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A STUDY OF SAFETY AND PRODUCTION PROBLEMS AND SAFETY STRATEGIES ASSOCIATED WITH INDUSTRIAL ROBOT SYSTEMS

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ABSTRACT

This thesis deals with a study of industrial robot use with particular reference to production systems in six companies. The main focus is on the hazards and production problems of robot use, the safety strategies developed and adopted and the problems for safeguarding the production systems. The thesis begins with an overview of the use of robots in industry and the aims and objectives of the study. Statistics on current levels of use including diffusion through industry and across tasks are described. A method of classification for robot designs is presented. The literature on robots, safety and production reliability is reviewed, with particular reference to health and safety at work, accident and safety research and the hazards of the use of robots.

The empirical study is described and the hypotheses and methods of study outlined. The six companies are presented as case studies which contain information on the industrial context, work organisation structures, working environment, robot systems' design and operation, safeguards, working practices and issues relevant to safety such as training and the involvement of safety personnel. The safety strategies in the case studies are analysed using a framework of strategic options. The robot systems are considered in terms of the identification of hazards, the elimination, containment or mitigation of hazards, the availability and allocation of scarce resources, the role of key interest groups and the technical and motivational control measures available in each case. Unanticipated consequences and adaptations to the safety strategies are also considered.

Comparable production problem data from 4 companies is considered in detail in order to identify major problems areas with robot systems, for example lost production time and frequency of problem occurrence. The severity of recorded incidents of lost production time and their underlying reasons are given particular emphasis. Safety implications of this data is considered by reference to a typical robot system. Risk analysis techniques are considered and their applicability to a study of hazards discussed. Event Tree Analysis is chosen to analyse the propagation of hazards through a series of actions and hazardous occurrences. The thesis concludes with a discussion of the findings, drawing implications for system design, working practices and safety strategies with industrial robot introduction and use, presenting a Guide for Robot Users and recommending areas for future research.

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The Head of the Mechanical Engineering Department and Director of the Centre for Robotic and Automated Systems, Professor Tom Husband also provided invaluable assistance, both in terms of access to the resources of the Centre and more personally in advice and comment on written material, some of which has been used in this thesis albeit in altered form.

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My parents have provided support on both an emotional and material basis for which I can never be sufficiently grateful. Their desire for the highest educational level that I could achieve has provided a continuous spur to supplement my own ambitions. I can only hope my achievements gives them pride in the product of their efforts.

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INTRODUCTION

The introduction of new technology in industry occurs for a number of reasons. The economic benefits of improvements in production, increased efficiency or better management control are commonly stated. It is also often argued that introduction of technological advances can improve working conditions, the intrinsic value of particular work tasks and the general level of health and safety at work. However, history has shown that along with the benefits of technological advances come a number of less welcome effects. The process of industrialisation in Britain beginning in the late 18th Century produced some significant improvements, notably to the general wealth of the population and less directly to their education. But it also generated unwelcome costs, like a polluted countryside, health hazards and an initially high industrial accident rate. The costs and benefits of industrialisation were not equally distributed to the population.

As an example of modern technological advance, automation similarly provides both costs and benefits. For example, industrial robots offer the possibility of improved health and safety as they can substitute for a human in hazardous environments, but the introduction of new machinery is likely to create some hazards. The ultimate success of the use of industrial robots will depend on finding solutions to problems they create, particularly in the fields of production, management and safety.

This thesis reports on research on safety and production problems and solutions associated with industrial robots and their production systems. It pays particular attention to management strategies as a basis for solving safety problems. This does not mean that safety engineering has been excluded, rather that the focus is on how safety engineering principles have been applied in practice.

The aims of the study were:

(1) to identify problem areas with industrial robot use - their hazards, problems with production and difficulties in the development and implementation of safety strategies.

(2) to distinguish safety strategies for different contexts in terms of their effectiveness and to suggest appropriate means for their adoption.

In the light of these aims, several objectives were formulated:

(a) The consideration of previous literature on robot hazards and guidance on safe robot use, to gain an understanding of the area, in preparation for the analysis of empirical data.

(b) The consideration of previous studies of production and reliability of relevance to a study of robot systems, to provide typical figures for production problems and reliability.

(c) The collection and analysis of data on safety and production problems associated with several representative robot production systems in industry.

(d) The study of the safety strategies adopted in each robot production system, identifying the elements of each strategy.

(e) The derivation of conclusions on major problem areas, on the difficulties and on conditions for effectiveness of safety strategies.

These aims and objectives provide the focus for the thesis.

