnson, 1991: chp4). Experiments are done when a researcher can manipulate behaviour directly, precisely, and systematically (Yin, 1994: p8). Furthermore, experiments can either be laboratory or field. Laboratory experiments are conducted via a designed laboratory situation using quantitative analytical techniques with a view to making generalisable statements applicable to real-life situations.

Field experiments extend laboratory experiments into real organisations, thereby achieving greater realism. Experiments are only feasible if the researcher has control over events (Robson, 1995: p44), and so the control that this strategy achieves in the setting is an advantage over all other research strategies.

A.4.4 Action Research Strategy

Action research is a form of applied research where the researcher attempts to develop results or a solution that is of practical value to the people with whom the research is working, and at the same time developing theoretical knowledge (Dick, 2003). It is a strategy that attempts to apply the principles of the true experiment in a natural setting (Gill and Johnson, 1991). It is also characterised as being an iterative process involving researchers and practitioners acting together on a particular cycle of activities, including problem diagnosis, action intervention, and reflective learning (Avison *et al.*, 1999). Through direct intervention in problems, the researcher wants to try out theory with practitioners in real situations, gain feedback from this experience, modify the theory as a result of this feedback, and try it again. Each iteration of the action research process adds to theory, and so it is more likely to be appropriate for a variety of situations. Action research “aims to transform the social environment through a process of critical enquiry - to act on the world rather than being acted on” (Miles and Huberman, 1994) and involves close involvement of the researcher with the participants. As such, action research is particularly applicable to situations where researchers become involved with organisations in order to help them achieve certain objectives. This involvement enables ‘privileged access’ to data and situations that are normally not easily accessible to the basic researcher (Clark, 1972, p22).

Despite some researchers positioning action research as a subset of case study research (*e.g.* Benbasat *et al.* 1987), there are significant differences between them. For example, in case study research the researcher is an observer while being an active participant in action research. The purpose of action research is often prescriptive and intervening, while case study tends to be exploratory. Action research also focuses on the research question type ‘how to’ and case study on ‘how’ and ‘why’.

The control of extraneous variables is a problem with action research (Gil and Johnson, 1991) due to the limited ability to set up control groups within a natural environment without interfering with it and thus reducing naturalism. This strategy is also traditionally restricted to a single organisation, and results are difficult to generalise because different researchers may interpret events differently (Whyte, 1991). Moreover, the personal ethics of the researcher are critical, since the opportunity for direct researcher intervention is

always present (Jenkins, 1985). Action research has also been criticised for its lack of systematic methods (Robson, 1995).

A.5 Data Collection Methods

A.5.1 Interviewing

Interviewing as a research method typically consists of a conversation (Kvale, 1996) for a specific purpose, involving the researcher(s) asking questions and the respondents answering (Rubin and Rubin, 1995). This method is widely used in social research (Robson, 2002: p269) and is commonly taken to be the ‘gold standard’ for qualitative research (Silverman, 1999: p291-292). According to Robson (2002: p271), in circumstances where individual perceptions of a process within a social unit (such as a work-group, department or whole organization) are to be studied prospectively, qualitative research interviews are the most appropriate. Wengraf (2001) argues that the interviews are designed for the purpose of improving knowledge and for going into matters in depth.

Interviews are particularly suitable for establishing what is in and on someone else’s mind and to find out those things that cannot be directly observed (Patton, 1987). According to Robson (2002: p272), the interviews are a flexible and adaptable method that have the potential of providing rich and highly illuminating material. Moreover, it is possible to modify the line of enquiry, follow up interesting responses and investigate underlying motives in a way that other self-administered questionnaires cannot. However, this might lead to the discussion of subjects less relevant for the research, which would consume precious time within the interview. Furthermore, the lack of standardisation raises concerns about reliability, while biases are difficult to rule out (Robson, 2002: p273). The fact that interviewing is time consuming also means it could lead to a reduction in the number of persons willing to participate, which might in turn lead to biases in the sample selected.

Interviews are commonly face-to-face (individual or group), but the telephone is increasingly being used because of the savings in time and resources it permits. Telephone interviews need to be conducted if interviewees are widely dispersed. Although face-to-face interviews are more expensive and time consuming, the ‘richness’ of the communication that is possible is much higher (Gillham, 2000a: p62). In addition, responsiveness and reflexivity are among the most important features of telephone interviews, but without the cost of setting individual meetings (Gillham, 2000a: p77). Regarding the process of inquiry, the researcher must address how much structure should be included. The researcher primarily has available three styles of interview structures, namely (i) structured, (ii) semi-structured, and (iii) unstructured (*Table A-2*).

Interview Type	Features
Unstructured <ul style="list-style-type: none"> • Oral or life history interviews • In-depth interviews • Clinical interviews • Group interviews 	Application <ul style="list-style-type: none"> • Qualitative research, e.g. cases study • When collecting interviewee's subjective experience • When it is possible to combine with documents and records analysis Key features <ul style="list-style-type: none"> • Takes the form of a free-flowing conversation with little structure • No standard list of questions • Rely heavily on the quality of the social interaction • Difficult to control focus • Traditionally only a few topics are discussed • Interviewer is open to the vagaries of the interviewee's interpretations
Semi-structured <ul style="list-style-type: none"> • Survey interviews • Group interviews • In-depth interviews 	Application <ul style="list-style-type: none"> • Qualitative research, e.g. cases study • When interviewee's perception of reality needs to be collected • When the interviewer has already identified a number of aspects to address • When time for interviewing is limited and interviewer wants key issues discussed Key features <ul style="list-style-type: none"> • Involves mostly open-ended questions • More flexibility and give the chance to collect interviewee's perceptions • Data analysis is more difficult and results harder to evaluate • Predefined question, although modifications are allowed • Interviewee uses his natural language instead of the interviewer concepts • More contact with the interviewee, which increases rapport
<ul style="list-style-type: none"> • Structured • Standardised interviews • Survey interviews • Clinical history taking 	Application <ul style="list-style-type: none"> • Quantitative research, e.g. surveys and options pools • When it is aimed to establish comparisons between different groups • Not suitable to collect feelings, believes or perceptions Key features <ul style="list-style-type: none"> • Same questions are used in every interview and in the same way • Low flexibility, i.e. do not allow to modify questions nor ordering • Most questions are close-ended

Table A-2: Categorisation of forms of interviewing

(after Burns, 2000: p423-426; Robson, 2002; Gillham, 2000a; Hancock, 2002)

A.5.2 Questionnaires

Questionnaires are a method used for getting information from people. They can be used in both mail surveys and interviews (Oppenheim, 1992: p100), although some question formats differ between these two types of data collection (Berdie *et al*, 1986). Moreover, despite questionnaires having their place as one method, they are of most value when used in tandem with other methods (Gillham, 2000b: p1). The model presented in *Figure A-2* shows the process in which the questionnaire can be used, and specifies the different players within the process together with their roles.

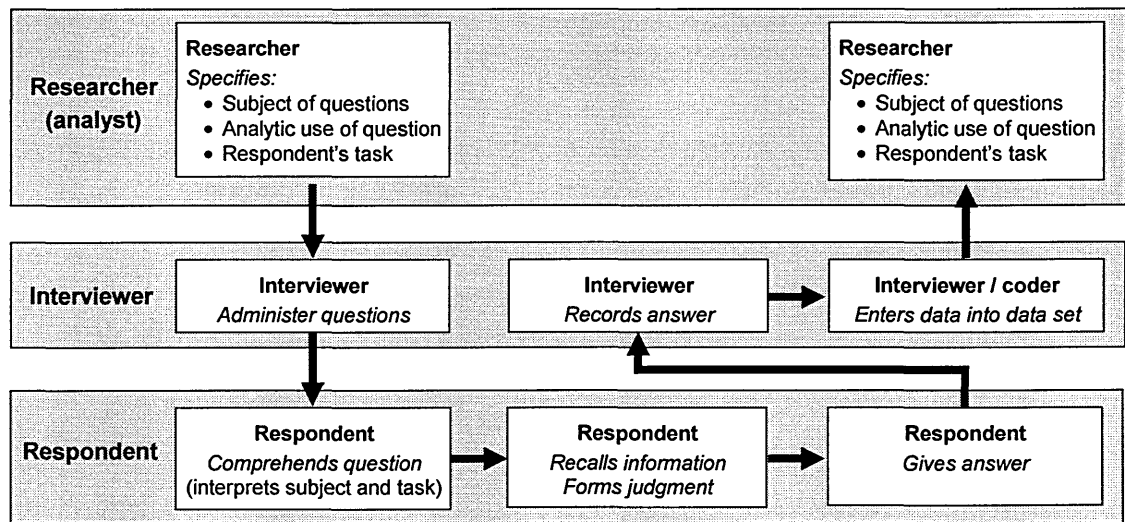


Figure A-2: Model for data collection
(after Czaja and Blair, 1996: p53)

Establishing the specifications of the questionnaire is the first phase of the process. This includes doing some planning and background reading, and defines the enquiry objectives from which results a conceptual framework. This is followed by the questionnaire design. Although each questionnaire has its particular purposes and problems, it is possible to present some general considerations that are common to most questionnaire designs (see for example Oppenheim, 1992: p101):

Questionnaires can include open (open-ended) and closed (close-ended) questions. Closed questions are those where possible answers are predetermined, *i.e.* respondents have to select one of the options. Although these questions allow less freedom of expression and can induce respondents, they are easy and quick to answer, analyse and, compute. Most questionnaires and structured interviews are composed entirely of closed-questions (Gillham, 2000b: p5). Open-questions are not followed by any kind of choice, and have to be answered in full. This approach is an easy way to ask for information, and respondents can qualify and clarify responses. However, they are more difficult to answer and analyse. Moreover, although open-questions can lead to a greater level of discovery, their number and kind has to be restricted to justify the ‘cost’ (Gillham, 2000b: p5).

One needs to compare key features, advantages and disadvantages of each method when selecting a suitable approach(es) to data collection. Table A-3 summarise some advantages and disadvantages of questionnaires.

Advantages	Disadvantages
<ul style="list-style-type: none"> • Data is easy to analyse • Low cost in time and money • Easy to get information from a lot of people quickly • Respondents can do it at their convenience • Lack of interview bias • Respondents' anonymity 	<ul style="list-style-type: none"> • The element of discovery is much reduced • Problems with data quality (completeness & accuracy) • Typically low response rate • Questions need to be simple and brief • Misunderstanding cannot be corrected • Assumes respondents have answers available

*Table A-3: Questionnaire advantages and disadvantages
(after Gillham, 2000b: 7-9)*

A.5.3 Documents and Records Analysis

Documents and records analysis is one method of data collection that is likely to be relevant to most case study topics (Yin, 1994: p81; Robson, 1995: p159). They include a wide range of written or recorded materials, *e.g.* minutes of meetings, formal studies, and service records. This method is not traditionally used as a main data collection method; rather they are used in conjunction with other sources of information, such as interviews and observation, to corroborate and augment evidence. This increases the internal validity of the research by allowing triangulation of data between multiple sources of evidence to be established. It is important to remember, as sometimes wrongly assumed, that these documents or records might be inaccurate or biased (Burns, 2000: p 467). As such, special care is needed in its selection. Conversely, people tend to be more careful on what they write or record than on what they say, and so documents and records might specify events and issues in greater detail than interviews can (Burns, 2000: p467).

Appendix B

B. ENQUIRY INSTRUMENTS

B.1 Questionnaire Survey

Cover Letter



22/07/2001

Subject: Maintenance survey of failure information

Dear Sir/Madam

I am a PhD student in the Manufacturing Systems Department of Cranfield University, where I am investigating a decision support system for maintenance. The system may be used by maintenance to improve their approach to troubleshooting and to better manage their failure records.

As part of the research, we are conducting a survey among maintenance experts that will address the following issues:

- Relevance of failure history records to assist maintenance;
- Current maintenance trends in managing failure histories;
- Relationship between machine users and vendors with regard to maintenance.

We would like to invite you to participate in this survey. If you feel the enclosed questionnaire addresses some of your concerns please take 10 minutes of your time to complete it. We will send you the results and survey findings and you might be pleasantly surprised with the usefulness of this feedback. Furthermore, you will also have the chance to follow up the research.

This questionnaire is intended for experts involved in the maintenance function (managers, engineers, supervisors, etc.). Moreover, it targets all areas of maintenance expertise across different industries

Therefore, I would appreciate if you could please complete as many questions as you can, and return the questionnaire in the enclosed pre-paid envelope, as soon as possible.

Please notice that your response will be treated in the strictest confidence, and to ensure individual anonymity all findings will be treated under industry sector headings. Further, even after you have submitted the questionnaire if you wish you may ask to withdraw your data from the survey.

Thank you for your collaboration.

Sincerely,

Jorge Juliao

Postal-survey Questionnaire

I. Failure histories - characterisation

Q1	Do you record failure histories from your machine tools?	☐ Yes	☐ No
----	--	------------------------------	-----------------------------

If YES please answer the questions in section A. If NO Please go to section B.

Section A: If you DO collect failure records

Q2	How would you rate the importance of failure history records to assist maintenance function? (1 = not important; 5 = very important)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
----	---	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Q3	Why do you record failure histories from your machines?	
a	To facilitate quicker repair of new failures	☐
c	To analyse failure modes and effects	☐
e	For machine vendor feedback	☐
b	To assist diagnosis of new failures	☐
d	To plan and schedule maintenance activities	☐
f	Other:	

Q4	How long have you been recording failure histories?			
☐ Less than 1 year	☐ 1 – 2 years	☐ 3 – 4 years	☐ 5 – 6 years	☐ Over 6 years

Q5	Do you use a classification system to record failure histories?	☐ Yes	☐ No
----	---	------------------------------	-----------------------------

Q6	From what failures do you record failure histories?	
a	All failures	☐
c	Failures that stop production	☐
e	Failures from complex machines	☐
b	Failures that cause excessive downtime	☐
d	Failures that are difficult to diagnose and repair	☐
f	Other:	

Q7	What type of system do you use for the collection and storage of failure histories?	
a	Paper-based	☐
c	Computer-based	☐
e	Own designed system (e.g. database)	☐
b	Paper and computer	☐
d	Commercial system (e.g. CMMS)	☐
f	Other:	

Q8	How would you rate your data storage system for data retrieval? (1 = very poor; 5 = very good)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
----	---	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Q9	How would you rate your data storage system for data export? (1 = very poor; 5 = very good)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
----	--	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Q10	How often do your maintainers refer to written descriptions of failure histories to solve new problems? (1 = never; 5 = always)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
-----	--	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Section B: If you DO NOT collect failure records

Q11 What are the reasons why you do not record failure histories?

a	You do not see it as useful	☐
b	Data collection is difficult and time consuming	☐
c	You do not have enough failure histories worth collecting	☐
d	Your maintenance management system does not support this type of information	☐
e	Your maintenance management system supports this information but retrieval is difficult	☐
f	Other	

II. Relationship between machine users and vendors

Q12	How do you rate the relationship with your machine vendor concerning assistance with machine maintenance? (1 = very poor, 5 = very good)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
-----	---	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Q13	Do you exchange any failure information with your machine vendor?	☐ Yes	☐ No
-----	---	------------------------------	-----------------------------

Q14	What do you feel that a database of failure histories for machine failures populated by users but vendor managed would benefit your organisation? (1 = not useful, 5 = very useful)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
-----	--	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------

Q15	Would you contribute your failure histories to build such a database?	☐ Yes	☐ No
-----	---	------------------------------	-----------------------------

III. General Questions

Q16	What is your job title?		E.g. maintenance manager			
Q17	What is your industry sector?		E.g. automobile, aerospace			
Q18	What is your industry type?		E.g. engine plant			
Q19	What is your main manufacturing process type?	☐ Process	☐ Mass	☐ Batch	☐ Jobbing	
Q20	What is the number of employees in your company?	☐ Less 50	☐ 50-99	☐ 100-299	☐ 300-499	☐ Over 500

If you would like to receive a copy of the summary report please give one contact

Your personal details it will be only used to communicate with you and never linked to the data.

Name		Address	
Company		Street	
Phone		City	
Fax		Post code	
E-mail		Country	

Manufacturing Systems Department, Cranfield University
Bedford, MK43 0AL UK

J.J.W.

e-mail Survey Questionnaire

MAINTENANCE SURVEY OF FAILURE INFORMATION

This questionnaire is used to evaluate the importance of failure histories to assist maintenance. It assess how failure histories are managed, and relates this to the relationship between machine vendors and users.

The questionnaire is aimed at all areas of maintenance expertise across different industries.

Your response will be treated in the strictest confidence, and to ensure individual anonymity all findings will be treated under industry sector headings

In return for your invaluable contribution to this research you will receive an in-depth report outlining the findings

THANK YOU

I. Failure Histories - characterisation

Q1

Do you record failure histories from your machine tools?

☐ Yes

☐ No

If YES please answer the questions in section A. If NO Please go to section B.

Section A: If you DO collect failure records

Q2

How would you rate the importance of failure history records to assist maintenance function? (1 = not important; 5 = very important)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

Q3

Why do you record failure histories from your machines?

a

To facilitate quicker repair of new failures

☐

b

To assist diagnosis of new failures

☐

c

To analyse failure modes and effects

☐

d

To plan and schedule maintenance activities

☐

e

For machine vendor feedback

☐

f

Other (please enter your comments here)

Q4

How long have you been recording failure histories?

(please click here to select)

Q5

Do you use a classification system to record failure histories?

☐ Yes

☐ No

Q6

From what failures do you record failure histories?

a

All failures

☐

b

Failures that cause excessive downtime

☐

c

Failures that stop production

☐

d

Failures that are difficult to diagnose and repair

☐

e

Failures from complex machines

☐

f

Other (please enter your comments here)

Q7

What type of system do you use for the collection and storage of failure histories?

a

Paper-based

☐

b

Paper and computer

☐

c

Computer-based

☐

d

Commercial system (e.g. CMMS)

☐

e

Own designed system (e.g. database)

☐

f

Other (please enter your comments here)

Q8

How would you rate your data storage system for data retrieval? (1 = very poor; 5 = very good)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

Q9

How would you rate your data storage system for data export? (1 = very poor; 5 = very good)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

Q10

How often do your maintainers refer to written descriptions of failure histories to solve new problems? (1 = never, 5 = always)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

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Section B: If you DO NOT collect failure records

Q11

What are the reasons why you do not record failure histories?

a

You do not see it as useful

☐

b

Data collection is difficult and time consuming

☐

c

You do not have enough failure histories worth collecting

☐

d

Your maintenance management system does not support this type of information

☐

e

Your maintenance management system supports this information but retrieval is difficult

☐

f

Other (please enter your comments here)

II. Relationship between machine users and vendors

To be answered by all respondents

Q12

How do you rate the relationship with your machine vendor concerning assistance with machine maintenance? (1 = very poor, 5 = very good)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

Q13

Do you exchange any failure information with your machine vendor?

☐ Yes

☐ No

Q14

What do you feel that a database of failure histories for machine failures populated by users but vendor managed would benefit your organisation? (1= not useful, 5= very useful)

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

Q15

Would you contribute your failure histories to build such a database?

☐ Yes

☐ No

III. General Questions

Q16

What is your job title?

E.g. maintenance manager

Q17

What is your industry sector?

E.g. automobile, aerospace

Q18

What is your industry type?

E.g. engine plant, assembly plant

Q19

What is your main manufacturing process type?

(please click here to select)

Q20

What is the total number of employees in your company?

(please click here to select)

If you would like a copy of the summary report please give one contact

Your personal details it will be only used to communicate with you and never linked to the data.

Address

Name

Street

Company

City

Phone

Post code

Fax

Country

E-mail

Comments: Please feel free to add any additional information or comments you fell may be useful to this survey research

Thank you for your time and effort

Press the Submit button to return your answer to us

Submit Questionnaire

Clear Questionnaire

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B.2 Questionnaire Guide: interviews of equipment vendors

1. Do you collect failure records from your maintenance servicing experiences and/or customer's experiences?

If YES:

2. How would you rate the importance of failure records to assist maintenance?
(1 – not important; 2 – little importance; 3 – neutral; 4 – important; 5 – very important)
3. Why do you collect failure records?
4. What type of system do you use to manage your failure records?
(1) only computer-based; (2) only paper-based; (3) both systems
Is your computer-based system self-designed or purchased from a vendor?
5. Do you have any criterion to select from which failures are records collected?
6. Do you use a classification system to organise your failure records?
(1) Yes; (2) No
7. How would you rate your overall satisfaction about the system you use to manage failure records?
(1 – very poor; 2 poor; 3 neither poor nor good; 4 good; 5 very good)
8. How would you the utilisation rate of the system you use to manage failure records?
(1 very poor; 2 poor; 3 neither poor nor good; 4 good; 5 very good)
9. What do you like most and less about the system you use to manage failure records?
10. How often do your maintainers refer to written descriptions of failure histories to solve new problems?
(1 very poor; 2 poor; 3 neither poor nor good; 4 good; 5 very good)

If Not:

11. What are the reasons why you do not collect failure records?

Relationship between users and vendors

12. How would you rate the relationship with your equipment customers concerning maintenance assistance?
(1 very poor; 2 poor; 3 neither poor nor good; 4 good; 5 very good)
13. Do you exchange any failure information with your customers?
(1) Yes; (2) No
14. What type of support information do you provide to your customers regarding maintenance assistance?
15. Do you consider customer's experiences when developing the troubleshooting/maintenance manuals?
16. What do you feel that a database of failure records populated by users but vendor managed would benefit your organisation?
(1 not useful; 2 little use; 3 neither useful nor not useful; 4 useful; 5 very useful)
17. Would you contribute your failure records to build such a database?
(1) Yes; (2) No

B.3 Questionnaire Guide: interviews of maintenance managers

PART I

As introduced in the presentation, the aim of this interview is to characterise both your maintenance information systems and maintenance support documentation, regarding troubleshooting assistance.

MAINTENANCE INFORMATION SYSTEM		MAINTENANCE SUPPORT DOCUMENTATION	
Q1. Characterise utilisation/usage _____ ☐			
	Prompts		
	- Utilisation/usage by supervisors/engineers		
	- Utilisation/usage by shop-floor staff		
Q2. Characterise level of satisfaction _____ ☐			
	Prompts		
	- Overall satisfaction		
	- Features you like		
Q3. Indicate problems, causes, effects/consequences _____ ☐			
	Prompts		
Problems	- Situations to improve	Problems	
	- Possible causes for the problems		
	- Effects/consequences of the problems		
Causes	1. Use of MIS to support troubleshooting;	Causes	
	2. Aggregation of maintenance documentation;		
Effects	3. Content of maintenance documentation;	Effects	
	4. Acquisition of failure information;		
	5. Management of failure information		
Q4. Indicate suggestions for improvement _____ ☐			
	Prompts		
Q5. Characterise user involvement in development _____ ☐			
	Prompts		
	- Do your staff participate		
	- Who participates?		
	- How?		
	- Importance		

PART II

This part of the interview aims to evaluate the importance of failure records to assist maintenance.