Chapter 1 provides an introduction to the technology of industrial robots. It describes robots in terms of their elements and classifies them according to the categories of elements that are in widespread use. The design of robot production systems is also described. The current use of industrial robots is discussed to show the areas of application commonly found for industrial robots. Production reliability research relevant to industrial robots concludes this chapter.

Chapter 2 deals with the background literature for health and safety at work. The context of health and safety at work is described with reference to the legislation, overall philosophy and controlling bodies. Safety research is also presented to show the pattern, causes and influencing factors of accidents. A summary of a framework for the management of safety strategies concludes this chapter.

Chapter 3 presents the literature on the benefits and hazards of industrial robot use. Authoritative statements on robot hazards are discussed and are supported by a number of previous surveys of accidents with industrial robot systems. The guidance provided in the literature on safe robot use is then presented.

Chapter 4 describes the background to the empirical study undertaken for the research. The aims and objectives of the study are described and propositions for the collection and analysis of data are provided and the data collection methods are outlined.

Chapter 5 presents systems descriptions from six robot user factories. The system layout, safeguarding features, working practices and training provisions are included in a detailed presentation of each system. Production problem data from four of these factories are then presented. The periods of production covered are given and the data analysed in a number of subsections. The overall figures are presented in tabular form with frequency percentages. Further analysis is made of underlying reasons for downtime the classification of incidents, robot related incidents and the distribution of downtimes. The safety implications of the production problem data are also considered.

Chapter 6 presents the analysis of the safety strategies in the six factories. The framework of the management of safety strategies, presented in Chapter 2, is used to identify the means adopted in each factory to achieve safety.

Chapter 7 considers the application of risk analysis techniques to the assessment of safety with industrial robot systems. Several techniques are considered as well as the constraints on their applicability. The application of Event Tree Analysis to the assessment of a typical robot welding system is presented and the findings of this assessment are generalised and applied to the industrial robot systems studied in the Empirical Study of this thesis.

Chapter 8 concludes this thesis with an assessment of the findings of this thesis in terms of the propositions given in Chapter 4. The findings are also used to develop a Guide for Robot Users, which is presented in the form of a checklist. The chapter ends with some recommendations for future research, which develops from the research reported in this thesis.

CHAPTER 1

INDUSTRIAL ROBOTS: THE TECHNOLOGY AND ITS USE

INTRODUCTION

This chapter describes the technology with which this thesis is concerned, namely industrial robot production systems. It deals first with a definition and specification of industrial robots. Secondly, the main components of industrial robot systems are described. This advanced form of production equipment is thus placed in the context of the equipment with which it is associated in a productive system. This section also includes a brief description of application areas. Thirdly, studies of the spread of robot use are considered, both within the U.K. and internationally. The chapter ends with a fourth section on production reliability studies of industrial robots and similar equipment, which gives an indication of the performance of advanced microelectronic equipment.

INDUSTRIAL ROBOT DEFINITION AND SPECIFICATION

Definition

The term 'industrial robot' is a common description for new automated production equipment. Yet a formal definition of an industrial robot is not universally accepted. A dictionary definition is given as "an apparently human-like automation" (New Scientist, 1980), drawing heavily upon the origins of the word, in Czech, meaning a worker or a performer of menial tasks. Websters 7th New Collegiate Dictionary gives a definition of a robot as "an automatic apparatus or device that performs functions ordinarily ascribed to human beings <u>or</u> operates with what appears to be almost human intelligence" (Engelberger, 1980). Robot Associations in this country and in the U.S.A. have attempted a better, more exact definition.

The British Robot Association (BRA) definition of an industrial robot, as a "reprogrammable device designed to manipulate and transport parts, tools or specialised manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks" has received wide support (e.g. Inbucon, 1982). The recent publication by the Machine Tool Trades Association (MTTA, 1982) takes this version as the basis for its definition, with only minor alteration and some additions, namely "an industrial robot is defined as a position controlled reprogrammable multifunctional manipulator having a number of degrees of freedom capable of handling materials, parts, tools or specialised services through variable programmed motions for the performance of a variety of tasks". The Robot Institute of America has adopted a definition that differs only slightly from this. However, one can say that to a large extent general usage in mechanical engineering circles considers a robot "A mechanical arm, with several degrees of freedom, that can carry out a wide range of human-like movements and is controlled by a computer" (New Scientist, 1980).