Q.6	Do you collect failure records from your maintenance experiences?
Q.7	How would you rate the importance of failure records to assist maintenance? (1 – not important; 2 – little importance; 3 – neutral; 4 – important; 5 – very important)
Q.8	Why do you collect failure records?
Q.9	What type of system do you use to manage your failure records? (1) only computer-based; (2) only paper-based; (3) both systems Is your computer-based system self-designed or purchased from a vendor?
Q.10	How would you rate the relationship with your equipment vendor concerning maintenance assistance? (1 very poor; 2 poor; 3 neither poor nor good; 4 good; 5 very good)
Q.11	Do you exchange any failure information with your customers? (1) Yes; (2) No
Q.12	What do you feel that a database of failure records populated by users but vendor managed would benefit your organisation? (1 not useful; 2 little use; 3 neither useful nor not useful; 4 useful; 5 very useful)
Q.13	Would you contribute your failure records to build such a database? (1) Yes; (2) No

B.4 Questionnaire Guide: interviews of CMMS developers

Questionnaire Guide - CMMS Developers

1. Does your CMMS have been designed to assist maintainers during failure troubleshooting?
Comment.

If YES, go to question 2. If NO, go to question 4.

2. Does your CMMS record any of the following types of failure information from past troubleshooting experiences, to cope with failure repairs?

		Yes	No
a	Brief description of the repair action taken (< 5 words)	☐	☐
b	Detailed description of the repair action taken (> 5 words) e.g. troubleshooting step-by-step	☐	☐
c	Identification of who repaired (e.g. owner, manufacture, contractor)	☐	☐
d	Craftspeople trade identification (e.g. mechanic, electrician)	☐	☐
e	Repair location (e.g. on site, repair shop)	☐	☐
f	Spare parts used	☐	☐
g	Special tools used	☐	☐
h	Description of the failure through a 'notes field' free text (location, symptoms, causes, etc)	☐	☐
i	Description of the failure diagnosis through a 'notes field' free text	☐	☐
j	Repair recommendations	☐	☐
k	Description of the operating conditions (when the failure occurred)	☐	☐
l	Description of eventual machine tool changes (compared with the initial stage)	☐	☐
m	Setting of the standards for the good working conditions	☐	☐

3. Does your CMMS records any other information besides the above, to the same purpose?

4. Does your CMMS use any of the following failure attributes to categorise/classify failures?

Location of the failure - identify where the failure is located		Yes	No
a	Equipment location - geographic location of the equipment in the factory	☐	☐
b	Equipment identification - characterises the type of equipment (e.g. manufacturer serial number)	☐	☐
c	Failure location at the equipment level	☐	☐
d	Failure location at the component level	☐	☐

Characteristics of the failure - failure attributes that identify each failure		Yes	No
e	Failure symptoms described at the <u>equipment level</u>	☐	☐
f	Failure symptoms described at the <u>component level</u>	☐	☐
g	Nature of the symptoms (e.g. progressive symptom, temporary symptom)	☐	☐
h	Combination of symptoms (describe more than one symptom)	☐	☐
i	Failure cause - brief description	☐	☐
j	Combination of causes - describe more than one cause	☐	☐
k	Failure nature (e.g. mechanical failure, electrical failure, etc)	☐	☐
l	Failure discovered (e.g. during installation, service, inspection, etc.)	☐	☐
m	Failure reason (e.g. unscheduled or scheduled intervention)	☐	☐

5. Does your CMMS consider any other attribute or characteristic to classify failures?

6. What are the purposes of the failure classification system?

7. Could you indicate main causes and effects of problems within CMMS development?
What are your suggestions?

Problems	
Causes	
Effects	
Suggestions	

8. Could you provide some background information about your CMMS like manuals, software demo, etc?
9. Would you be interested on being contacted to discuss our findings or for further information?

THANK YOU FOR YOUR TIME.

B.5 Case Studies Instruments

1. Repair data to support troubleshooting

The aim of this section is to evaluate what are the most repair data from experiences of failure troubleshooting to be included in the failure records, in order to facilitate the repair of new failures (troubleshooting). Therefore, we would like you to rate the following pieces of information.

Repair actions		Very poor			Very good		
a	Brief description of the repair actions	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
b	Detailed description of the repair actions	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
c	Step-by-step repair actions	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
d	Repair recommendations	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
e	Repair actions that were not successful	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
f	Repair duration	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
Resources							
g	Identification of who performed the job (e.g. owner, manufacture, contractor)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
h	Worker trade identification and number (e.g. mechanic, electrician)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
i	Repair location (e.g. on site, repair shop)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
j	Spare parts needed	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
k	Special tools needed	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
l	Materials needed	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
General							
m	Description of the failure diagnosis (how failures were diagnosed)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
n	Failure cause(s)1(brief description)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
o	Failure effects (brief description)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
p	Failure nature (e.g. mechanical, electrical)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
q	Failure consequences (brief description)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
r	Failure criticality	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
s	Method of observation (indication of the method used to detect the failure)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
u	Operating conditions (when the failure occurred)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
v	Eventual machine tool changes (compared with the initial stage)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
x	Standards settings for good working conditions	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	
	Other:	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	

2. Failure attributes to classify failure records

The aim of this section is to evaluate what are the most relevant failure attributes to identify and classify failure records. The main objective of the classification is to facilitate maintainer's access to experiences about past failure-troubleshooting. Therefore, according to your experience we would like you to rate the following failure attributes.

Equipment identification – identify the equipment that has a failure		Very poor					Very good				
a	Equipment location (geographic location of the equipment in the factory)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
b	Equipment identification (e.g. equipment type, serial number, vendor ID)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
Failure location – locate the failure within the equipment											
c	Failure location at equipment level	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
d	Failure source (lowest level item to which the failure can be isolated)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
	Other:	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
Failure description – brief description of what the failure exhibited and caused											
e	Failure symptom(s) described at the lowest level the failure can be isolated	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
f	Failure symptom(s) described at the equipment level	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
g	Nature of the symptoms (e.g. progressive symptom, temporary symptom)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
h	Failure effect (consequence of a failure mode in terms of the operation)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
i	Combination of symptoms (multi-symptoms)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
		☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
General											
j	Failure cause(s) (circumstances that have led to the failure)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
k	Failure consequence(s) (in what way each failure matters)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
l	Failure nature (e.g. mechanical failure, electrical failure, etc)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
m	Failure discovered (e.g. during installation, service, inspection, etc.)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
n	Failure reason (e.g. unscheduled or scheduled intervention)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
o	Work order number	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
	Other:	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					
	Other:	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5					

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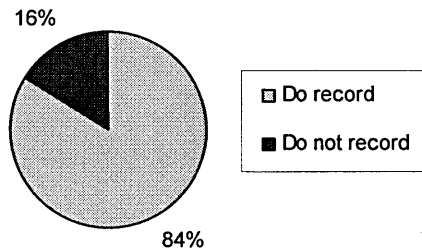
Appendix C

C. ENQUIRY RESULTS

C.1 Results of the Questionnaire Survey of Maintenance Practitioners

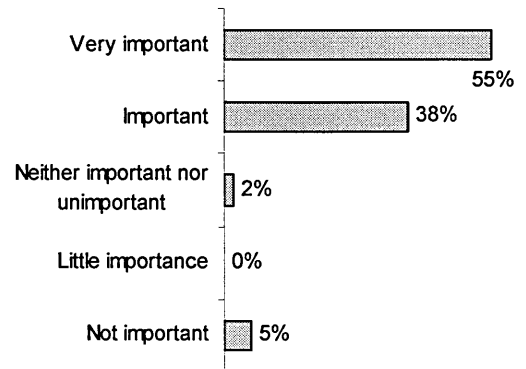
Question 1: Do you record failure histories from your machine tools?

	Nr.	%
Replies	111	
Responses	111	100%
Yes	93	84%
No	18	16%



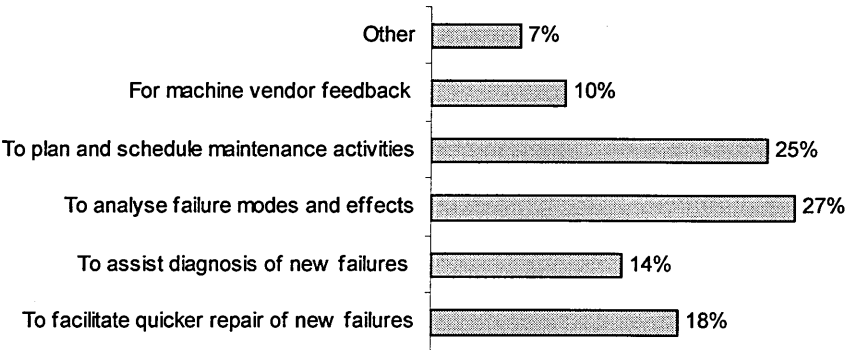
Question 2: How would you rate the importance of failure history records to assist maintenance function?

	Nr.	%
Replies	111	
Responses	93	84%
Not important	5	5%
Little importance	0	0%
Neither important nor unimportant	2	2%
Important	35	38%
Very important	51	55%



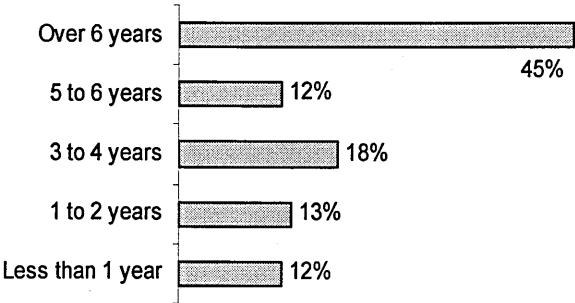
Question 3: Why do you record failure histories from your machines?

	Nr.	%
Replies	111	
Responses	93	84%
Quick repair	44	18%
Assist diagnosis	34	14%
Analyse failure modes & effects	65	27%
Plan & schedule maintenance	60	25%
Feedback to vendor	24	10%
Other	16	7%
Total number of answers (all options)	243	



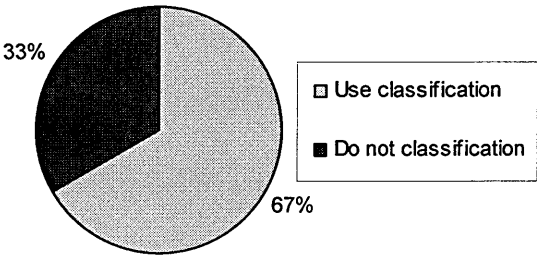
Question 4: How long have you record failure histories?

	Nr.	%
Replies	111	
Responses	93	84%
Less than 1 year	11	12%
1 to 2 years	12	13%
3 to 4 years	17	18%
5 to 6 years	11	12%
Over 6 years	42	45%



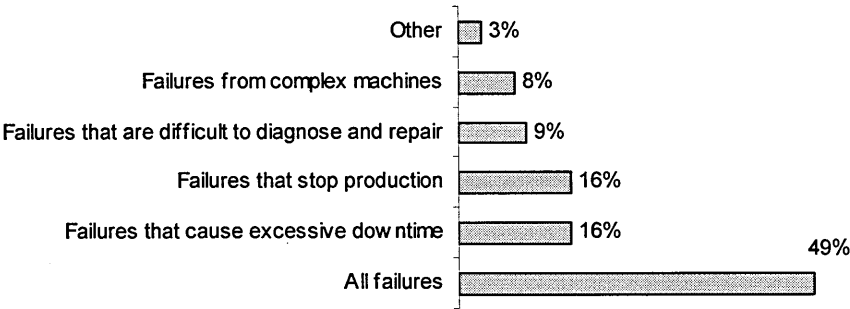
Question 5: Do you use a classification system to record failure histories?

	Nr.	%
Replies	111	
Responses	93	84%
Yes	62	67%
No	31	33%



Question 6: From what failures do you record failure histories?

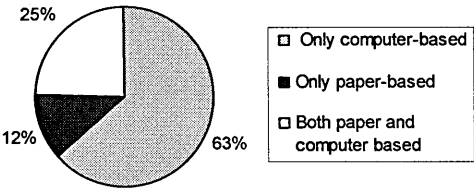
	Nr.	%
Replies	111	
Responses	93	84%
All failures	63	49%
Failures that cause excessive downtime	20	16%
Failures that stop production	20	16%
Failures that are difficult to diagnose and repair	12	9%
Failures from complex machines	10	8%
Other	4	3%
Total number of answers (all options)	129	



Question 7: What type of system do you use for the collection and storage of failure records?

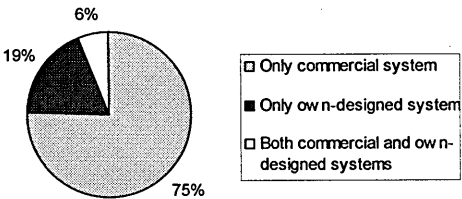
Computer-based system vs paper-based system

	%
Responses	84%
Only computer-based	63%
Only paper-based	12%
Both paper and computer based	25%



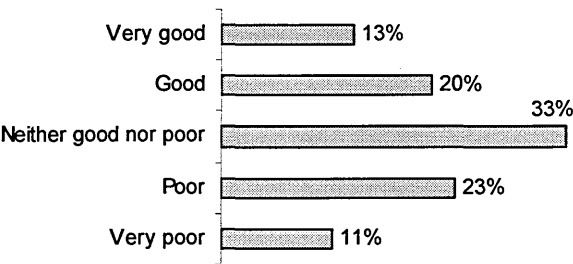
Commercial system vs own-designed system

	%
Responses	84%
Only commercial system	63%
Only own-designed system	12%
Both commercial and own-designed systems	25%



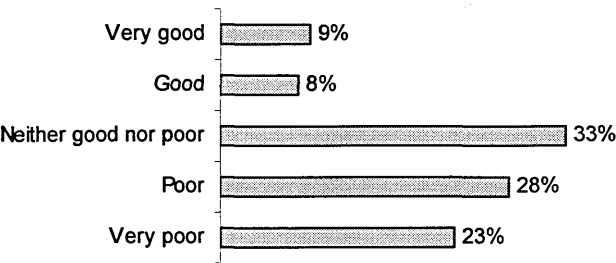
Question 8: How would you rate your data storage system for data retrieval?

	Nr.	%
Replies	111	
Responses	93	84%
Very poor	10	11%
Poor	21	23%
Neither good nor poor	31	33%
Good	19	20%
Very good	12	13%



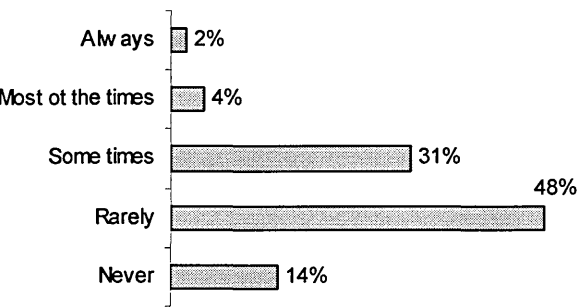
Question 9: How would you rate your data storage system for data export?

	Nr.	%
Replies	111	
Responses	93	84%
Very poor	21	23%
Poor	26	28%
Neither good nor poor	31	33%
Good	7	8%
Very good	8	9%



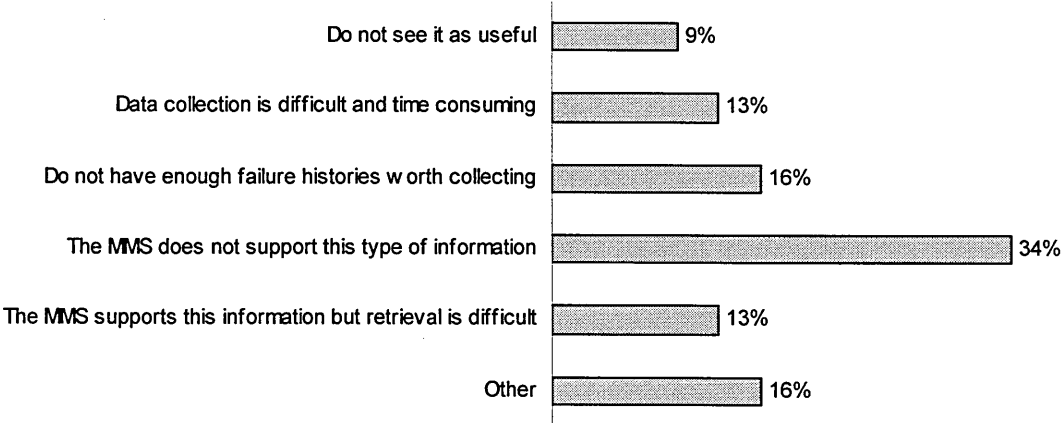
Question 10: How often do your maintainers refer to written descriptions of failure histories to solve new problems?

	Nr.	%
Replies	111	
Responses	93	84%
Never	13	14%
Rarely	45	48%
Some times	29	31%
Most of the times	4	4%
Always	2	2%



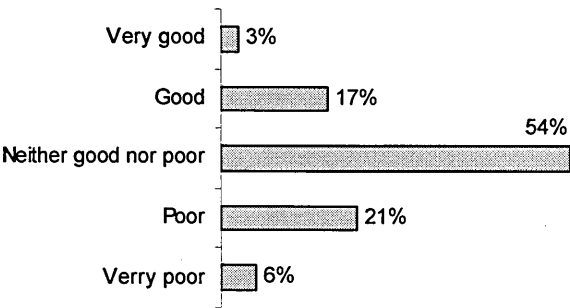
Question 11: What are the reasons why you do not record failure histories?

	Nr.	%
Replies	111	
Responses	18	16%
Do not see it as useful	3	9%
Data collection is difficult and time consuming	4	13%
Do not have enough failure histories worth collecting	5	16%
The maintenance management system does not support this type of information	11	34%
The maintenance management system supports this information but retrieval is difficult	4	13%
Other	5	16%
Total number of answers (all options)	32	



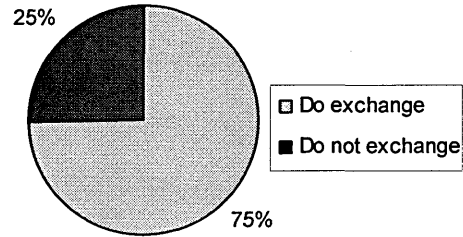
Question 12: How do you rate the relationship with your machine vendor concerning assistance with machine maintenance?

	Nr.	%
Replies	111	
Responses	109	98%
Very poor	6	6%
Poor	23	21%
Neither good nor poor	59	54%
Good	18	17%
Very good	3	3%

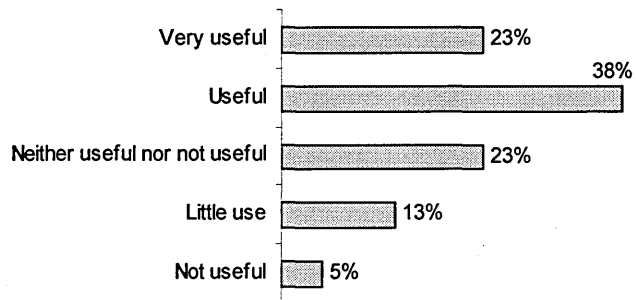


Question 13: Do you exchange any failure information with your machine vendor?

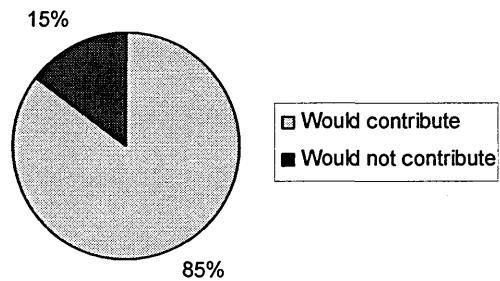
	Nr.	%
Replies	111	
Responses	111	100%
Yes	83	75%
No	28	25%

**Question 14: What do you feel that a database of failure histories for machine failures populated by users but vendor managed would benefit your organisation?**

	Nr.	%
Replies	111	
Responses	111	100%
Not useful	5	5%
Little use	14	13%
Neither useful nor not useful	25	23%
Useful	42	38%
Very useful	25	23%

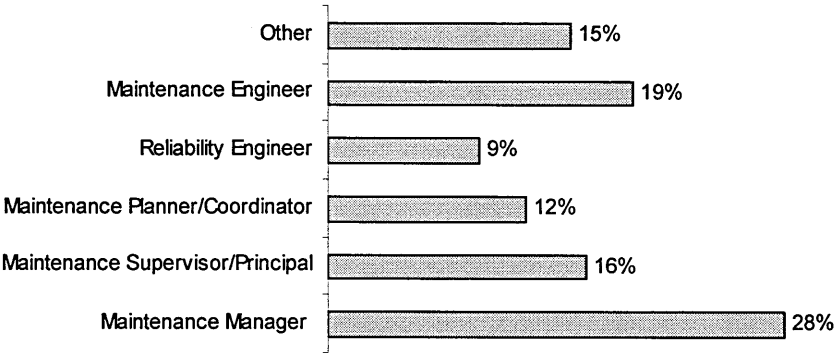
**Question 15: Would you contribute your failure histories to build such a database?**

	Nr.	%
Replies	111	
Responses	109	98%
Yes	93	85%
No	16	15%



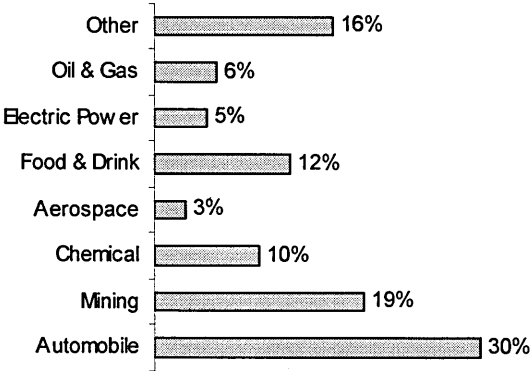
Question 16: What is your job title?

	Nr.	%
Replies	111	
Responses	106	94%
Maintenance Manager	30	28%
Maintenance Supervisor/Principal	17	16%
Maintenance Planner/Coordinator	13	12%
Reliability Engineer	10	9%
Maintenance Engineer	20	19%
Other	16	15%



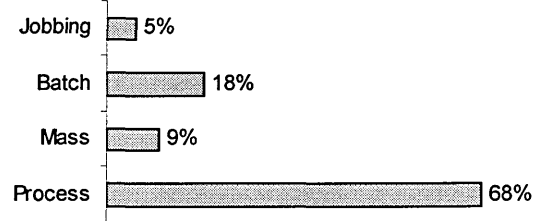
Question 17: What is your industry sector?

	Nr.	%
Replies	111	
Responses	105	93%
Automobile	31	30%
Mining	20	19%
Chemical	10	10%
Aerospace	3	3%
Food & Drink	13	12%
Electric Power	5	5%
Oil & Gas	6	6%
Other	17	16%

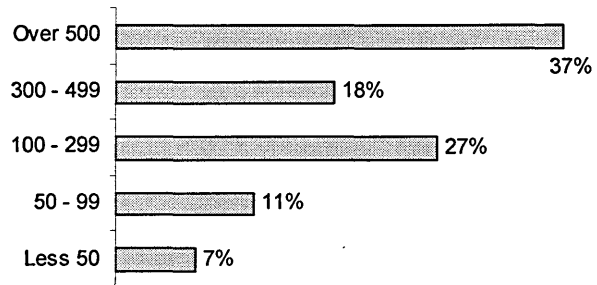


Question 19: What is your main manufacturing process type?

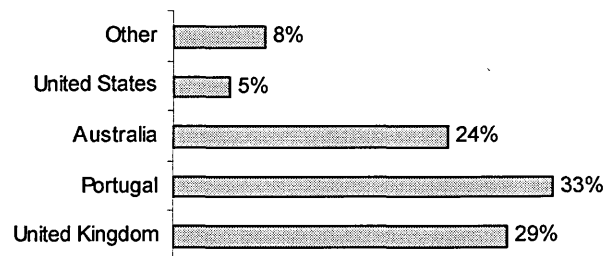
	Nr.	%
Replies	111	
Responses	96	85%
Process	65	68%
Mass	9	9%
Batch	17	18%
Jobbing	5	5%

**Question 20: What is the total number of employees in your company?**

	Nr.	%
Replies	111	
Responses	105	93%
Less than 50	7	7%
50 - 99	12	11%
100 - 299	28	27%
300 - 499	19	18%
Over 500	39	37%

**Which country are you from?**

	Nr.	%
Replies	111	
Responses	99	88%
United Kingdom	7	7%
Australia	12	11%
Portugal	28	27%
Other	19	18%



C.2 Results of the Interviews of Equipment Vendors

Question 1: Do you record failure histories from your machine tools?

Question 2: How would you rate the importance of failure history records to assist maintenance function?

	Nr.
Replies	7
Responses	7
Yes	6
No	1

Question 1

	Nr.
Replies	7
Responses	6
Not important	0
Little importance	0
Neither important nor unimportant	0
Important	2
Very important	4

Question 2

Question 3: Why do you record failure histories from your machines?

Question 4: How long have you been recording failure histories?

	Nr.
Replies	6
Responses	6
Improve machines reliability	6
Control and management purposes	6
Downtime control/analysis	4
Assist maintenance servicing	3
Provide better service to customers	4

Question 3

	Nr.
Replies	6
Responses	6
Less than 1 year	0
1 to 2 years	0
3 to 4 years	0
5 to 6 years	0
Over 6 years	6

Question 4

Question 5: Do you use a classification system to record failure histories?

Question 6: From what failures do you record failure histories?

	Nr.
Replies	6
Responses	6
Yes	4
No	2

Question 5

	Nr.
Replies	6
Responses	6
All failures	6

Question 6

Question 7: What type of system do you use for the collection and storage of failure records?

	Nr.
Responses	6
Only computer-based	1
Only paper-based	0
Both paper and computer based	5

Computer-based system vs paper-based system

	Nr.
Responses	6
Only commercial system	4
Only own-designed system	2
Both commercial and own-designed systems	0

Commercial system vs own-designed system

Question 8: How would you rate your data storage system for data retrieval?

Question 9: How would you rate your data storage system for data export?

	Nr.
Replies	6
Responses	6
Very poor	1
Poor	1
Neither good nor poor	4
Good	0
Very good	0

Question 8

	Nr.
Replies	6
Responses	6
Very poor	0
Poor	4
Neither good nor poor	2
Good	0
Very good	0

Question 9

Question 10: How often do your maintainers refer to written descriptions of failure histories to solve new problems?

Question 11: What are the reasons why you do not record failure histories?

	Nr.
Replies	6
Responses	6
Never	1
Rarely	2
Some times	3
Most of the times	0
Always	0

Question 10

	Nr.
Replies	6
Responses	0

Question 11

Question 12: How do you rate the relationship with your customer concerning assistance with machine maintenance?

Question 13: Do you exchange any failure information with your customers?

	Nr.
Replies	6
Responses	6
Very poor	0
Poor	0
Neither good nor poor	1
Good	5
Very good	0

Question 12

	Nr.
Replies	6
Responses	6
Yes	6
No	0

Question 13

Question 14: What do you feel that a database of failure histories for machine faillores populated by users but vendor managed would benefit your organisation?

Question 15: Would you contribute your failure histories to build such a database?

	Nr.
Replies	6
Responses	6
Not useful	0
Little use	0
Neither useful nor not useful	0
Useful	1
Very useful	5

Question 14

	Nr.
Replies	6
Responses	6
Yes	6
No	0

Question 15

C.3 Results of the Interviews of Maintenance Managers

Question 1 & Question 2

Utilisation and satisfaction of MIS and MD in troubleshooting assistance

Issues of Q1 & Q2		Companies								
		A	B	C	D	E	F	G	H	I
I1	[Q1] Utilisation by maintenance supervisors/engineers									
	Maintenance information system	4	3	4	4	3	4	4	3	4
	Maintenance documentation	3	2	4	3	2	3	-	2	3
I2	[Q1] Utilisation by maintenance technicians/shop-floor									
	Maintenance information system	3	3	3	3	2	2	3	2	2
	Maintenance documentation	2	2	3	2	2	2	-	2	3
I3	[Q2] Overall satisfaction									
	Maintenance information system	3	2	3	3	2	2	3	2	2
	Maintenance documentation	3	3	4	3	2	3	-	3	4
I1; I2	1 = <i>Never</i> ; 2 = <i>Rarely</i> ; 3 = <i>Sometimes</i> ; 4 = <i>Often</i> ; 5 = <i>Always</i> ; (-) = do not know or no answer									
I3	1 = <i>very low</i> ; 2 = <i>low</i> ; 3 = <i>medium</i> ; 4 = <i>high</i> ; 5 = <i>very high</i> ; (-) = do not know or no answer									

Question 3&4

Issue 1: Use of MIS to support troubleshooting

<i>Problem Description</i>
<ul style="list-style-type: none"> • Although MIS collect troubleshooting information, their main purpose is to provide direct support to maintenance technicians during troubleshooting. • MIS are complex and not user friendly, particularly for maintenance technicians to use. • Maintenance technicians not trained enough to use MIS.
<i>Effects</i>
<ul style="list-style-type: none"> • The level of complexity of MIS is so high that users lose interest and spend more time to understand the system than to get information. Consequently, maintenance technicians are not motivated to refer to the MIS to support troubleshooting. • Maintenance technicians tend to use their own experience and skills to solve problems rather than referring to MIS. • Difficult to access and manipulate specific information to support troubleshooting; getting the right information is time consuming. • Much training of maintenance technicians is needed for them to use the MIS.
<i>Causes</i>
<ul style="list-style-type: none"> • MIS are not being designed to provide direct support to maintenance technicians during troubleshooting. MIS are more oriented to assist preventive, accounting, and administrative activities. • IT experts who develop MIS do not have sufficient maintenance experience and rarely efficiently collect user requirements. • Lack of contact between developers and end-users.
<i>Suggestions</i>
<ul style="list-style-type: none"> • Add new features to the MIS that make them more self-orientated to support troubleshooting and easy to use by maintenance technicians. • In order to meet specific needs, user requirements should be integrated in the new MIS development, <i>i.e.</i> practitioners should have more interaction in MIS development; only at a level that they can understand. • Make MIS easier to use and with a shallower learning curve.

Question 3&4

Issue 2: Aggregation of maintenance documentation

Problem Description
<ul style="list-style-type: none"> • Lack of aggregation in maintenance documentation. Troubleshooting information is dispersed through diversity of locations and of document types (not aggregated in a single place). • Most maintenance documentation is still paper-based. • Maintenance documentation is commonly difficult to access; time consuming to find specific information to support troubleshooting. • MIS generally do not provide an efficient way of linking the different type of MD that simplifies their utilisation for troubleshooting.
Effects/Consequences
<ul style="list-style-type: none"> • Maintenance technicians not motivated to use MD; they only refer to MD if they fail to solve the problem, if the problem is too specific, or if they do not have previous experience on a particular problem. • Commonly, maintenance documentation is physically based away from the work place of maintenance technicians (poor portability).
Causes
<ul style="list-style-type: none"> • Aggregation of documents and cross-references between documents and pieces of information are difficult due to the paper-based nature of most documents. • Maintenance documentation provided by different sources (e.g. equipment vendors and design room), and in different formats (e.g. paper and digital). The diversity of documents and of the existence of multiple formats limits aggregation. • Difficult to integrate maintenance documentation in the MIS.
Suggestions
<ul style="list-style-type: none"> • If all maintenance documentation was digital (electronic), it would be easier to aggregate documents into a single database and establish cross-references between different documents and specific information contained in the documents.

Question 3&4

Issue 3: Content of maintenance documentation

<i>Problem Description</i>
<ul style="list-style-type: none"> • Maintenance manuals: <ul style="list-style-type: none"> ○ Traditionally provided by the equipment vendors and rarely take into account the context in which equipment operates. ○ Constantly quotes to contact the vendor for guidance on troubleshooting. ○ Not all equipment vendors provide maintenance manuals, and same manuals are sometimes designed for more than one piece of equipment. ○ Although they are found useful to support troubleshooting, they are commonly limited to a few 'standard' failures or to regular PM activities. ○ Rarely include tacit knowledge that represents experience of maintenance technicians. • Failure records: <ul style="list-style-type: none"> ○ Are not efficiently designed to collect failure information to support troubleshooting. ○ Work experience in troubleshooting and elimination of failures is traditionally not available, <i>i.e.</i> describing what was found and done is commonly missing in the failure records. ○ Specific information to support troubleshooting difficult to be retrieved. ○ Users do not know exactly what to include in the failure records. • Other documents: <i>e.g. operation manuals, equipment manuals and drawings</i> <ul style="list-style-type: none"> ○ Although they are found useful to support troubleshooting, they tend to be complex for maint. technicians to use. ○ Not much intuitive to use by maintenance technicians. • Most documents are paper-based.
<i>Effects/Consequences</i>
<ul style="list-style-type: none"> • In general, maintenance documentation is rarely used to support troubleshooting. • Many failures are not efficiently managed because technicians do not refer to maintenance documentation to support troubleshooting. For example, rather than correcting the failure causes, in some cases maintenance technicians correct only the failure symptoms. • Maintenance technicians generally find it time consuming and tedious to search for information in technical manuals.
<i>Causes</i>
<ul style="list-style-type: none"> • Operation conditions of equipment and field experiences are not commonly included in the maintenance manuals because vendors, which generally do not have feedback from end-users, traditionally develop these manuals. • Non-standard failures are those to which maintenance technicians commonly need more support, and those are not traditionally included in the maintenance manuals. • Failure records are not so often used by technicians because specific information on troubleshooting is commonly missing. • Most failure records forms were not initially designed to directly support troubleshooting. • Specific information to support troubleshooting is difficult to be retrieved from failure records because commonly same form is used to collect data to support PM activities, administrative activities, and troubleshooting. • Difficulties finding specific information to support troubleshooting are among the main reasons for the lack of utilisation of maintenance documentation. • Documents like operation and equipment manuals are complex to use by maintenance technicians because they are not exclusively designed to support troubleshooting. • The paper-based nature of most documents makes updates difficult to make and distribute through the users.

Issue 3: Content of maintenance documentation (cont.)**Suggestions**

- Optimise the content of failure records because this information enhances a better understanding of the nature of equipment failures, and is potentially more self-oriented to support troubleshooting and intuitive to use than other type of documentation, e.g. technical manuals. An important statement was "experience is an important element of maintenance technician's competencies in finding the reason for an accurate malfunction".
- Link/integrate troubleshooting information from maintenance manuals, failure records, and other documents.
- Encourage the collection of experiences of past failures. The collection of this information facilitates knowledge transfer from experienced technicians to novices and less experienced technicians. Moreover, it provides guidance on troubleshooting, avoids solving problems by "guessing", and increases self-confidence. Particularly of novices that are commonly afraid of failing.
- Encourage maintenance technicians to write their failure experiences and find a strategy to overlap the fear of technicians representing and sharing their knowledge. They are afraid this would replace people.
- Identify a structure for problem solving that can be used to represent/write the troubleshooting experiences.

Question 3&4**Issue 4: Acquisition of failure information****Problem Description**

- Acquisition of failure information (data collection) is time consuming and expensive.
- Maintenance technicians not motivated to write failure records.
- Experimental knowledge acquired by technicians with experience and training is difficult to "extract" from technician's heads. In general, maintenance technicians fail to provide clear and sufficient information about problems they experience, because this knowledge is unstructured and intuitive
- The identification of failures traditionally suffers from lack of description.
- Do not know how much data needs to be collected and best method to get data from field.
- Many forms and spreadsheets floating around that are making it hard to get consistent data.
- Maintenance technicians are more comfortable using spreadsheets (paper-based).

Issue 4: Acquisition of failure information (cont.)

<i>Effects/Consequences</i>
<ul style="list-style-type: none"> • Lack of failure information/data; although some interviewees reported that more data is collected that it is really needed or used. • With paper-based documents, maintenance technicians often update their own copies, which are kept in their possession and not share with others. • Failures ill described make difficult the correct identification of failure records. • Detailed reports commonly result in incomplete reports, most fields are not completed. • Tick-boxes are commonly use to reduce to speed and facilitate collection; however it was claimed that they origin less accurate information. On the other hand, written descriptions imply more analysis work. • Unclear and missing information makes difficult both to assign the best person to perform the job, and to provide all resources needed for the job. • Descriptions of problems are particularly difficult to understand when they are done by a person who does not contacted directly with the problem. • Paper-based systems increase time to analyse and validate data.
<i>Causes</i>
<ul style="list-style-type: none"> • The missing experimental knowledge is caused not only by a lack of motivation and time, but also because maintenance technicians fear losing their jobs. • Work pressure limits the time of maintenance technicians to do clerical work (collect data and write reports). • Maintenance technicians are traditionally not motivated to collect data because they commonly do not know exactly why they are collecting data and how they will benefit from it. • One of the causes for unclear and missing information is that problems are often not reported by those who found or dealt directly with the problem; rather, they are reported from a second person who usually has limited knowledge about the problem itself. • Maintenance technicians traditionally are not motivated to collect/write failure records because they do not commonly refer to them and do not see any contribution using them.
<i>Suggestions</i>
<ul style="list-style-type: none"> • Make data collection forms as simple as possible, and minimise requested information to the strictly necessary. • Not to ask for information that technicians might not know. Seek data that will be used and from those directly linked to the job. Separate data to be filled by maintenance technicians (e.g. troubleshooting information) from that by engineers (e.g. reliability data), i.e. identify domains of expertise. • Generate an optimised format to collect and report failure information that facilitates failure identification, speeds response to problems, and can be standardised for most failures. In these forms, data to support troubleshooting and data to assist PM activities, accounting etc needs to be made distinct. Design a system that also suits maintenance technician's needs. • Explain to maintenance technicians why they are collecting data, and how they will benefit from it, in order to increase motivation on data collection. • Failure records are probably the best way to collect part of the expertise of maintenance technicians. • Promote the collection of experiences of past failures because they allow new knowledge to be developed. • Train maintenance technicians in data collection methodologies. • Although spreadsheets are good for data collection, a database is much faster and safer.

Question 3 & 4

Issue 5: Management of failure information

Description
<ul style="list-style-type: none"> Information concerning previous failures is commonly not aggregated or classified in a way that facilitates retrieval and use, particularly by maintenance technicians. Most current classification and coding systems are not creating meaningful results. Majority of companies investigated, "miscellaneous" failures or "failure not listed" were the highest failure types. At a majority of companies, there is the feeling that most collected data is not being used. Many companies collect failure information for many years and most of this information is paper-based, causing storage, portability and search problems. However, there is a tendency to start using electronic documents to manage failure information. Failure information updates from equipment vendors are difficult to integrate with company's records. Tendency to classify failure records using only equipment attributes, <i>i.e.</i> failure records are assigned with an equipment code, which is then associated with a repair code. The large amount of failure information makes it difficult to identify failures.
Effects/Consequences
<ul style="list-style-type: none"> Due to difficulties retrieving failure information from records, maintenance technicians generally find it time consuming and tedious to search for failure information; this leads to a lack of use of failure information in troubleshooting support. Difficulty handling collected data is one of the causes for the feeling that more data is being collected than is used. The equipment code classification of failure information makes it difficult to relate similar failures from different equipment types, and to extract precise information from equipment with an extensive number of records. Using the equipment code classification, too many records are pulled out when the equipment code is introduced, and maintenance technicians receiving too much information begin to ignore it.
Causes
<ul style="list-style-type: none"> Although attempts have been made to develop systems to classify and code failure information, to be used to support troubleshooting, most respondents claimed that no efficient way has been found yet. The main question appears to be "How to classify and organise failure information?" Failure records, when organised, are classified using mainly equipment attributes, <i>i.e.</i> failure records tend to be classified using equipment codes. This equipment-code classification is characterised as inflexible and limited regarding the access to failure records. At most companies electronic documents are being managed as paper-based documents, <i>i.e.</i> documents are simply placed in folders without links or cross-references that facilitate the retrieval of troubleshooting information, and not merged into a single database. Most maintenance technicians are experienced field personnel that have great technical experience but little IT experience, <i>i.e.</i> computer skills and database knowledge. This lack of IT skills causes problems retrieving failure information to support troubleshooting. Failure information is difficult to retrieve from records because of deficiencies in the way failures are described. Maintenance technicians describe each failure in their own way, commonly use a long and single paragraph, and use particular nomenclature. This process limits the identification of failures.

Issue 5: Management of failure information (cont.)

Suggestions

- The development of an optimised system to classify failure records would facilitate access to experiences of past failures, which potentially would make failure troubleshooting more efficient.
- Integrating all failure records into a single database classified according to a structure that links (relates) similar failures from different types of equipment, and be intuitive to use by maintenance technicians.
- Development of a classification structure to identify failures and categorise failure records based on equipment attributes and failure attributes to establish cross-references between the different types of maintenance documentation. The failure attributes should reflect what maintenance technicians see, hear and feel when failure occurred, e.g. failure symptoms and failure source.
- Use categories for similar equipment and failure types to classify failure records.
- Code the failure description to facilitate the identification of failures.
- Analyse how maintenance technicians describe/characterise failures in order to identify attribute classes of failures.
- Provide more IT training for maintenance technicians.
- Investment in IT towards electronic documentation, since searching is easier with electronic documents than it is with paper documents.
- Supervisors must validate failure information before entry into the system.
- Development of an on-line-support system (help-desk) based on failure records would provide quick diagnosis and preparation for corrective activities.
- All interviewees recognised that failure records are probably the most important maintenance document type to support troubleshooting. Efficient management of this information could be of considerable use in achieving a better decision-making environment for troubleshooting

Question 5

End-user involvement in MIS and MD development

<i>Problem Description</i>
<ul style="list-style-type: none"> • Involvement of maintenance technicians in MIS and MD development is generally non-existent. • Involvement of maintenance engineers and supervisors in MIS development is generally low. However, their involvement is higher in MD development. • Managers are most involved in MIS development. • End-user requirements are generally not considered in MIS and MD development.
<i>Effects/Consequences</i>
<ul style="list-style-type: none"> • Low utilisation rate of MIS and MD by end-users during failure troubleshooting. • Systems often fail to meet end-user needs. • Large amount of data is collected but not used, while potentially useful data is missed.
<i>Causes</i>
<ul style="list-style-type: none"> • The level of involvement in the MIS development by end-users is traditionally low or non-existent because MIS are commonly purchased from a vendor, which, with a few exceptions, do not collect end-user requirements. • Since MD tends to be self-developed, end-user participation is higher than for the MIS. • An <i>ad hoc</i> approach tends to be used to collect end-user requirements. The absence of a structured process to collect and analyse end-user requirements is one of the causes of the low involvement in systems development. • It is difficult to arrange the right timings for developers and end-users to meet and discuss systems development. • The non-collection of user requirements is viewed as a primary reason for the lack of functionality of systems when supporting troubleshooting.
<i>Suggestions</i>
<ul style="list-style-type: none"> • Most interviewers believed maintenance technicians would be more enthusiastic about using the system if they were directly involved in its development. • Input user requirements in systems specifications. • End-users should have more interaction in systems development, and their participation should be encouraged and allowed. • Definition of a structured process to guide the collection and analysis end-user requirements that specify the stages to gather and analyse data. • Brainstorming sessions were indicated as the most suitable method to collect end-user requirements. Questionnaires were also suggested.

C.4 Results of Case studies

C.4.1 Questionnaire results

1. Repair data		Compay A				Company B						Company C					
Repair Actions																	
a	Brief description of the repair actions	4	5	5	4	4	5	5	5	5	5	4	5	3	5	5	
b	Detailed description of the repair actions	5	3	4	5	5	4	4	4	4	4	5	4	3	4	4	
c	Step-by-step repair actions	5	5	4	5	4	5	5	5	5	5	3	5	5	5	5	
d	Repair recommendations	5	5	5	5	5	5	5	5	5	5	4	4	5	5	5	
e	Repair actions that were not successful	3	2	2	3	4	3	3	3	4	3	4	3	2	3	3	
f	Repair duration	3	2	1	2	4	3	3	3	2	3	4	3	1	3	3	
Resources																	
g	Identification of who performed the job	4	3	4	3	5	3	2	3	2	3	4	2	2	3	3	
h	Worker trade identification and number	5	4	5	4	5	4	5	5	3	4	5	4	4	5	5	
i	Repair location	4	3	4	3	5	3	4	4	3	4	4	2	3	3	2	
j	Spare parts needed	5	4	5	5	5	4	5	5	3	4	5	3	5	5	4	
k	Special tools needed	5	4	5	5	5	5	4	5	3	3	5	3	4	5	5	
l	Materials needed	5	4	5	4	5	4	3	4	3	3	5	3	4	3	4	
	Other: Support documentation	5	5	4	5	-	-	4	-	5	-	-	-	-	-	5	
General																	
m	Description of the failure diagnosis	5	5	5	5	5	5	5	5	4	5	5	4	5	5	5	
n	Failure cause(s)	5	5	5	5	5	5	5	4	4	5	5	4	5	5	5	
o	Failure effects	3	2	3	3	4	2	3	1	2	1	3	1	2	3	2	
p	Failure nature	4	3	4	4	5	4	3	3	2	4	4	1	2	4	3	
q	Failure consequences	4	3	4	3	4	3	2	2	2	3	4	1	2	4	3	
r	Failure criticality	3	4	4	3	4	2	3	2	3	2	5	1	2	3	2	
s	Method of observation	4	3	4	3	4	3	4	3	4	3	3	2	4	2	4	
u	Operating conditions	3	2	3	2	4	2	3	2	2	1	4	2	3	2	3	
v	Eventual machine tool changes	3	2	2	2	4	2	3	1	2	1	3	1	2	2	2	
x	Standard working conditions	2	3	2	3	3	2	2	3	2	1	3	2	1	3	4	
1 = very poor; 2 = poor; 3 = neither poor nor good; 4 = good; 5 = very good (-) = no answer																	

Table C-1: Questionnaire results: repair data

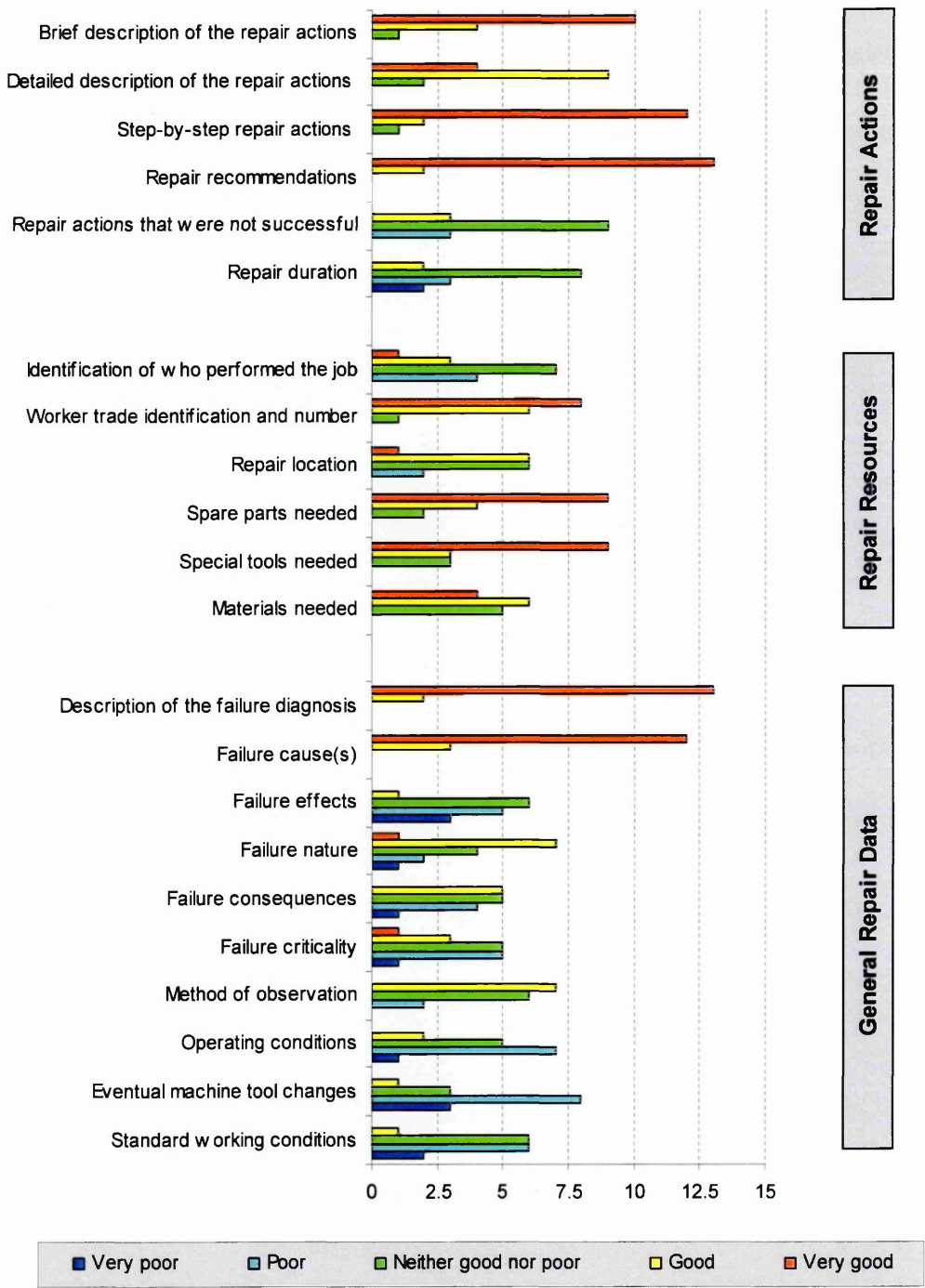


Table C-2: Repair data: integrated results of the three companies

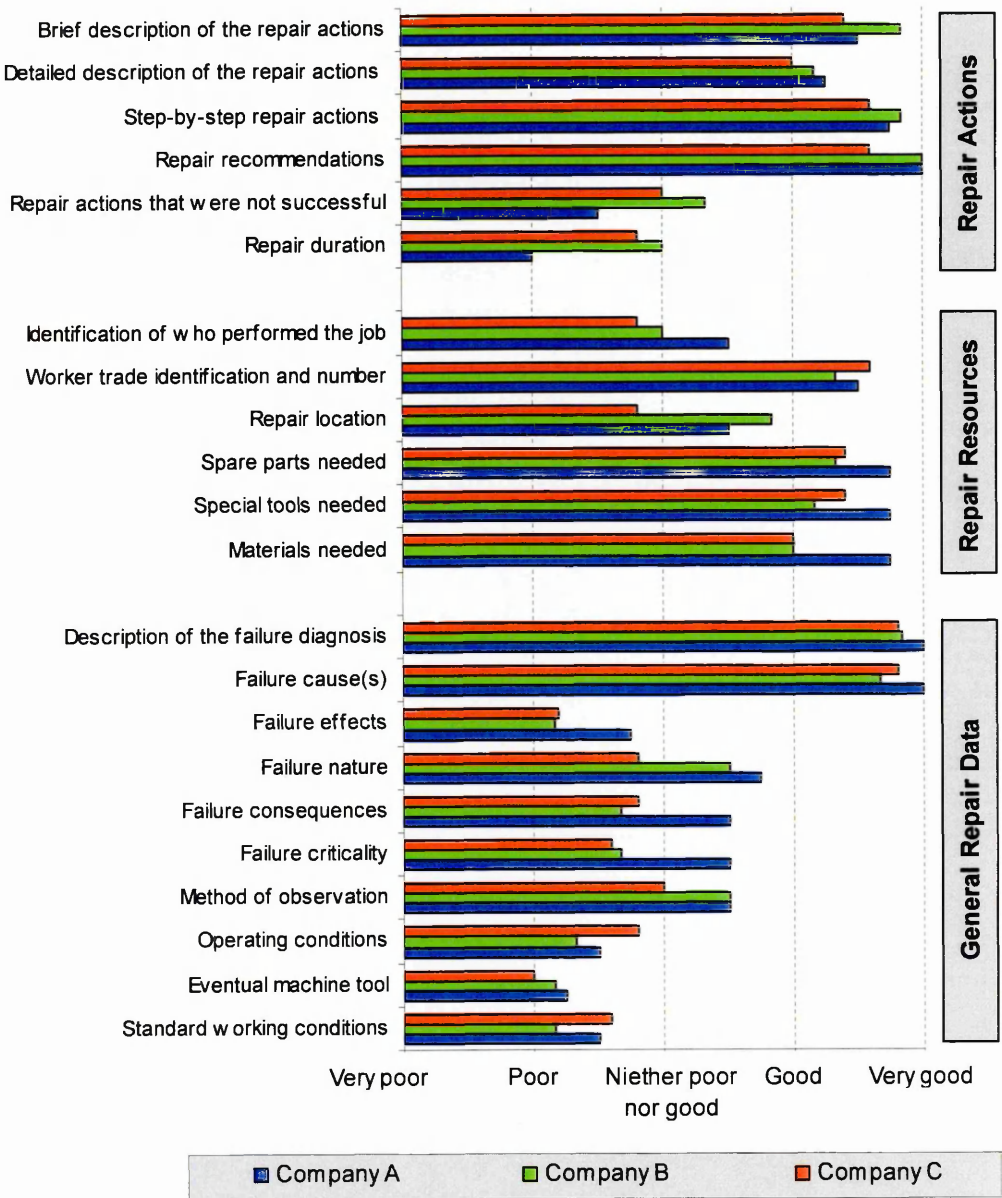


Table C-3: Repair data: average of results by company

2. Record Attributes		Compay A					Company B					Company C							
Equipment identification & Failure Location																			
a	Equipment location		4	3	4	5		4	4	5	3	4	4		5	4	3	5	4
b	Equipment identification		5	5	4	5		5	5	5	4	5	5		5	4	4	5	5
c	Failure location at equipment level		3	3	3	3		3	4	2	4	3	4		2	3	3	4	3
d	Failure source (lowest identified level)		5	5	5	5		5	4	5	5	4	5		5	5	4	5	5
Failure description – brief description of what the failure exhibited and caused																			
e	Failure symptom(s) lowest eq. level		3	2	4	3		3	4	2	5	2	3		3	2	4	3	4
f	Failure symptom(s) at equip. level		5	5	5	5		5	4	5	4	5	4		5	5	4	5	4
g	Nature of the symptoms		4	5	4	5		4	4	5	4	3	3		4	3	4	3	4
h	Combination of symptoms		4	3	3	4		3	3	4	5	3	3		4	4	3	4	3
i	Failure effect		5	4	4	5		5	4	4	5	4	5		4	3	4	5	4
General																			
j	Failure cause(s)		1	2	3	2		1	2	3	3	2	3		2	2	3	2	3
k	Failure consequence(s)		3	3	3	1		2	3	3	2	4	1		3	2	3	4	3
l	Failure nature		4	4	5	4		4	3	4	5	5	3		4	3	4	3	4
m	Failure discovered		3	3	4	3		2	3	4	2	4	3		4	3	3	2	4
n	Failure reason		5	4	5	4		5	3	4	4	3	4		4	3	4	4	3
o	Work order number		3	4	4	3		4	2	4	3	4	2		4	3	3	4	4
	Other: repair-action code		-	4	-	4		-	-	-	4	-	-		-	-	-	4	-
	Other: Alarm messages		5	-	5	-		4	-	-	-	4	-		-	-	-	-	-
1 = very poor; 2 = poor; 3 = neither poor nor good; 4 = good; 5 = very good (-) = no answer																			

Table C-4: Questionnaire results: records attributes

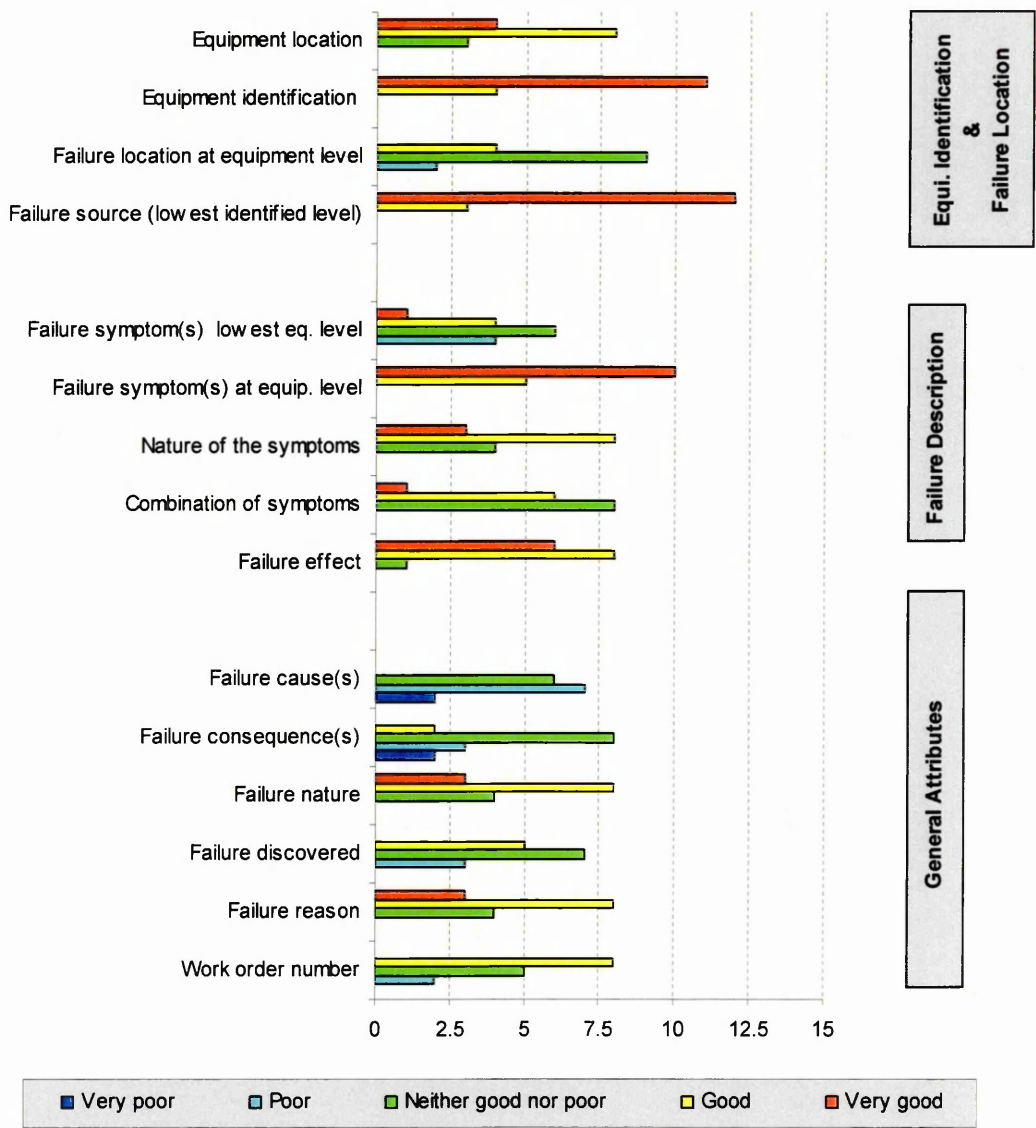


Table C-5: Records attributes: integrated results of the three companies

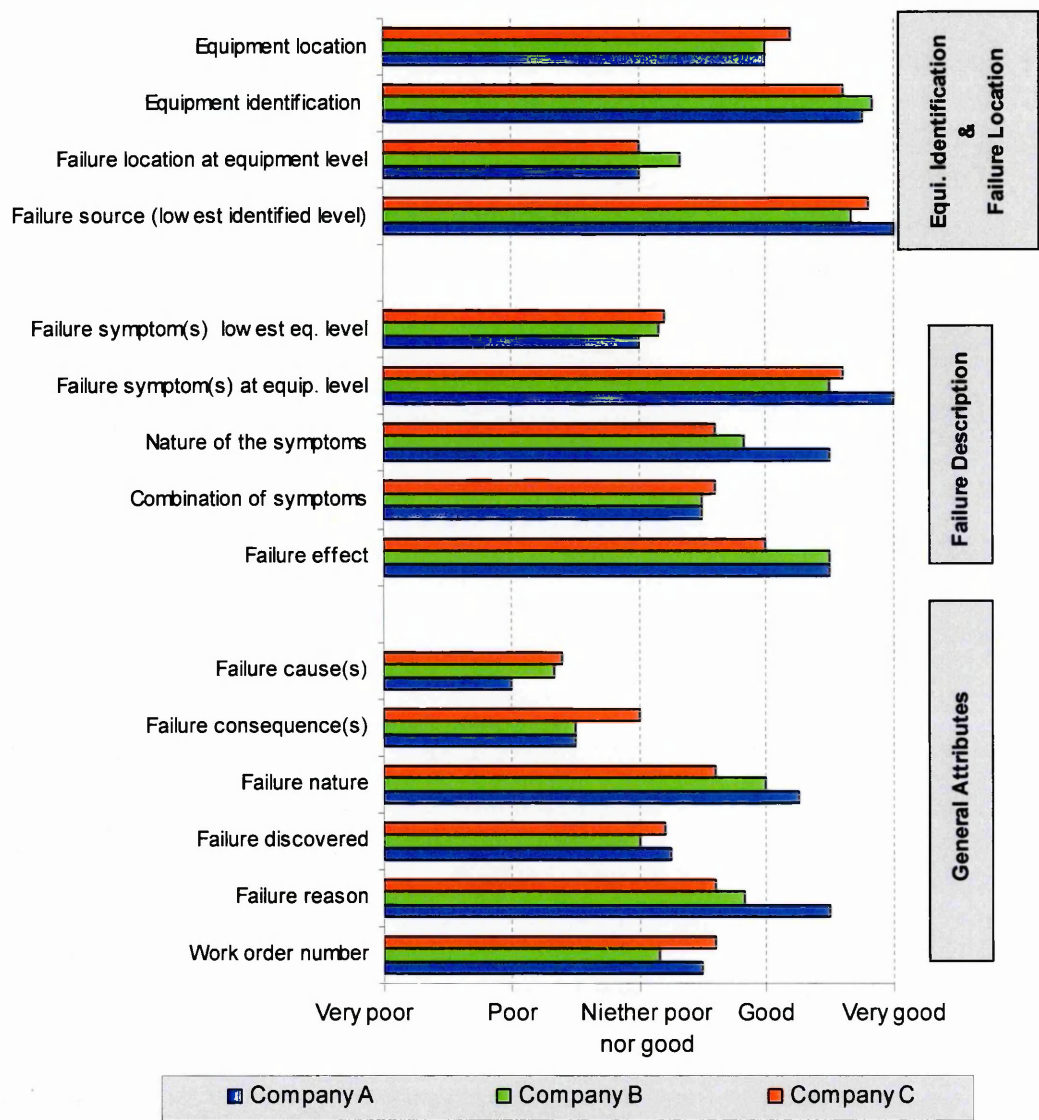


Table C-6: Records attributes: average of results by company

C.4.2 Results of Records Analysis

1. Repair Data		Company A		Company B		Company C	
Repair Actions		%	Field	%	Field	%	Field
	Description of the repair actions	99%	X	98%	X	98%	X
	Brief description of the repair actions	19%	-	25%	-	30%	-
	Detailed description of the repair actions	68%	-	66%	-	60%	-
	Step-by-step repair actions	12%	-	7%	-	8%	-
	Repair recommendations	20%	-	15%	-	12%	-
	Repair actions that were not successful	2%	-	3%	-	2%	-
	Repair duration	90%	X	95%	-	96%	-
	Action type	92%	X	89%	X	81%	X
	Cause of maintenance	68%	X	73%	X	84%	X
Resources		%	Field	%	Field	%	Field
	Identification of who performed the job	0%	-	0%	-	0%	-
	Worker trade identification	95%	X	85%	X	89%	X
	Number of workers needed	39%	-	56%	-	49%	-
	Repair location	62%	X	37%	X	0%	-
	Spare parts needed	98%	X	94%	X	96%	X
	Special tools needed	15%	-	25%	-	23%	-
	Materials needed	34%	-	48%	-	39%	-
General		%	Field	%	Field	%	Field
	Description of the failure diagnosis	18%	-	21%	-	17%	-
	Failure cause(s)	9%	-	31%	X*	12%	-
	Failure effects	18%	-	29%	X*	20%	-
	Failure nature	41%	-	78%	X	82%	X
	Failure consequences	4%	-	22%	X*	6%	-
	Failure criticality	0%	-	19%	X*	8%	-
	Method of observation	1%	-	3%	-	7%	-
	Operating conditions	3%	-	28%	X*	5%	-
	Eventual machine tool changes	21%	X	6%	-	2%	-
	Standard working conditions	23%	-	23%	-	12%	-

% - indicates the percentage found in the records

X* - field for reliability data

X - records form has a dedicated field

(-) - record form has not a dedicated field

Table C-7: Records results: repair data

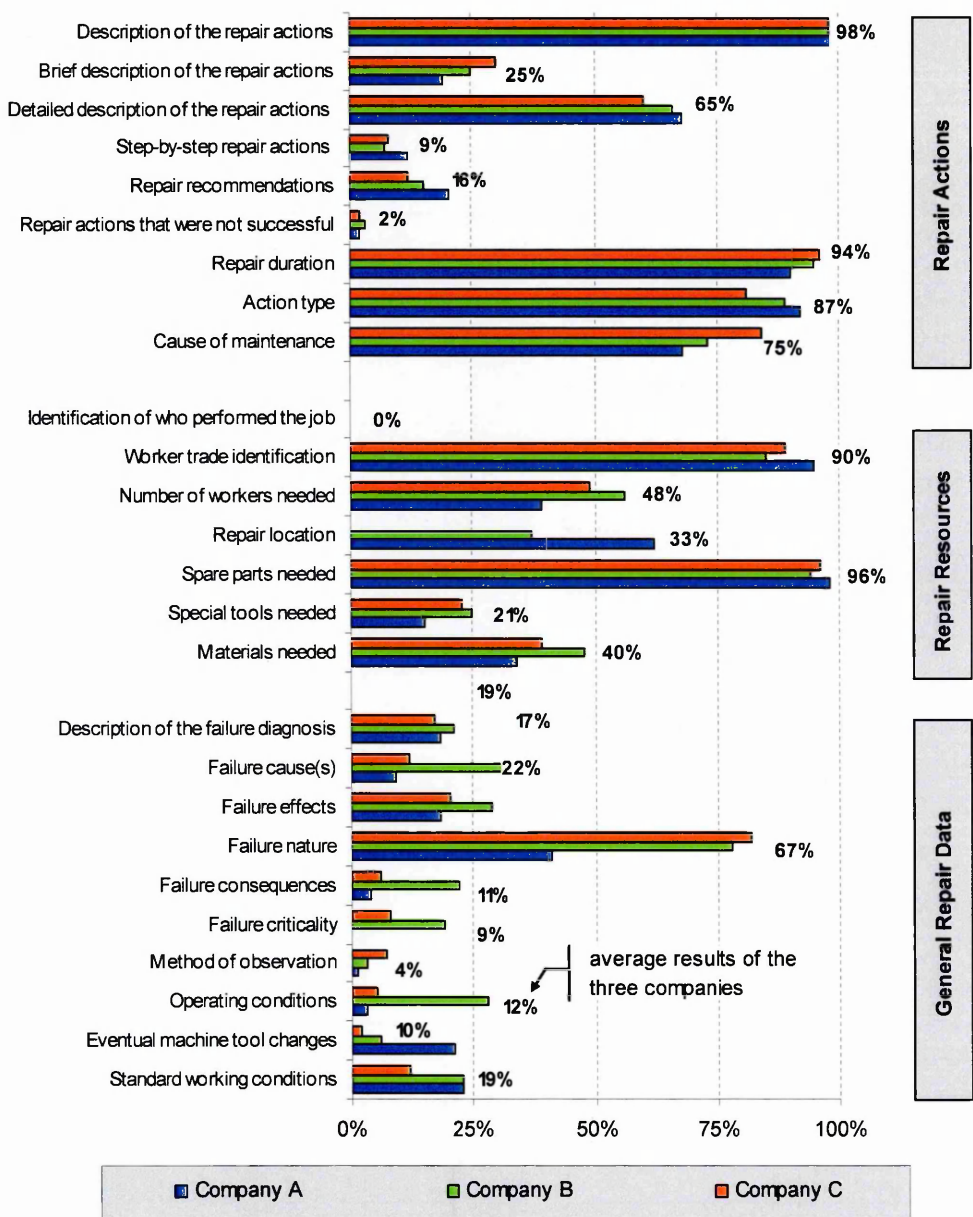


Table C-8: Repair data: average of results by company

2. Records Attributes		Compay A		Company B		Company C	
Equipment identification		%	Field	%	Field	%	Field
a	Equipment location	98%	X	97%	X	98%	X
b	Equipment identification	99%	X	98%	X	98%	X
c	Failure location at equipment level	92%	-	89%	-	90%	-
d	Failure source (lowest identified level)	8%	-	9%	-	11%	-
Failure description		%	Field	%	Field	%	Field
e	Failure symptom(s) lowest eq. level	18%	-	5%	-	9%	-
f	Failure symptom(s) at equip. level	53%	-	77%	X	55%	-
g	Nature of the symptoms	38%	-	44%	-	35%	-
h	Combination of symptoms	12%	-	18%	-	9%	-
i	Failure effect	85%	-	67%	-	71%	-
General		%	Field	%	Field	%	Field
j	Failure cause(s)	26%	-	31%	-	35%	-
k	Failure consequence(s)	5%	-	3%	-	6%	-
l	Failure nature	56%	-	64%	-	47%	-
m	Failure discovered	3%	-	2%	-	10%	-
n	Failure reason	1%	-	21%	-	19%	-
o	Work order number	0%	X	91%	X	95%	X

% - indicates the attribute percentage found in the records

X - records form has a dedicated field

(-) - record form has not a dedicated field

Table C-9: Records results: Records attributes

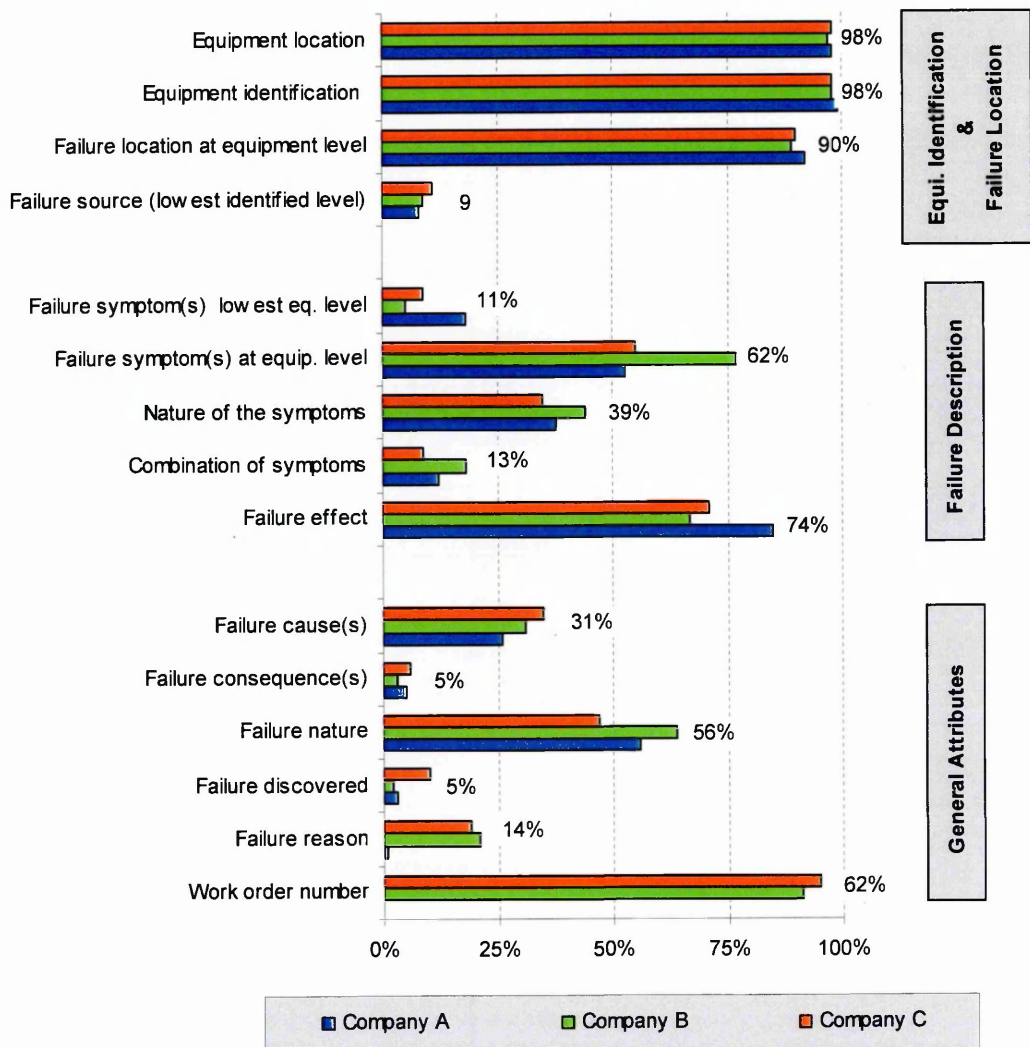


Table C-10: Records attributes: average of results by company

Appendix D

D. SAMPLES OF ENQUIRY REPORTS

D.1 Report of the Questionnaire Survey of Maintenance Practitioners

The following report presents the results of the first part of the mail survey, i.e., the results from the survey conducted in Portugal are not included. All respondents that asked for the survey results received a copy of this report. In addition, was published into a popular maintenance Web Site.

Failure Information Survey Results

Worldwide

By Jorge Juliao & Richard Greenough
Cranfield University – Manufacturing systems
October 2002

1. INTRODUCTION

The results of a maintenance survey on failure information are presented in this report. The survey was conducted using a questionnaire, which was posted to maintenance personnel at 100 UK companies, posted at the Plant Maintenance Resource Centre Website, and used in a survey of maintenance managers attending a short course in Australia. The survey was conducted between July and August 2002 and, mainly addressed the following issues:

- Use of failure history records to assist maintenance;
- Current maintenance trends in managing failure histories;
- Relationship between machine users and vendors with regard to maintenance.

The report summarises the findings coming from seventy nine valid responses.

2. FINDINGS SUMMARY

- Overall, 84% of respondents record failure histories from their machine tools. The majority of these respondents classified the failure history records as very important to assist their maintenance function. The most common reasons why failure histories are being collected are as follows; to plan and schedule maintenance activities and, to analyse failure modes and effects;
- The respondents that do not collect failure history records claimed that one of the main reasons is because their maintenance management systems do not support the feature of recording failure histories;
- 70% of respondents who record failure histories use a system to classify failures. Almost half of the respondents who record failure histories keep records of all failures and have no criterion to select the failures that should be recorded;
- The majority of the respondents who record failure histories use a computer-based system to collect and store their failure histories. Commercial systems are more commonly used than own-designed systems. Only 9% of respondents use only paper-based systems;
- On average respondents classify their data storage system as poor for data export purposes;
- On average respondents that record failure histories reported that their maintainers rarely refer to written descriptions of failure histories to solve new problems;
- Overall, 72% of respondents do exchange failure information with their machine vendors. However, the majority of respondents classify their relationship with vendors, concerning assistance with machine maintenance, as neither good nor poor;
- Overall, on average respondents reported that a database of failure histories for machine failures that is populated by users but vendor managed would be useful for their organisation. In addition, a significant 85% of respondents said that would contribute their failure records to build such a database;

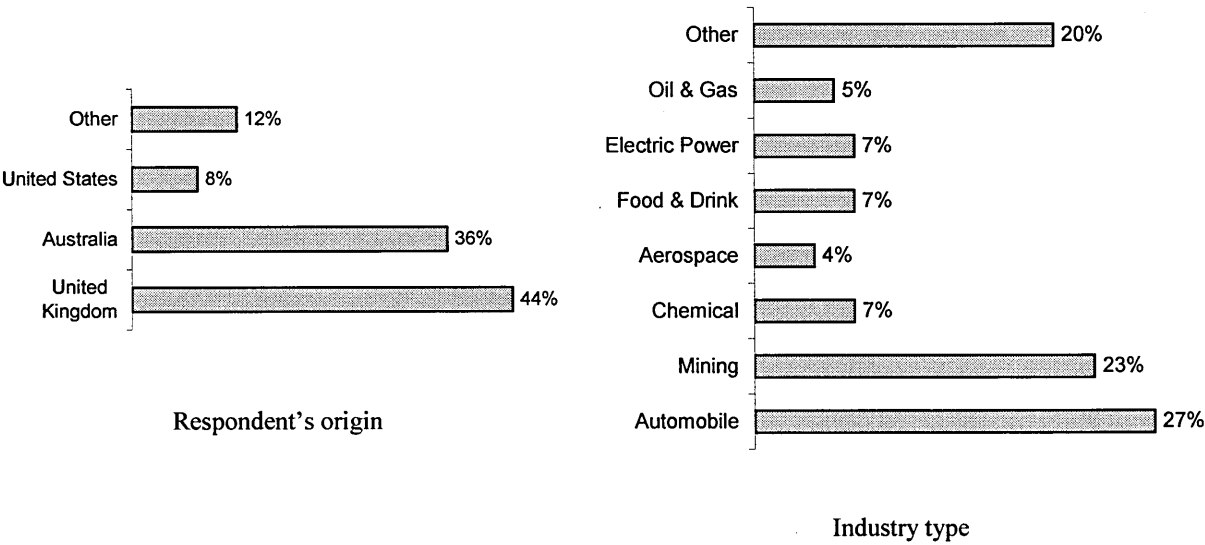
- An analysis of the responses showed that there is no relation between the non collection of failure records and, the industry type, the company size and the process type.

3. RESPONDENT DATA

The general questions about the respondent data were answered by 72 respondents (90%).

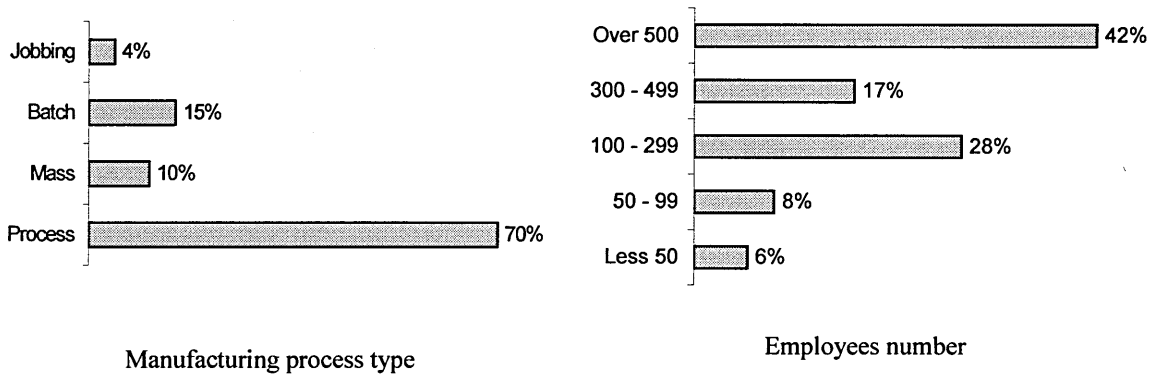
Respondent’s origin and industry type

The majority of the respondents are from the United Kingdom and Australia, which represent 80% of sample. The responses came from a wide range of industries, which were classified into the groups showed in the following diagram. Automobile and mining were the most widely represented types of industry.



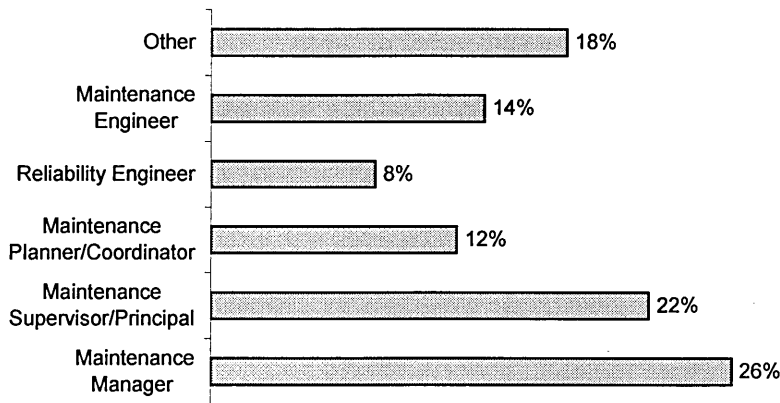
Respondent’s manufacturing process type and employees number

Process manufacturing is used by 70% of respondents as their main production typology. Nearly half of respondents represent large companies, which have over 500 employees.



Respondent’s job title

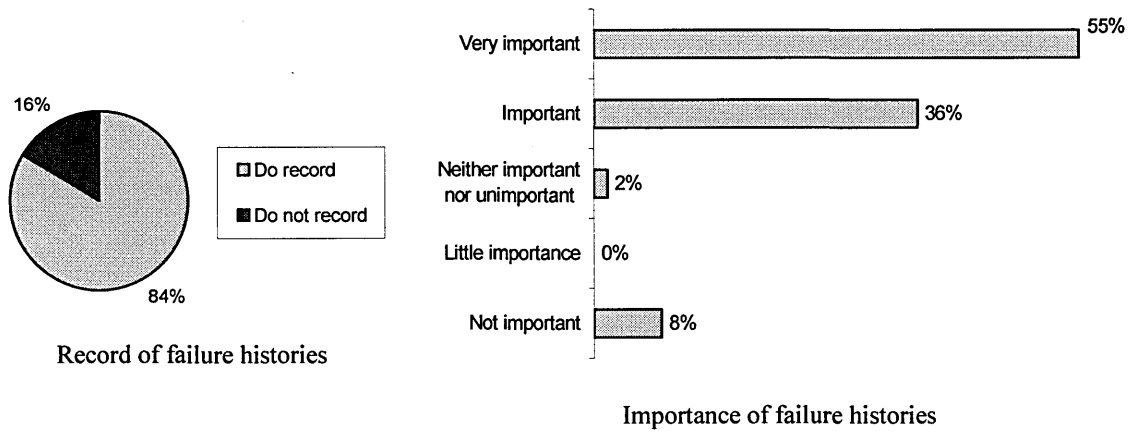
The most representative respondent’s job positions were maintenance manager and maintenance supervisor/principal, which together represent nearly half of the sample.



4. FAILURE HISTORIES RESULTS

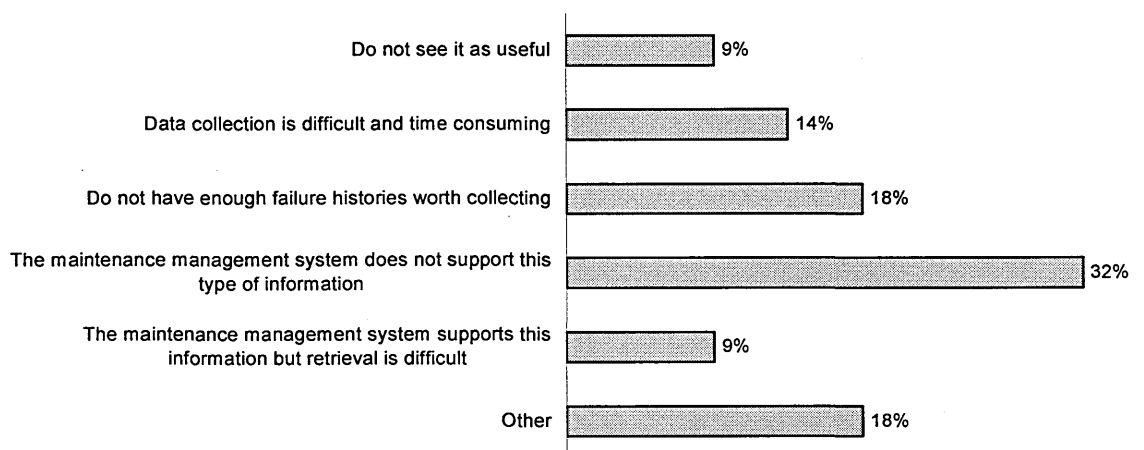
Failure histories record and importance

84% of all respondents answered that they record failure histories from their machine tools. The majority of respondents (55%) who record failure histories rated them as very important to assist their maintenance function.



Reasons why some respondents do not record failure histories

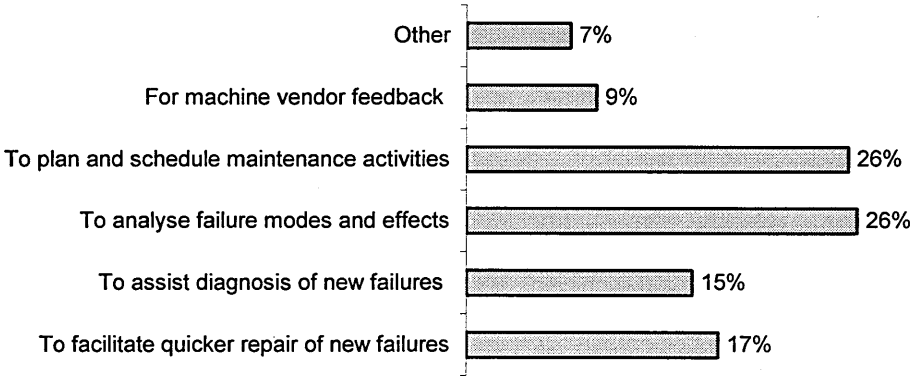
Only twelve respondents (16%) reported that do not record failure histories. Among them, maintenance management systems that do not support the feature of recording failure histories were pointed out as one of the main causes for not recording failure histories.



Additional reasons for not recording failure histories were pointed out by some respondents as; (i) not having time to work on the shop floor and do paper/computer work and (ii) due to the complexity of their maintenance management system.

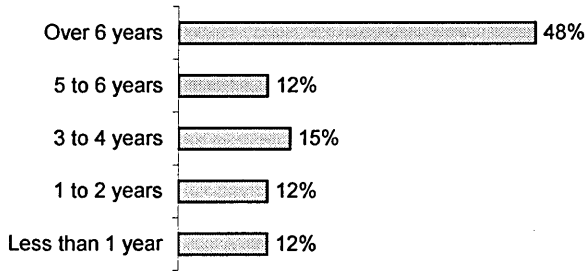
Reasons for failure histories record

Among the respondents who record failure histories, the two most common reasons why failure histories are being collected are to plan and schedule maintenance activities and to analyse failure modes and effects.

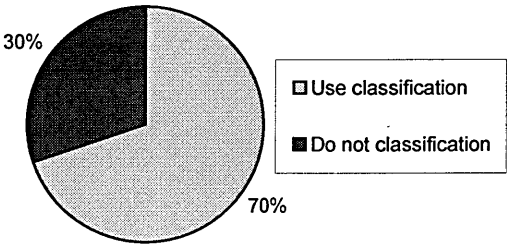


Time recording failure histories and use of a failure classification system

Almost half of the respondents who record failure histories have collected data for more than 6 years and 70% use a classification system to record failure histories.



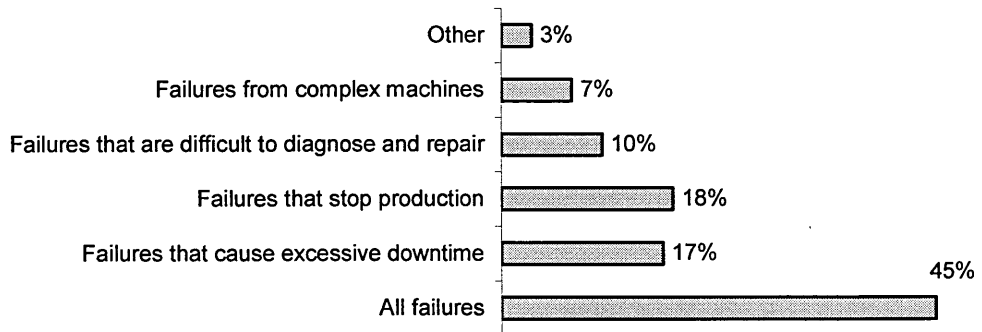
Time recording failure histories



Use of a failure classification system

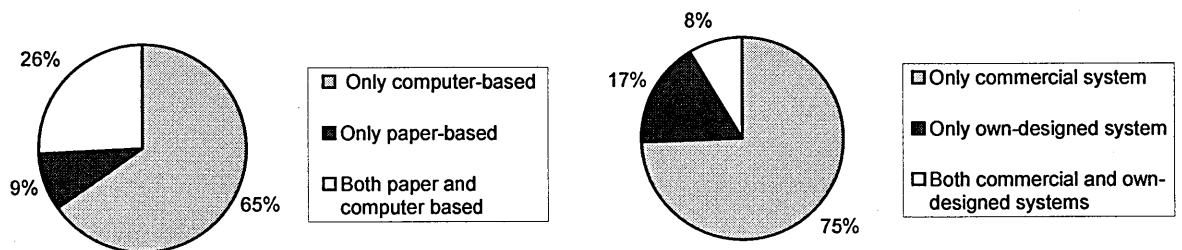
What type of failure histories are being recorded

Nearly half of the respondents who record failure histories have no criterion to select the failures that should be recorded and so they record all failures, whether minor or major.



Type of system used to collect and store failure histories

The majority of the respondents who record failure histories use only a computer-based system to collect and store their failure histories. A significant number of respondents (26%) use both paper and computer based systems. Commercial systems are more commonly used than the own-designed systems. A small number of respondents (9%) use only a paper-based system.

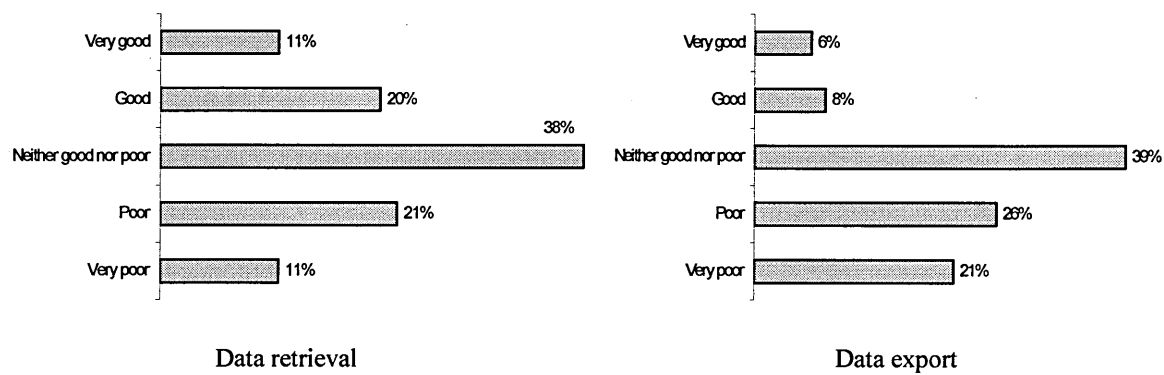


Computer-based system vs paper-based system

Commercial system vs own-designed system

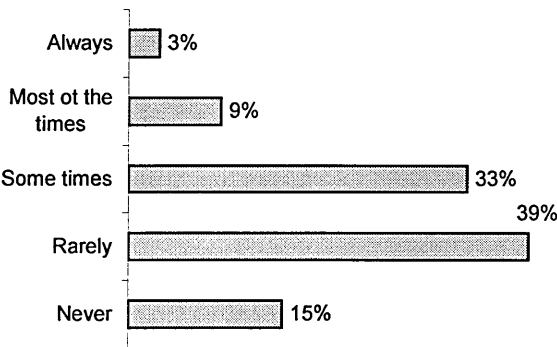
Rate of the data storage system for data retrieval and data export

The respondents were asked to rate their failure data storage system for data retrieval and export. On average respondents who record failure histories classified their storage systems as neither good nor poor for data retrieval and, as poor for data export.



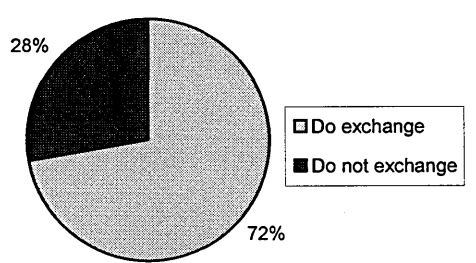
Frequency maintainers refer to written descriptions of failure histories to solve new problems

On average, respondents who record failure histories reported that their maintainers rarely refer to written descriptions of failure histories to solve new problems.

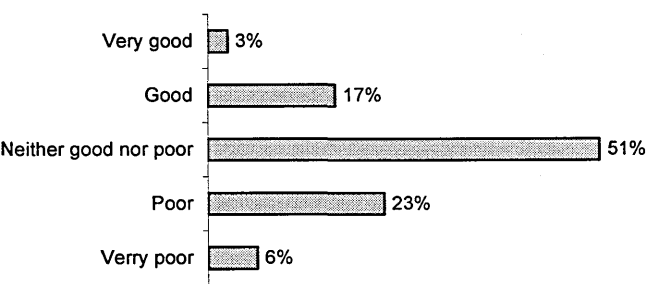


5. RELATIONSHIP BETWEEN MACHINE USERS AND VENDORS

The questions regarding the relationship between machine tool users and vendors were answered by all respondents. A significant 72% of respondents do exchange failure information with their machine tool vendors. The majority of respondents classify the relationship with the vendor, concerning assistance with machine maintenance, as neither good nor poor.



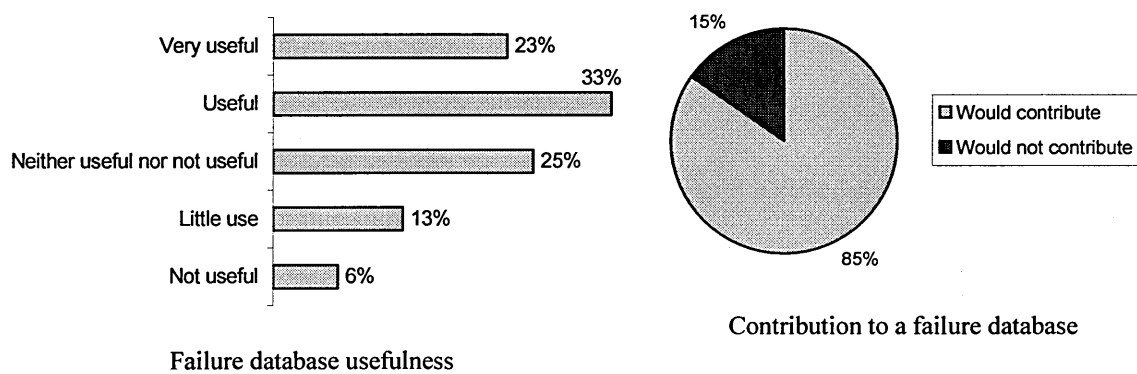
Exchange of failure information with vendor



Respondent's relationship with their machine vendors

6. FAILURE DATABASE

Respondents were asked whether they feel that a database of failure histories for machine failures populated by users but vendor managed would be useful. They were also asked if they would contribute their failure histories to build such a database. All respondents answered these questions. On average respondents find the failure database useful and, 85% of respondents reported that they would contribute their data to such a database.



7. FUTURE ENHANCEMENT

We would like to thank all who contributed to this survey and welcome any comments on the results shown in this report. In the near future we will be running a second survey which aims to identify the most important attributes of machine failures, and to evaluate what is the most important information from failure troubleshooting to be recorded in the failure reports.

The results of both surveys will be used to generate a failure classification and coding system. This system will be the backbone for the development of a decision support system for maintenance, which may be used by maintenance to improve their approach to troubleshooting downtime failures.

The contribution of all maintenance experts will be essential to this research. Therefore, if this research addresses some of your concerns please participate. In return, besides the reports with the findings you will have the change to follow up the research, which we believe will be of great use to your organisation.

D.2 Case Study Report

Company overview

Company A is a machine tool (MT) company that offers advanced CNC machine tools from some of the worlds leading producers. Some examples of these machines include: CNC lathe, multi-axis turning centre, a high speed horizontal machining centre, and flexible manufacturing cells. The company also manufacture some of their own machines. In addition to selling machines, this company provides maintenance servicing to their customers. They claim themselves to be a one machine tool company that is proud of its record on the service and back-up front. They provide maintenance service all over the UK and overseas.

The maintenance service, consisting of a team of six maintenance engineers, is mainly provided at the customer's site. However, some maintenance services might also be done at the company's site by a technical team. The company has a service support desk led by a service manager. The service manager receives the service requests from customers either by phone or fax. Depending on the complexity of the problem, the service manager might provide either the actions to be taken to solve the problem or assigns a service engineer to do the job at the customer's site.

Case study objectives

This case study is focused on the maintenance servicing of this company, in particular on how maintenance information is used and managed. The main objectives are as follows:

- Identify and analyse the support documentation system of the company regarding the maintenance service;
- Analyse the relationship between machine tool manufactures, vendors, and users regarding the exchange of maintenance information;
- Identify patterns in the descriptions of failures and repair actions from both the customer's and service engineer's point of view;
- Identify how a documentation system might improve maintenance service.

Case study methodology

- Service manager interview
- Analyses of service requests and service reports
- Service engineers interview
- Machine-tool customers interview

In all the interviews a semi-structured approach consisting of open and closed questions was followed.

A group interview was performed with the maintenance-service engineers of the company. Four engineers attended to the meeting. The meeting was structured as follows: (i) brainstorm in which open questions were suggested to discussion, (ii) an individual questionnaire was given to each engineer, and (iii) final discussion.

Regarding the documentation analysis, twenty folders of service reports were selected at random from the company’s storage system. Each folder represented one company. In total, 155 valid reports were analysed. The reports came from a wide range of machine types and from different service engineers. In addition, fifty service requests reports filled by the customers were randomly selected and analysed.

Findings from service manager interview

This section summarises the findings of two visits to the company where the service manager was interviewed. The interviews mainly targeted their maintenance information system analysis.

Documentation

The company uses the following documentation to support service:

Maintenance manuals	Service reports
Troubleshooting manuals	Service requests
Service bulletins	

The maintenance manuals are provided in paper format by the machine tool (MT) manufacturers. These manuals contain such information as machine specification, machine settings, and preventive maintenance schedules. According to the service manager these manuals are rarely used for troubleshooting because, being paper-based, it is difficult to

make a quick search, which inhibits the manual's use. In addition, it was claimed that these manuals are not intuitive and do not contain much about failure troubleshooting.

Some MT manufacturers provide troubleshooting manuals for their machines. The main aims of these manuals are to facilitate failure diagnosis and to provide repair instructions to those engineers responsible for servicing the machines. Of all the MT manufacturers providing machines to the surveyed company, only one has a troubleshooting manual. This paper-based manual was found to provide troubleshooting instructions for the most common problems; the same manual can be used with different machine types. This manual is designed in a 'decision tree' format where failures are classified into 25 categories. According to the company these manuals are very useful for maintenance service.

Complementary to the troubleshooting manuals, some MT manufactures provide service bulletins to the MT vendors on a regular basis. In this company the bulletins are received by e-mail in a 'pdf' format. These bulletins usually report design problems for which a solutions has been found. Most of these upgrades result from feedback from those responsible for servicing the machine tools. The company is not using any method of failure categorisation; bulletins files are simply filed into a folder, which makes them difficult to search and inhibits their use.

The service request forms are completed by the customers and faxed to the service company when maintenance service is required. These forms primarily include customer details, equipment identification, a written description of the problem, the alarm message displayed (if known), and a tick-box to identify the type of service required.

After the job has been completed, the service engineer completes a service report (usually at the customer's site). This report describes the service that has been performed. It might report one or more failures. Service reports contain six basic types of information, as follows:

1. Customer details
2. Tick-box of safety checks, modifications by the customer, and a tick-box of maintenance tasks performed
3. Written description of the service requested, and an indication if the fault was demonstrated by the customer
4. Written description of the actions taken, the name of the service engineer, and the date
5. Resources used and costs report
6. Customer check out

These reports are mainly used for control and to report work completed. They provide information to control costs, resources, and jobs performed for each customer. They are also used to help find solutions for reoccurring problems. In addition, they are used by customers to carry out their own control, since a copy of the report is provided for their use.

Information exchange

It was found that the company does not wish to share directly all their information on failure troubleshooting with MT users (customers). They claimed to be afraid of losing their customers. They pointed out that customers might use that information either to fix the failures themselves or to contracting servicing from companies other than their own. However, all their customers receive a copy of each service report of the work performed on their machines.

The company reported that MT manufacturers are keen to receive feedback information on their machines from the vendor, since it helps them to improve reliability and to produce service bulletins. However, manufacturers do not want their service bulletins to be passed directly to MT users. A possible reason is that these bulletins show some of the weaknesses of the machine.

Service request

The simplified form of the service requests that the company currently uses has resulted from more complex ones previously used. The older forms were designed to collect more details about the customer's problems; however they realised that most fields were not being completed by the customer. They also tried to simplify the gathering of information by using tick-boxes, but found that inaccurate information was being collected. Customers were simply ticking boxes without thinking. From their long experience the company found that more accurate information is retrieved from written descriptions. They analyse the written description and filter/retrieve the information considered important. From the company's point of view, most customers are too sensitive to give much information concerning the problem that requires servicing.

In general, they found it difficult to understand the customer's problem when reported. However, one of their MT manufacturers provides machines with an automatic diagnostic system, which allows users to easily identify a restricted number of failures (32 types). When any of the listed problems occur, the system produces an alarm (message of error). This system was designed primarily to help MT users to diagnose and report failures to service. According to the company, this system is of great use because it helps them to

identify and correct problems. Nevertheless, they claimed that many failures reported by customers are not recognised by the diagnostic system.

In general, customers often fail to provide clear and sufficient information about the problems they have, which makes it difficult both to assign the best person to perform the job and to provide all the resources needed for the job (e.g. parts and tools). Consequently, the service engineers sometimes need to travel first to the customer just to diagnose the problem. To minimise this travelling, the service company usually phones the customer for a clearer definition of the problem. It was also accounted that sometimes problems are not reported by those who found them but from a second person that usually had limited knowledge about the problem itself. Consequently, it is even more difficult to understand the problem.

Service reporting

According to the service engineer manager, the two most important attributes to report failures (problems) are the location and symptoms of the failure. The equipment identification is essential to locate failures. The equipment identification is provided by both machine and control identification, which are identified by both type and serial number. The type is defined by a code that indicates the manufacturer and the model (e.g. Fadal VMC 4020). The serial number is a unique code usually assigned by the manufacturer. He also pointed out that the failure descriptor (e.g. mechanic, electric, etc.) is important for identifying failures. It should be noted that the current service report form has been use for several years.

Storage systems

The company uses both a paper-based and a computerised system to store information regarding the machines servicing. All paper-based service reports are classified only by customer. Also, since records have been maintained for the last 20 years, the volume of information stored is considerable. Therefore, it is currently very difficult to search for particular failures that occurred previously in a specific machine. The company claimed that it would be important for them to have a system that allowed easy search for previous failures. This would facilitate the troubleshooting of reoccurring failures.

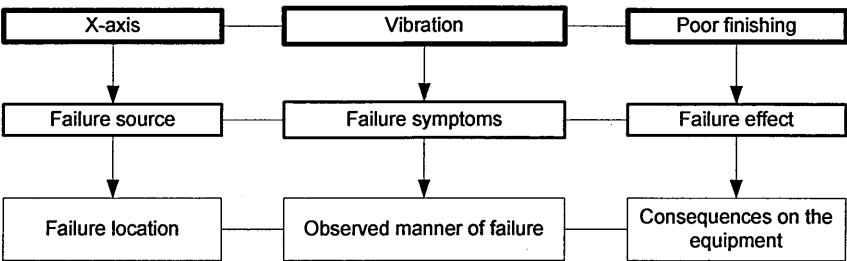
Findings from service reports analysis

The main objective of analysing the service reports was to analyse how service engineers report both the description of the problems (failures) and the repair actions from their maintenance service.

Problem descriptions

The written descriptions of the problems commonly consist of one sentence, while, generally, a maximum number of two sentences is used. The analysis of this field showed that the most common failure attributes to describe problems are: (i) the failure location, (ii) the failure symptoms, and (iii) the failure effects.

The failure location commonly indicates the lowest level item to which the failure can be isolated. This item is identified by its name, e.g. spindle, Z axis, control, motor. In the literature this failure attribute is usually designated by failure source. Associated to the failure source engineers usually report what they can see, feel, and hear about the problem. In other words they describe the observed manner of failure, which is commonly designated by failure symptoms. Some examples of failure symptoms are: noise, vibration, and leak. It should be noticed that failure symptoms sometimes are linked with adjectives, e.g. ‘high vibration’, ‘excessive noise’. It was also observed that the consequences of the failures in terms of operation, function, or status of the equipment were commonly associated to the failure source, e.g. motor X stopped, Y-axis not moving. These consequences are usually designated by failure effects, and may be associated with one or more failure symptoms. It should be noted that failure effects are different from failure causes. The former answer the question ‘what happens’, the second answer the question ‘how does it matter’.



Example of a failure description

Although not so common as the above attributes, it was found in some service reports failures characterised by their nature. The failure nature describes the origin of the failure, e.g. mechanical, electrical, hydraulic, lubrication, and pneumatic.

On the other hand it was found that the failure causes, failure consequences, failure criticality, and method of observation are not usually recorded in the service reports.

Actions description

A description of the actions taken by service engineers when solving the customer's problems were also analysed from the service reports. Typically, brief step-by-step descriptions of the repair actions are presented. These steps usually indicate the task performed and the name of the item to which the task is associated. The most common tasks found were repair, fit, investigate, install, check, commissioning, re-commissioning, test, replace, update, remove, change, and reload. These action steps are generic, i.e. they indicate what to do but it do not describe how to do it. An example is 'replace the lubricant unit filter'. It was also found that the majority of reports provide some indication of how the problems were diagnosed. It is worth noting that some reports indicated that a number of actions were not taken successfully.

Findings from service requests

Fifty service request forms were analysed in order to identify how machine tool problems are described by the machine tool users. As described above, the service request form has a field where customers write a description of the problem they want fixing. Only this particular field was analysed from the service requests.

The majority of the problem descriptions analysed were vague and unclear. Most of the descriptions could only be understood by experienced engineers, which confirms the findings of the interview. The most common pattern found in the problem description was the location of the failure. Almost all problem descriptions include the identification of the component or part that has had a problem (failure source). However, many problems were found to be described only by the indication of the component or part that failed, e.g. 'motor X failure'. It was uncommon to find the indication of the failure effect. However, failure effects associated to the failure source were found in some descriptions. Similar to the service reports, the indication of the tasks that customers wanted to be performed is commonly found in the service requests.

Findings from the group interview to service engineers

The main objectives of this group interview were:

1. Analyse if access to experiences of past failure-troubleshooting is important for maintenance service;
2. Identify the most relevant attributes to identify failures in order to facilitate access experiences of past failure-troubleshooting;
3. Identify what is the most important information to help service engineers during failure troubleshooting.

This section presents a summary of the main findings of the group interview to service engineers.

Failure records

The service engineers classified as very important the access to failure records in order to see how failures were fixed in the past. In particular they pointed out that would be significant for them accessing the failure reports of each other. Their current system does not allow this interchangeability because it is a paper-based system and service reports are not classified in a way that facilitates its access. Therefore, they do not use at all the service reports that are produced.

According to all engineers interviewed maintenance service can be improved if easy and quick access is provided to failure records, which should include experiences about failure-troubleshooting.

The engineers are willing to be given of more paper work and provide more details about failure troubleshooting if this information would be accessible to them afterwards. They also reported that would be happy to introduce themselves the information and produce detailed failure reports into a soft-system if they were given the means for it, e.g. a laptop or a 'PALM'. A soft-system may be generated to produce information for both service report and failure report. This would avoid same failure information to be written twice.

The main requirements reported by the service engineers for a documentation system to assist failure troubleshooting are as follows:

- (i) Be as simple as possible and easy to use;
- (ii) Provide a clear and standard format for the failure definition;
- (iii) Include relevant information for failure diagnosis and troubleshooting;

- (iv) Allow direct report and storage by those who deal first with the failures and troubleshooting;
- (v) The amount of information to include in the failure reports should be restricted to the minimal possible.

In addition, the engineers pointed out that failure reports should be generated for all failures. It should be noticed that most of the failures that they face are relatively complex, otherwise the machine tool customers would not contract the service.

Failure identification and description

The engineers reported that one of their main problems is the identification of the failures when reported by their customers. They claimed that customers give poor descriptions of the failures. According to them the main reason is because commonly failures are reported not by those who first see the failure but by others that are not aware of the problem.

The engineers do agree that a common format to describe failures should be derived. This would facilitate failure reporting by both customers and service engineers. They evidenced that the automatic diagnosis system that some machines have facilitates the identification of failures. However, this system is limited to a certain failure types, and some times the alarm produced does not correspond to the failures that are assigned.

According to the engineers the most important attributes to describe failures are as follows:

- (i) The equipment identification: geographic location of the equipment, equipment type and serial number;
- (ii) The failure location: indication of the failure source at the lowest level item to which the failure can be isolated;
- (iii) The failure symptoms: indication of what the failure exhibited, which should be preferable described at the failure source level. If known multiple symptoms should be indicated.

After the above failure attributes the failure effect and the failure nature were the most rated attributes to describe failures. In addition, the failure causes, consequences, the reason of the failure, and the process of failure detection were found by the engineers as not relevant to describe the failure.

Regarding the description of what the failure exhibit service engineers consider more intuitive designate them by failure symptoms rather than failure mode. Also, concerning the designation of the failure nature they prefer to use the term failure nature rather than the failure descriptor.

Failure information to include in the failure reports

The most relevant failure information to be included in the failure reports it was characterised into three main categories: (i) repair actions, (ii) resources, and (iii) general.

Regarding the repair actions engineers reported that the most important thing to include in the failure reports is a step-by-step description of the repair actions, where each repair action should be briefly described (less than five words). Nevertheless not as much important as the previous, repair recommendations and repair actions that were not successful were pointed also as relevant to be included in the failure reports. According to the engineers detailed descriptions of the repair action are not recommended. These descriptions would make harder the collection, and its contribution it would not be so significant. Those who will be using the failure reports to assist troubleshooting are mainly maintenance experts who are aware of their job and need just some guidelines.

The spare parts, tools and materials needed for failure troubleshooting were pointed out by the engineers as the most important resources that should be recorded in the failure reports. Since the engineers do service offsite it is important for them to know exactly what resources for each failure troubleshooting are needed. The indication of the worker trade and number it was also found relevant, but less important than the previous resources. This might be due to the fact that each engineer is able to perform almost any type of service and most times only one is assigned to the job. They do not find relevant the identification of who performed the job (e.g. manufacturer, contractor) neither the repair location (e.g. on site, repair shop) for the troubleshooting process.

Both descriptions of the failure diagnosis and failure cause(s) were classified by the engineers as very important information to assist failure troubleshooting. The engineers pointed out that commonly they do not have time to perform a proper diagnosis and identify the failure causes, because the machines need to be running in the shorter time possible. Therefore, sometimes the symptoms are corrected but not the causes. However, they pointed out that when the failure diagnosis and causes are known they should be reported because they constitute a good source of information to perform failure troubleshooting efficiently. Both nature of the failure and changes that were made in the machines were found as relevant information to assist troubleshooting, but not as much as the diagnosis and causes. The failure effects, consequences, criticality, method of failure observation and operating conditions were found by the engineers as not important failure information to assist troubleshooting.

Conclusions

The documentation system currently used by the surveyed company is not optimised to assist service during failure troubleshooting. The paper-based maintenance manuals, which are usually provided by all MT manufactures, usually do not have much information that can be used for failure troubleshooting. Also, these manuals are found to be not very intuitive and difficult to consult. The troubleshooting manuals, provided by a few MT manufactures, are very useful for identifying and correcting failures. However, they are restricted to a few classes of failures and are not available in a digital format. Consequently, they cannot be integrated with a soft-system.

Most of the service requests fail to provide a clear identification of a customer's problems, which makes failure diagnosis and troubleshooting difficult. The MT customers need to be motivated to provide clear definition of their problems. Also, if customers were given a full list of (typical) problems that have occurred in each machine to select from, it would facilitate the reporting of problems to service. In addition, structuring the problem description into a few classes would help to identify problems. The results of the study demonstrated that failure descriptions should be preferably classified or structured according to the following categories: (i) failure location, (ii) failure source, (iii) failure symptoms, and (iv) failure effect.

The repair actions descriptions should be reported in a step-by-step format, representing sequentially the actions that need to be taken to solve the problem. However, it was found in the current reports that these descriptions normally only indicate 'what' to do rather than 'how' to do it. If these reports are intended to be used to help troubleshooting reoccurring failures, they should include information on how to fix the problems. In addition, according to the service engineers, each step of the repair actions should present a brief description (less than five words) of the actions that needs to be taken. Furthermore, the most important resources to be included in the service reports, in order to assist servicing, are a list of spare parts, tools and materials needed for the failure troubleshooting. Finally, both descriptions of failure diagnosis and failure causes should also be included in the report whenever known.

Since the company does not wish to pass this information directly to customers, they need to create an internal document to store more detailed information. Alternatively, a soft-system may be created from which both reports to the customer (service report) and internal report (failure report) may be generated. Some requirements for this documentation system, are as follows:

- Be as simple as possible;

- Provide a clear and standard format for the failure definition;

- Provide information for both accounting and for assisting service;

- Allow direct collection by service engineers;

- Each failure report should contain only one failure type;

- The amount of information should be restricted to what is really necessary.

Appendix E

E. GLOSSARY OF TERMS

Term	Definition	Source
Area	Physical, geographical, or logical segmentation within the site.	ISA S88.01-1995
Asset	The buildings, plant, machinery and other permanent <i>items</i> required by the user to produce and supply the product.	BS 3811: 1993
Availability (performance)	The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.	BS 4778-3.2: 1991
Breakdown	Failure resulting in the non-availability of an item.	BS 3811: 1993
Classification	The act of grouping items into classes.	BS 3811: 1993
Coding	The act of systematically sequencing, identifying and presenting items within their class or classes.	BS 3811: 1993
Component	A sub-item of an item, usually removable in one piece and interchangeable with other, standard components (e.g. truck engine).	[1]
Computerised maintenance management system	A computerised system to assist with the effective and efficient management of maintenance activities through the application of computer technology. It generally includes elements such as a computerised work order system, as well as facilities for scheduling routine maintenance tasks, and recording and storing standard jobs, bills of materials and applications parts lists, as well as numerous other features.	[1]
Condition based maintenance	Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. NOTE Performance and parameter monitoring may be scheduled, on request or continuous.	BS EN 13306, 2001
Corrective maintenance Breakdown maintenance	The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function. This action may consist of repair, restoration or replacement of components.	BS 4778-3.2: 1991 and [1]
Corrective Planned Maintenance	All resources necessary to accomplish the tasks are planned and available before intervention. Work performed according to a set scheduled.	Duffuaa, 1999
Craftsperson Tradesperson	A skilled maintenance worker who has typically been formally trained through an apprenticeship program.	[1]
Critical failure	A failure which is assessed as likely to result in injury to persons, significant material damage or other unacceptable consequences.	BS 4778-3.2: 1991
Data	A representation of facts, concepts or instructions in a formalised manner suitable for communication, interpretation or processing by human beings or by automatic means.	BS 3811: 1993
Deferred maintenance	Corrective maintenance which is not immediately initiated after fault recognition but delayed in accordance with given maintenance rules.	BS 4778-3.2: 1991

Term	Definition	Source
Diagnosis	The art or act of deciding from symptoms the nature of a fault.	BS 3811: 1993
Disable stage Outage	A state of an item characterised by its inability to perform a required function.	BS 4778-3.2: 1991
Downtime	The time interval during which an item is in a down state. Out of service as a result of an item failure. Note that the time that an item is available, but not utilised is generally not included in the calculation of downtime.	BS 4778-3.2: 1991 and [1]
Equipment class Unit	Class of equipment units, e.g. all pumps. At higher level, a class consists of equipment that provides a similar function. How the equipment works may be different; for example, reciprocating pumps and centrifugal pumps are physical different, but they are both still pumps and they both provide a similar function. This is equipments are classified according to their primary function.	ISO 14224:1999 Duell, 2003
Equipment unit	Specific equipment unit within an equipment class as defined within the main boundary. In this level the primary function remains the same and how the function is performed becomes more similar. Equipments with fairly common object parts or maintainable items and technical characteristics are classified into the same group.	ISO 14224:1999 Duell, 2003
Enterprise	Organisation that coordinates the operation of one or more sites	ISA S88.01-1995
Failure	The termination of the ability of an item to perform a required function. Note that after failure the item has a fault. Also, "failure" is an event, as distinguished from "fault", which is a state. An item does not need to be completely unable to function to have a failure. For example, a pump that is still operating, but is not capable of pumping the required flow rate, has failed. Additionally, in reliability centred maintenance terminology, a failure is often called a <i>functional failure</i> .	BS 4778-3.2: 1991 and [1]
Failure analysis	The logical, systematic examination of a failed item to identify and analyse the <i>failure mechanism</i> , the failure cause and the consequences.	BS 4778-3.2: 1991
Failure cause	The circumstances during design, manufacture or use which have led to a failure.	BS 4778-3.2: 1991
Failure classification	The allocation of a failure to one of the failure types given in section 04 of BS 4778-3.2:1991.	BS 3811: 1993
Failure consequences	A term used in reliability centred maintenance. The consequences of all failures can be classified as being either hidden, safety, environment, operational, or non-operational. Analyse in what way each failure matter, safety consequences, and operational consequences	[1]
Failure descriptor	Apparent, observed cause of the failure. As normally reported into the maintenance management system.	ISO14224:1999
Failure discovery	Method by which failure was detected, e.g. during installation, service, inspection)	
Failure effect	The consequences of a failure mode in terms of the operation, function or status of a system. e.g. starter motor fails to operate, start motor speed less than specified.	BS 5760-5:1991

Term	Definition	Source
Failure mechanism	The physical, chemical or other process which has led to a failure.	BS 4778-3.2: 1991
Failure mode (reliability concept)	Observed manner of failure. Represents what the failure exhibit. (ISO 14224:1999) The effect by which a failure is observed (BS 5760-5:1991)	ISO14224:1999 BS 5760-5:1991
Failure Nature (failure descriptor)	Characterises the nature of the failure, e.g. mechanical failure , electrical failure.	
Failure symptoms	Event that represents what the failure exhibited (observed manner of failure) at equipment level, e.g. fail to start on demand, noise, and vibration.	
Failure reason	Indication of the motive that lead to the intervention, e.g. unscheduled, scheduled.	
Failure report	A document reporting departure of an <i>item</i> from an acceptable condition.	BS 3811: 1993
Failure source	A failure source is the lower-level component to which the failure of an item can be isolated. Failed item. e.g. x-axis, electric motor.	(Moss, 1985)
Fault	The state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. Note that a fault is often the result of a failure of the item itself, but may exist without prior failure.	BS 4778-3.2: 1991
Fault analysis	The logical, systematic examination of an item to identify and analyse the probability, causes and consequences of potential faults.	BS 4778-3.2: 1991
Fault correction	Actions taken after fault localisation to restore the ability of the faulty item to perform a required function.	BS 4778-3.2: 1991
Fault diagnosis	Actions taken for recognition, fault localisation and cause identification.	BS 4778-3.2: 1991
Fault localisation Fault location	Actions taken to identify the faulty sub-item or sub-items at the appropriate indenture level.	BS 4778-3.2: 1991
Fault mode	One of the possible states of a faulty item, for a given required function. Note that the use of the term "failure mode" in this sense is now deprecated.	BS 4778-3.2: 1991
Fault modes and effects analysis (FMEA)	A qualitative method of reliability analysis which involves the study of the <i>fault modes</i> which can exist in every sub-item of the item and the determination of the effects of each fault mode on other sub-items of the item and on the required functions of the item.	BS 4778-3.2: 1991
Fault modes, effects and criticality analysis (FMECA)	A qualitative method of reliability analysis which involves a <i>fault mode and effects analysis</i> together with a consideration of the probability of their occurrence and the rating of the seriousness of the faults.	BS 4778-3.2: 1991
Fault recognition	The event of a fault being recognised.	BS 4778-3.2: 1991

Term	Definition	Source
Fault report Incident report	A document reporting the detection of a <i>fault</i> or the occurrence of an incident, giving details of its nature, symptoms and consequences as far as is known.	BS 3811: 1993
Fault tree	A logic diagram showing which fault modes of sub-items or external events, or combinations thereof, result in a given fault mode of the item.	BS 4778-3.2: 1991
Fault tree analysis (FTA)	An analysis to determine which <i>fault modes</i> of the sub-items or external events, or combinations thereof, may result in a stated fault mode of the item, presented in the form of a fault tree.	BS 4778-3.2: 1991
Feedback	A written or oral report of the success or failure of an action to achieve its desired result that can be used to influence design, performance and costs.	BS 3811: 1993
Flow chart Procedure chart	A graphical representation of a procedure, usually using symbols connected by flow lines.	BS 3811: 1993
History record	A record of the history of the operation of an item for use in the analysis and design of the <i>item</i> .	BS 3811: 1993
Immediate maintenance Emergence	Maintenance that is carried out immediately after a fault has been detected to avoid unacceptable consequences.	BS EN 13306, 2001
Infant mortality	The relatively high conditional probability of failure during the period immediately after an item returns to service.	[1]
Information technology	The technology or recording, storing, transmitting, processing and displaying data.	BS 3811: 1993
Inspection	Any task undertaken to determine the condition of item, and/or to determine the tools, labour, materials, and equipment required to repair the item.	[1]
Item	Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered.	BS 4778-3.2: 1991
Maintainable item	Item that constitutes a part, or an assembly of parts, that is normally the lowest level in the hierarchy during maintenance. Maintainable items are lists that identify significant components that make up each item in an equipment class. These components do not generally have a unique plant identifier.	ISO 14224:1999
Maintenance	The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a stage in which it can perform a required function.	BS 4778-3.2: 1991
Maintenance action Maintenance task	A sequence of elementary maintenance activities carried out for a given purpose. Examples are fault diagnosis, fault localisation, functional check-out, or combination thereof.	BS 4778-3.2: 1991
Maintenance history	A record of past maintenance tasks that is used for the purpose of maintenance planning.	BS 3811: 1993
Maintenance philosophy	A system of principles for the organisation and execution of maintenance.	BS 4778-3.2: 1991

Term	Definition	Source
Maintenance schedule	A comprehensive list of items and the maintenance required, including the interval at which maintenance should be performed.	BS 3811: 1993
Maintenance strategy	A long-term plan, covering all aspects of maintenance management that sets the direction for maintenance management, and contains firm action plans for achieving a desired future state for the maintenance function.	[1]
Mean time between failures	The expectation of the time between failures	BS 4778-3.2: 1991
Mean time to failure (MTTF)	The expectation of the time to failure	BS 4778-3.2: 1991
Outage Shutdown	A term used in some industries (notably power generation) which is equivalent to a shutdown.	[1]
Planned maintenance	The maintenance organised and carried out with forethought, control and the use of records to a predetermined plan.	BS 3811: 1993
Preventive maintenance	The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.	BS 4778-3.2: 1991
Reliability (performance)	The ability of an item to perform a required function under given conditions for a given time interval. Note that is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.	BS 4778-3.2: 1991
Reliability	The probability that an item can perform a required function under given conditions for a given time interval. Note that is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.	BS 4778-3.2: 1991
Reliability centred maintenance (RCM)	A systematic approach for identifying effective and efficient preventive maintenance tasks for equipment and items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks.	BS 3811: 1993
Reliability data	Data on characteristics permitting quantitative evaluation of reliability	BS 3811: 1993
Repair	That part of corrective maintenance in which manual actions are performed on the item. Any activity which returns the capability of an item that has failed to a level of performance equal to, or greater than, that specified by its functions, but not greater than its original maximum capability. An activity which increases the maximum capability of an item is a modification.	BS 4778-3.2: 1991 and [1]
Root cause analysis Root causes	The root cause is the underlying cause of a problem. For example, you can snake out an old cast or galvanized sewer line every month and never be confident that it will stay open. The root cause is the hardened buildup inside the pipes which necessitates pipe replacement. Analysis would study the slow drainage problem and determine what was wrong and also estimate the cost of leaving it in place. Some problems (not usually this type of example) should not be fixed. Root cause analysis will show this.	[1]
Scheduled maintenance	The preventive maintenance carried out in according with an established time schedule.	BS 3811: 1993

Term	Definition	Source
Subunit	Assembly of items that provide a specific function that is required for the equipment unit within the main boundary to achieve its intended performance.	ISO 14224:1999
Supplier Vendor	The provider of the asset to the user	BS 3811: 1993
Technical manual	A document that communicates appropriately and effectively specific direction, data and information about the product.	BS 3811: 1993
Unplanned maintenance	The maintenance carried out to no predetermined plan. Any maintenance activity for which a pre-determined job procedure has not been documented, or for which all labour, materials, tools, and equipment required to carry out the task have been not been estimated, and their availability assured before commencement of the task.	BS 3811: 1993 and [1]
Unscheduled maintenance Breakdown maintenance	The maintenance carried out, not in accordance with an established time schedule, but after reception of an indication regarding the state of an item. (it is a maintenance strategy)	BS 4778-3.2: 1991 and [1]
User	The individual who, or organisation that, operates or uses the product.	BS 3811: 1993
Work order Job card (deprecated) Standard job	A written instruction detailing work to be carried out and methods to be used. The prime document used by the maintenance function to manage maintenance tasks. It may include such information as a description of the work required, the task priority, the job procedure to be followed, the parts, materials, tools and equipment required to complete the job, the labour hours, costs and materials consumed in completing the task, as well as key information on failure causes, what work was performed etc.	BS 3811: 1993 and [1]

[1] - Plant maintenance resource centre

[2] – Reliability centre Inc.

Appendix F

F. CLASSIFICATION AND CODING BACKGROUND

F.1 Definitions and General Concepts of Classification

In this section only the most relevant classification concepts and terms are defined, regarding the scope of the thesis. The definitions presented here are not exhaustive. They do, however, provide the basic terminology to begin our discussion. In this thesis it will not be attempted to give a formal definition of classification due to the little agreement between the diverse theories of classification. Any attempt certainly would contradict any rule of diverse theories. Instead, it will be introduced and discussed some general concepts about classification.

F.1.1 Introduction

Classification and coding practices are as old as the human race. They were used by Adam, as recorded in the Bible, to classify and name plants and animals, by Aristotle to identify basic elements of the earth, and in more modern times to classify concepts, books, and documents (Allen, 1998).

Large data sets can prove complex to understand, and it is useful to have methods of summarizing and extracting information from them. This is becoming increasingly important due to the large amounts of data that are now being collected and stored electronically. The subject of classification is concerned with the investigation of sets of 'objects' in order to establish if they can validly be summarized in terms of a small number of classes of similar objects. The methodology has been used in many different disciplines, and the parts of the subject that are relevant for a particular investigation depend on the nature of the data and the questions of interest. (Gordon, 1999)

Classification is a very general problem, and there are several tasks from a wide range of domains that can be cast into classification tasks. This includes character or speech recognition, fault detection, fault diagnosis, process control, action planning, and much more. More specific examples of where an automatic classification system has practical use includes assistance in making medical diagnosis based on symptoms, and product quality control (Holst, 1997).

F.1.2 Definition of Classification

“In its simplest form, classification is merely defined as the ordering of entities into groups or classes on the basis of their similarity. Statistically speaking, we generally seek to minimise within-group variance, while maximising between-group variance. This means that we arrange a set of entities into groups, so that group is as different as possible from all other groups, but each group is internally as homogenous as possible. By maximising both

within-group homogeneity and between-group heterogeneity, we make groups that are as distinct (non overlapping) as possible. These are general goals that specific classification techniques may alter somewhat.”

The classification terminology is not always consistent used by different users. Pankhurst (1991), for example, distinguishes between identification and classification. He refers that for biologist, identification usually means finding the name for a specimen of animal or plant, and the specimen to be identified is usually assigned to a species, and whatever sort of object is in question, it cannot be identified unless there is already a classification of like objects with which the new object can be compared. So, to him, supervised classification is identification and the word classification is used for the result of an unsupervised classification (Hand, 1997).

Some authors define classification as sorting (Connell, 2000), on other hand there others that make a distinction between classification and sorting (Zopounidis, 2002a). According to Zopounidis (2002b) classification refers to the assignment of alternatives into groups, which are not necessary ordered. Whereas sorting refers to the problem in which the alternatives should be classified into groups, which are ordered from the best to the worst. Thus, while classification is based on nominal measurements (attributes), sorting is based on ordinal measurements (criteria). For example, in medical diagnosis the identification of the disease of a patient according to his/her symptoms is a classification problem (the potential diseases are the groups and the symptoms are the attributes), since is impossible to establish a preference ordering between the diseases (Zopounidis, 2002a). According to Bailey (1994; p4) classification is simply a general process of grouping entities by similarity.

F.2 Advantages and Disadvantages of Classification

Advantages (after Bailey, 1994)

Description. Classification is the premier descriptive tool. A good classification allows the researcher to provide an exhaustive and perhaps even definitive array of types. All types are not only listed, but they are listed in a side-by-side format that allows the researcher to ascertain quickly how a particular type scores on a particular dimension and which types are contiguous to a particular type.

Reduction of complexity. Classification allows condensing huge masses of data about populations or concepts into a small number of salient types, which greatly simplifies the data analysis.

Identification of similarity. Classification procedures allow recognising similarities among cases, and group similar cases together for analysis, without to concentrate on very different cases that may not be of immediate interest. For example, the identification of similarities is the key to medical diagnosis. If we can identify cases as being similar, we can find the persons that suffer from identical symptoms. This done, we are in a position to identify the underlying illness.

Identification of differences. Classification procedures allow differentiating between different cases, so that dissimilar cases can be separated for analysis, rather than remaining mixed together.

Presenting an exhaustive list of dimensions. A good classification not only shows an exhaustive set of types, it also shows the exhaustive set of dimensions on which the types are based. Also, it shows the relationships between the types and dimensions, in the sense that each type is located on all dimensions.

Comparison of types. A good classification allows comparing types quickly and easily. One can select types in different areas of the typology and compare them. This gives a quick appraisal of the similarities and variation in the classification and the general qualities inherent in the classification.

The inventory and management of types. The full classification is one of the best inventory tools a researcher has. It allows one to quick locate any needed type, and to know at all times what types are available for analysis.

Versatility. A good classification is very versatile. It can not only represent the items studied, but also locate them within a property space formed by combining the variables utilizing in the analysis.

Disadvantages

A common criticism is that classification may be static rather than dynamic. However, some of the problems are usually associated not to the classification process itself but to the statistical methods that they incorporate. Another alleged problem is the difficulty of selecting dimensions and finding cases for classifications. An additional criticism to classification is that while small ones may be simplistic and of limited value, very large ones may be unmanageable and too complex to use efficiently. However, the computer cluster analysis can minimise some of these problems. (Bailey, 1994; 14)

F.3 Classification Approaches

According to Bailey (1994), classification involves the ordering of cases in terms of their similarity and can be broken down into two essential approaches: typology and taxonomy. The former is primarily conceptual, the latter empirical. According to Cormack (1971) distinction should be made between three types of classification procedures:

- *Hierarchical classification*, in which the classes are themselves classified into groups, the process being repeated at different levels to form a tree;
- *Partitioning*, in which the classes are mutually exclusive, thus forming a partition of the set of entities;
- *Clumping*, in which the classes or clumps can overlap, and a clump and its complement are treated as different types of class.

Distinction must also be made between situations in which entities in one class are or are not required to be distant from entities in another class: situations termed respectively classification and dissection by Kendall (1966). All collections of entities can be dissected but not all can be classified. However, dissection does not serve any purpose.

Natural and artificial classification. The distinction between things that are relatively easy to classify, such as natural phenomena, and those which are not, is implied in a distinction that used to be made between natural and artificial classifications, that is, between classifications designed to order objects in the real world and those designed to order books on shelves (Svenonius, 1983).

Manual Classification. Manual classification efforts require tremendous input of effort and rigorous quality-control processes in order to compensate for human's limited ability to apply classification rules in a consistent fashion. In practice, the cost of a high quality manual classification can be prohibitive. As a result, usually either quality suffers or organisations look to technology for assistance.

Partially-automated classification. Partially-automated classification involves human specification of classification rules, but automated (and therefore consistent) application of those rules. The weak link in partially-automated classification is in the creation of the rules. Without a quality-control process, poorly-thought-out classification rules can result in the misclassification or non-classification of very large numbers of documents. Consistent application of rules means little if the rules themselves are flawed. Yet, with well-thought-out rules a partially-automated classification system can provide a good blend of human judgement and computational efficiency/consistency.

Largely-automated classification. In largely- automated classification, a computer learns classification rules by evaluating a training set of already-categorised documents. The system then classifies new documents according to the rules it has learned from the training sets. Human auditing is necessary in order to verify that the rules the system has learned are leading to accurate classification decisions. A human editor can manually override classification decisions by moving wrongly categorised documents to different categories. There are two main weaknesses with such systems. The first involves the training set of documents. Usually, the training set of already-categorised documents is the result of a manual effort. If the training set is large, the inconsistency of manual categorisation can create an original flaw in a largely automated system's categorisation rules. Consequently, if the training set is small it is unlikely to provide a sufficient basis for the system to categorise an inflow of new object. The second main weakness involves a lack of transparency for the categorisation rules themselves. In largely-automated systems, the rules that the system has learned are either difficult to comprehend or altogether inaccessible. As a result, such systems are hard to audit for quality.

F.3.1 Unsupervised vs. Supervised Classification

A given set of objects can be classified in many different ways, resulting in a diverse range of grouping depending on the observed features used. Even for a given set of features, different classes could be obtained and a given object placed in a different class depending on the relative significance assigned to these features (Bailer-Jones, 1996).

Unsupervised classification refers to the process of defining classes of objects. When we are presented with a collection of objects and the aim is to formulate a class structure to decide how many classes there are and which of the objects in the collection belong to which classes. This classification it is also known as cluster analysis or unsupervised pattern recognition. According to the objective unsupervised classification can be divided in two types: (i) one type seeks to identify naturally occurring structures in nature, and (ii) the other type (sometimes called partitioning or dissection) simply seeks convenient divisions of the collection of objects. An example of this classification comes from marketing applications, where the population of potential purchasers is divided up into different types, not because of any belief that they are qualitatively different, but simply because it leads to a more efficient marketing strategy (Hand, 1997).

With the ***supervised classification*** the class structure is known a priori and the aim is to format or formulate rules, which allow one to allocate new objects to their appropriate classes (true classes). This is classifying an object into one of a pre-specified set of classes. This classification is also known as supervised pattern recognition. Each object is described in terms of a *vector of features* (numerical or nominal), and the group of features form a

measurement space or *feature space*. The aim of the exercise is to formulate a rule for assigning objects to their true class (which is typically unknown). For that is necessary to find a sample of objects for which the feature vectors and the true class are known, in order to create a *design set*. Thus, this sample is used to construct a general rule, which can be used to predict the classes of new objects, based solely on the measurement vectors of these new objects. The design set objects has known classifications: a *supervisor* has determined their true classes. In unsupervised classification, in contrast, there is no supervisor telling us the true classes: it is up to us to define the true class structure. The supervised classification is particular useful in prognostic situations, where we want to identify the class of an object before conventional measures of true class become possible (Hand, 1997).

Input attributes					Class attribute
Temperature	Ground	Sky	Air	Wind	Weather
Low	Cold	Dark	Dry	High	Snowy
High	Hot	Bright	Dry	Low	Sunny
Medium	Cool	Dark	Wet	High	Rainy
High	Hot	Bright	Dry	High	Windy

Table F-1: Example of a classifier input file - database (Higgins, 1993)

As a set of examples (called training set)

With supervised classification the input to a classification system is a database, such as that shown in *Table F-1* (Higgins, 1993). Here, each row of the database is an independent example; the columns will be referred to as attributes of the data, and each value of the output attribute is a class in which the data may be placed. Therefore, giving the input attributes one can learn to predict the value of the output class by looking at examples of all the attributes. For each example, the correct class is provided. (Higgins, 1993; pp 4).

Classification can act in two different ways, either by the assignment of objects to existing classes or by the creation of the classes from the data. In the former case, the classes are either ‘fundamental’ – existing independently of the measurements – or they were previously ‘invented’. The second mode of classification consists of both creating the classes from the data assigning the objects to them. Using a set measured features on a group of objects, we can draw up classes which group similar objects together, and isolate them from dissimilar objects, i.e. minimise intra-group variance whilst simultaneously maximizing inter-group variance. This form of classification is called *unsupervised*, because the classes are not formed and discriminated only on the basis of the observed

features: No external information regarding the existence of the classes is used. One technique for achieving such classification is *cluster analysis*. (Bailer-Jones, 1996)

Although explicit external information is not used in unsupervised classification, it would be wrong to suppose that such schemes are free from external bias and are somehow more 'objective'. Classes are formed based upon the similarity of objects, but a decision has to be made as to what constitutes 'similar'. The relative significance of the observed features has to be assigned, and a distance metric which measures the separation between objects in the feature space must be selected. The effects of data selection must likewise be considered. In most classification applications, the data used to create the classes will be a sample of all objects. Ideally this sample would be representative of the superset of all objects – so that the classes obtained are general – but there are often observational or experimental selection effects which bias the frequency or representation of objects in the sample. (Bailer-Jones, 1996)

F.4 Classification Requirements/Principles

One of the classification requirements is *objectivity* (Silvestri and Hill, 1964; in Cormack, 1970), which means that independent people will reach similar conclusions. Another requirement is *stability* (Jones and Needham, 1968; in Cormack, 1970). A classification is said stable when it remains virtually unaltered when new data is entered.

According to Pickett (1996) a proper classification is based on four fundamental principles:

- Only permanent characteristics contained within the information, data or parts must be selected and used in designing the classification;
- The definition of the classification categories must be precise and unambiguous.
- The classification must be comprehensive, i.e. the categories are capable of including all that comes within the scope of the classification as well as providing adequate space for future expansion;
- The essential needs and requirements of each particular user must be established and the best compromise achieved.

Regarding the construction of an ideal classification and coding system Pickett (1996) presents the following rules:

- Constant length, in order to obtain ease in handling either manually or by electronic data processing equipment;

- Comprehensive, i.e. contain as much usable and significant information within the meaning of each digit as possible;
- Applicable to the widest range of items possible. Over-specialisation will narrow the field of application;
- Only permanent characteristics of the information, data or parts should be selected and used in the construction of the classification;
- Each digit should have a unique meaning with a group of digits, i.e. fixed digital significance;
- The classification should be mutually exclusive but should not separate similar parts or items because of other minor variation;
- Adaptability to present and future design and requirements.

The construction of the complete classification requires an accurate description of each item, otherwise the system will be illogical and allow an item to be identified in two or more different positions (Petroff, 1986; in Picket, 1996). The selection of characteristics and their systematic arrangement must be the overall requirements which classification has to satisfy. (Picket, 1996).

F.5 Classification Methodology

Ball (1970) suggests the following questions to guide the developing an appropriate classification:

Basic theoretical questions

- What are the goals of the user?
- What assumptions are made about the underlying structure of the data?
- Does the user have examples of well-defined groups on the basis of which he wishes to develop a discrimination scheme, or does he have a relatively undifferentiated set of objects whose underlying structure he wishes to explore by clustering on the basis of inter-object similarity?
- Does the user primarily wish to group variables or to group objects?

Questions concerning the nature of the variable and objects

- How are the variables and objects determined to be worthy of study in the first place?
- How are the variables scaled and counted?
- How are individual variables (or objects) combined into a single number that can be used to measure similarity between objects (or variables), or to measure the similarity of an object (or variable) to a class?

Questions related to the availability of computer capabilities

- What techniques and existing programs contain the desired ingredients? How well does an implemented program accomplish its theoretical objectives?
- Can classes of techniques be identified? What are the characteristics of each class, and what is focused on the definition of that class?
- What other techniques does the user plan to use in conjunction with techniques for sorting into groups? How should results from various techniques be integrated to provide a coherent overall view of the data?
- How would a user prefer results of sorting be presented to him?
- What criteria should be used in evaluating results?

F.6 Classification and Coding Systems

Classification Coding. This technique classifies items by their principal characteristics. There are basically three methods for doing this: (Watts, 2000; pp79)

- *Purchase a packaged system.* There are several packaged systems on the market that have served some companies well. Requires one or more people to be trained, to code each new item, and to filter out duplicates.
- *Naming convention.* Make sure that Descriptions and Name on drawings are done with considerable discipline. Your CAD/PDM probably has the ability to do key word search. The result is a crude but effective classification system.
- *Database fields.* Devise your own class code in your database. Set aside a separate field for each element that is a significant item characteristic. This will require report writer programming to make it useful.

The intent of any coding/classification system is the same - to aid the company, especially the Engineers, in four ways:

- Allows the Design Engineer to avoid reinventing the wheel. That is, to use an already designed item. Without a classification coding system, the engineer may well conclude that it is easier to create a new part than to try to find an existing one.
- Similarly, it allows the Company to standardize. In other words, to sort through similar items and to designate only certain ones to use in future designs. Other items would probably be phased out of existing designs and made obsolete.
- Engineers can more easily find similar items for possible substitution. This is very helpful to manufacturing when a critical part shortage arises.
- Allows the Industrial or Manufacturing Engineer to utilize Group Technology to produce similar items in manufacturing cells. It can also help in the machine loading of molding machines, for example.

Coding. Coding is an intellectual demanding task that involves the identification of categories, defining and refining them as well as the boundaries between them. Consists of a system of symbols for information processing that reflects the similarities and differences in the classification method. Note that coding, like classification is means, not ends. Coding can be used for classification purposes. Coding involves intellectual and clerical processes. The role of computer software tends to be limited to assisting the analyst with the clerical tasks involving coding. The intellectual tasks remain the responsibility of the analyst (Tesch, 1990). Coding with computer assistance should bring benefits in time saved on clerical tasks, less tedium and better quality analysis (Weitzman and Miles, 1995; in Catterall, 1996). However, there are a number of drawbacks associated with employing computers in coding.

Characteristics of a good coding system:

- Classes and terms used are familiar to users
- Hierarchical relationships designed into the system must reflect user preference.
- All classes and terms must be mutually exclusive
- The number of items in each class must be approximately equal, and large enough to assure far fewer classes than components
- Must be expandable to include new classes and items
- Notation should be simple and non-ambiguous to apply, recognise and communicate

F.7 Classification and Coding Systems Applications

Following are some examples of classification & coding system applications.

Medicine: performing medical diagnosis through the classification of patients into diseases groups on the basis of some symptoms;

Pattern recognition: examination of the physical characteristics of objects or individuals and their classification into appropriate classes. Letter recognition is one of the best examples in this field;

Human resources management: assignment of personnel into appropriate occupation groups according to their qualifications;

Production systems management and technical diagnosis: monitoring the operation of complex production systems for fault diagnosis purposes;

Marketing: customer satisfaction measurement, analysis of the characteristics of different groups of customers, development of market penetration strategies, etc.

Environment and energy management, ecology: analysis and measurement of the environmental impacts of different energy policies, investigation of the efficiency of energy policies at the country level;

Financial management and economics: business failure prediction, credit risk assessment, bond rating, etc.

Parts numbering systems. The systems that exist for coding and grouping parts are too numerous to mention; however, a few that are better known are BRISCH from United Kingdom, OPITZ from Germany, MICLASS from Netherlands, CODE from USA, and KK-3 from Japan. The BRISCH system is a hierarchical or monocode and works through the classification code to the most detailed characteristics with significance of each digit dependent on the preceding number. Polycodes give primary consideration to the parameters affecting the production of a component part and are exemplified by: OPITZ system, a nine-character code; CODE, an eight-character system, and MICLASS, a 12-character code. Monocodes such as BRISCH are mainly of use to the design-oriented plant, while polycodes are primarily suited to a manufacturing environment (Carson, 1983).

Group Technology: classification and grouping components according to their similarity in shapes, to form design families. Components that are not similar in shape may still require similar manufacturing processes and may be classified and grouped to form production family (Pickett, 1996).

G. TOOLS TO SUPPORT THE DOCUMENTATION SYSTEM DESIGN

G.1 Task Support System

Based on the work of Tjahjono (2003: p16) the term Task Support System (TSS) is used hereafter to represent both EPSS (Electronic Performance Support System) and ITSS (Iterative Task Support System). The main purpose of TSS is to support workers' activities by providing a constantly available source of information that is accessible on-demand, *i.e.* they are essentially sources of information to support tasks. Moreover, in the context of this research, TSS only refers to industrial applications type. Although the look and feel between industrial and non-industrial applications may be similar, the differences between both affect their design (Tjahjono, 2003; p23). *Table G-1* presents the main differences between the two types of applications.

The TSS focus on computer-related technologies (McGraw, 1994; Reynolds and Araya, 1995). Some authors emphasise the use of multimedia and hypermedia technologies (*e.g.* Stevens and Stevens, 1995), whereas others (*e.g.* McGraw, 1994) considered that expert systems and artificial intelligence are needed to develop TSS. Moreover, according to Tjahjono (2003: p17) the hypertext and hypermedia technologies, the World Wide Web, the computer-based training systems, and the electronic documentation systems are the main technologies used within industrial TSS. *Table G-2* briefly presents some of the features that characterise these technologies.

The application of industrial TSS, and related systems, has been applied for many purposes. Some examples areas follows: adaptive hypermedia for maintenance, maintenance diagnostics, digital maintenance manuals, quality control, and assembly operations. *Table G-3* summarises the previous work that have conducted in this area.

In addition, there are many good reasons for using hypermedia as a task support systems. *Table G-4* presents some of these reasons.

	Industrial Hypermedia TSS	Non-Industrial Hypermedia TSS
Task	<ul style="list-style-type: none"> • Complex, procedural, industrial tasks • Step-by-step & interdependent • Requires visual inspection and judgement • Maybe time and safety critical • The use of hardware/too/complex equipment 	<ul style="list-style-type: none"> • Less complex, non industrial and typically intellectual tasks • Not necessarily sequential tasks • Less likely to be critical to safety of users
User	<ul style="list-style-type: none"> • Typically shop floor workers with low to moderate computer experience 	<ul style="list-style-type: none"> • General users with typically moderate to high computer experience
Information Content	<ul style="list-style-type: none"> • High level of diversity • Many different information sources and formats • Industrial task related • Information supplied or managed by task experts 	<ul style="list-style-type: none"> • Less diverse information sources and formats
Information structure	<ul style="list-style-type: none"> • Reflects user's mental model of task to avoid disorientation & cognitive overhead • More sequential navigation, less non-linear access 	<ul style="list-style-type: none"> • General usability criteria is sufficient • Fewer restrictions, can be purely non-linear access
Environment	<ul style="list-style-type: none"> • Maybe noisy and dirty • May have poor lighting • Workspace may constraint ergonomics • More pressure in obtaining the information 	<ul style="list-style-type: none"> • Less disturbance, e.g. in offices, internet cafes • More attention paid to ergonomics • Less hazardous to users' health and less likelihood of contaminant ingress
Infrastructure	<ul style="list-style-type: none"> • Computers with low to moderate spec • Need more robust system due to more specific purpose • Restricted access privilege • May not guarantee 24/7 support 	<ul style="list-style-type: none"> • Usually high spec computers • Freedom to configure software/plugin-ins • Easy access to support
Purpose	<ul style="list-style-type: none"> • Setup procedure, troubleshooting guides • Quality documents, governed by legislation or standards 	<ul style="list-style-type: none"> • Information retrieval, information archival, e-commerce, entertainment • Less influenced by legislation

Table G-1: Industrial vs. non-industrial TSS applications
(after Tjahjono, 2003)

Technologies	Features
Hypertext, Multimedia, and Hypermedia	<p>Hypertext provides non-sequential information access as opposed to 'reading traditional text' on paper, <i>i.e.</i> the reader can jump from text to text without needing to follow a linear sequence (Nelson, 1995)</p> <p>Multimedia allows integration of text, images, sound and video (Gunasekaran and Love, 1999). Enables to convey information with large degree of comprehension.</p> <p>Hypermedia systems integrate hypertext and multimedia, <i>e.g.</i> World Wide Web. It uses associative relationships among information contained within multiple media for the purpose of facilitating access to, and manipulation of, the information encapsulated by data (Lowe and Hall, 1999). Differs from multimedia in the way in which a user navigates between text, images and videos. The user may decide the path or the sequence to take when a number of options are available and control the duration of the information to be presented (Nielsen, 1995).</p>
World Wide Web	The information system that attracts more users. It has become an important part of the infrastructure of TSS (Dickelman, (2000), <i>e.g.</i> web-based task support systems.
Computer-based & Web-based trainings (CBT & WBT)	Mainly used for training. CBT is considered to be the backbone of the early TSS. CBT tend to be stand-alone, where multiple versions have to be developed for different operating systems. CBT difficult to navigate in a non-linear fashion (Hall, 1998). The WBT adds web features to the CBT, thus content is hosted on the web server and is accessible from any web browser regardless of its operating system.
Electronic Documentation Systems	<p>Electronic documentation systems can be generated for two mainly reasons: archiving purposes and to serve as online help.</p> <p>The archiving purpose is usually found in an extremely high number of documents where document tracking is crucial (Haywood, 1999). The primary considerations for these types of electronic documents are the formal document structure and the standard file format. The PDF is perhaps the most commonly used format for this type of electronic document (McKinley, 1997: p53).</p> <p>Electronic documents may serve as online help and be integrated to be displayed directly on visual display units. Here, the user interface and the presentation style of the information are more important to ensure usability (Hulme, 1984).</p>

Table G-2: TSS - Technologies features

Case	Task to deal with	Purpose	Enabling technology	Findings
CATS and CATSII (Kasvi <i>et al</i> , 1994)	Assembly operations (Television)	Training of new operators	Multimedia	Multimedia can be used as a training tool in an industrial environment
HOTS (Kasvi <i>et al</i> , 1994)	Assembly operations (DC converter)	Training and performance support	Multimedia	Multimedia is better than paper-based instructions. Users prefer to use HOTS than the conventional system.
Task Supporter (Kasvi <i>et al</i> , 2000)	Light assembly	Task support	Multimedia	Failure of system caused by inability of the industry to update the content easily
Ryobi System (Kasvi <i>et al</i> , 1996)	Machine set up & calibration (balancing motor armature)	Task support, digital manual	Hypermedia	Hypermedia is a viable technology for task support. Shop floor operators endorsed the hypermedia system.
APPLE A (Rea <i>et al</i> , 1998)	Assembly planning	Task support, decision making	Hypermedia, Web	Overcome problems associated with paper documents; matching assembly job and skill availability
ADAPTS (Brusilovsky and Cooper, 1999)	Maintenance (helicopter)	Task support	Adaptive hypermedia, user modelling	Integrated adaptive hypermedia with condition-based maintenance
QALive (Ockerman <i>et al</i> , 1999)	Quality Assurance	Assist QA engineers to inspect products; training refreshers	Hypermedia	QALive acts as a expert advisor and expert performance support. Improve task support
IPM (Pham <i>et al</i> , 1999)	Maintenance and diagnosis	Product support, troubleshooting guides	Hypermedia, web, expert system	Product information and diagnostic into an integrated, intelligent product support
FIRM (Crowder <i>et al</i> , 2000)	Maintenance & diagnosis	Information management	Open hypermedia	Feasibility of open hypermedia in industry; linked various types of documents in their native format.
Digital manuals (Greenough <i>et al</i> , 2001)	Maintenance (engine machining line)	Task support)	Hypermedia	Creation of cost-effective hypermedia maintenance manuals using PDF from the legacy documents.
EMI (Greenough <i>et al</i> , 2000)	Assembly operations (mobile phones)	Task support, training	Hypermedia, Web	Well acceptable by end users who liked use of video and computer animation to illustrate assembly steps.

Table G-3: Previous work in industrial TSS
(after Tjahjono, 2003; p33-34)

Features	Reasons for using hypermedia as a TSS
Information Association	<p>The hypermedia links allow a human being to partially mimic how human brain associates pieces of information through non-sequential access (Ginige et al, 1995) and uses this relationship to construct understanding of the information.</p> <p>These systems have a similar structure to a book. However, the principal difference is that, with hypermedia, the user will be able to locate the support quickly by following the links.</p>
Embedded Support System	<p>Hypermedia allows the link to be embedded within the task (Raybould, 2000), so it enables direct access to the support system from the point where the task is carried out. The impact is that the task and the support system, which were previously physically separated in the conventional support system, can now be integrated.</p>
Improved Comprehension	<p>It enables a new way of delivering learning experiences to users more efficiently, because hypermedia links together multimedia objects (Najjar, 1995).</p> <p>For example, the use of animation or digital video together with textual description result in better understanding than the textual description alone (Mayer and Anderson, 1991). Moreover, people supported with multimedia objects complete tasks faster than people who had text only (Kasvi et al, 2000).</p>
Language barrier	<p>Multimedia can break the language barrier, because of the use of animation and illustrations (Neiminen et al, 1995).</p>

Table G-4: Reasons for using hypermedia as a TSS
(after Tjahjono, 2003; p21-22)

G.2 Integrated EDM and DBM

This section describes the integration of Electronic Document Management Systems (EDMS) and Database Management System (DBMS).

Documents, despite having a tremendous capability of holding a great deal of multifaceted information, have their own weaknesses. The real weakness of documents, and this has little to do with storage or display technology, is that they are difficult to search. Because most of the information content of a document is un-coded and because there is very little in the way of search engines for un-coded data, documents are difficult to search. Once stored, they are difficult to find unless they have been indexed with exactly the criteria for which one is searching. Unfortunately, information is of little use if it cannot be found readily when needed (Banyay, 1999).

On the one hand, a DBMS is a tool that has tremendous capabilities to search and reproduce information to which it has access, in the combinations that users generally require. The weakness of the DBMS, however, is that it generally has access to only a limited perspective on a small body of information. On the other hand, an EDMS is a tool that can house vast amounts of content about a body of information, from a multitude of perspectives. The primary weakness of an EDMS, however, is that once the information is stored it is difficult to find. Neither one of the tools on its own seems capable of meeting the expectations for comprehensive information management. They do however have complementary strengths. With the DBMS, information is relatively easy to find, and, with the EDMS, information content is vast and rich. If one could successfully combine these strengths, then one would have a tool that might meet the expectations of the business community better. The combination might not meet all of the expectations, but would certainly be superior to either tool in stand-alone mode. The whole promises to be greater than the sum of the parts in this case. The logical question arises, "Why use a DBMS to store data?" Why not use the EDMS to store the information, and use the DBMS to store the data about the EDMS or metadata? This would enable one to search the DBMS for the combination of information that one requires contained in the EDMS. This is exactly the approach that many leading vendors of document management applications, such as *FileNet* and *Documentum*, have taken. Both vendors use a relational database to store the metadata that points to various data stores, such as magnetic or optical disk, that house the documents (Banyay, 1999).

The DBMS in many of these document management systems has evolved beyond simple metadata, which just houses pointers to content documents. These second-generation document management systems have developed the concept of the virtual document. The metadata in second-generation document management applications also contains far richer

information, such as a comprehensive history of the virtual document. The history may contain work-in-process information or information about each member document, such as the time each was added to the document collection, who entered it, and from which application (Banyay, 1999).

The combination of DBMS and EDMS certainly offers advantages over either in standalone mode; however, the degree of the advantage can be deceptive. The metadata in the database is just that, data about the document and not about all of the information within the document. Here is the crux of the matter. What is metadata but distillation? If the only way to find a wealth of information is through the limited perspective of its metadata, then the information is not nearly as valuable as if one could find it from the multitude of perspectives contained within the information itself (Banyay, 1999).

Whatever the solution to reducing the effects of data distillation, it is not something that will be totally eliminated within the near future. Combining the strengths of a DBMS and an EDMS, however, definitely provides better access to a larger volume of information than if either one is used alone. The combination is by no means a panacea, but it is a step or a number of steps in the right direction toward solving the information processing problems that knowledge workers face every day (Banyay, 1999).

As the marriage between the DBMS and the EDMS evolves further, there may be a new dawn for IT. This new dawn will be true electronic information processing rather than electronic data processing. The real payoff in this evolution and in developments of this nature is that it may eventually solve the seeming paradox of information processing in the office environment.

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