Specification

To most engineers the task of finding an exact formal definition would be a mere exercise in semantics. Their interest in the technology would probably rest on the device's capabilities and whether the introduction of a robot is economically justifiable. From this view-point "there is a continuum of 'robot-like devices' commercially available, at one extreme the manipulator, at the other pick-and-place unit" (Machinery and Production Engineering, 1982). The commonly accepted view of an industrial robot places it in the middle ground of this continuum, and within this middle ground there is another continuum of devices available. However, a common factor runs through all the types of robots, in that they have a "programmable control system which endows the device with a high level of versatility and enables it to be changed from one sequence of movements to another easily and relatively quickly" (Machinery and Production Engineering, 1982). This continuum of types of robots can be listed in broad generic groups as a means of classifying robots:- (from Inbucon, 1982).

Class	Definition
1) Manual Manipulator (or manipulator mentioned above)	Operated directly by a human being - to provide 'muscle'. Used in handling dangerous or heavy materials. Cannot be considered within a strict definition of an industrial robot.
2) Fixed Sequence robot.	Operates independently in accordance with a predetermined programme which cannot be changed easily.
3) Variable sequence robot.	Operates independently in accordance with a range of interchangeable programmes.
4) N.C. (numerically-controlled) robot.	Operates in response to numerical input data.
5) Playback robot.	Operates in accordance with a sequence which it has been 'taught' by a human being.
6) Intelligent robot.	Automatically adapts its sequence to the signals from built-in sensors.

In all these types (excluding the manual manipulator) there is a common element of a control system which is automatic and can be reprogrammed. One could say that all robots have 3 basic elements; the controller, the power supply and the mechanical design (Industrial Robot Specification, 1984). The controller 'remembers' the task and controls the motions of the manipulator by means of a microprocessor unit; the power supply provides the power to do the work (usually one of 3 types:- hydraulic, electric or pneumatic); and the manipulator is the mechanical unit or arm which performs the work. In addition robots are specified by their programming methods, the type of end-effector which is used and the dynamic performance of the robot. Each of these aspects of robot specification are discussed below.

The controller

The various types of robots can be differentiated according to their controls, that is, whether they are servo or non-servo controlled, point-to-point or continuous path control. At the least complex end of the scale of robots, there are the non-servo powered, limited (or fixed) sequence robots. These use a series of mechanical stops and limit switches to control the movements of arm and hands. The robot can then be moved from one position to another, but the path (and speed) in between is not defined. The controls simply switch the drives on and off at the two ends of travelling. This type is usually termed the 'pick-and-place' robot.

A servo mechanism can be used instead of mechanical(or electro-mechanical) stops to achieve positional accuracy. Such a device gives out an electrical signal proportional to the limb position. As the limb moves closer to the desired position, the signal reduces until the limb stops in the correct position. With the use of a memory to record the various positions, the robot has point-to-point servo control. The robot controller provides information about a series of points through which the robot hand must pass, with the attitude of the various parts of the limb before and after the movements. The paths to be traced by the various parts of the limb of the robot is not controlled. The control unit must therefore have the capability to take the optimum path from one point to another. Such a robot is much more expensive than the non-servo controlled robot (Industrial Robot Specifications, 1984), but is often necessary, especially in the handling of heavy or fragile loads.

It is sometimes necessary to specify the whole path of the robot arm all the way through the operation and for this continuous path control is essential. In a way, continuous path control is merely an extension of point-to-point control, with the robot memory being large enough to record considerably more points in the robots motion - enough to make the path control continuous to all intents and purposes. Servo-control is essential on robots for continuous path motion. There is also a need for a large memory storage with this kind of control, and as a result magnetic tape or disc is sometimes employed instead of a micro-chip. These robots are also typically lighter than point-to-point robots and have a lower load capacity although some large continuous path robots are in operation. A small percentage of robots (10%) are of this kind (Industrial Robot Specifications,1984). Thus the vast majority of robots are point-to-point controlled.

The power supply

Different sources of power may co-exist on the same industrial robot for the different articulations required. These are usually of three types:-

a) Electrical
b) Pneumatic
c) Hydraulic.

The electrical drive system has usually been assigned the smallest share of the robot population (20% - Industrial Robot Specifications, 1984).

Pneumatic systems appear in 30% of robots - mainly in limited sequence robots (Industrial Robot Specifications, 1984). These have the merit of being cheaper than the other drives and also inherently more reliable (hence reducing maintenance costs). What is more, it is common for companies to have compressed air lines already installed. However, the use of compressed air as a drive mechanism does not permit easy control of either speed or position and also developments in the two competing drive systems have improved in their relative reliability. It appears that the choice in power supply is becoming increasingly one between electrical and hydraulic with an increasing share for electrically driven robots.

Hydraulic cylinders and motors have the advantage of being more compact and also allowing high levels of force and power while giving accurate control. Electric motor systems can suffer the disadvantage of lacking stiffness in the power transmission through gearing and ball screws. As a result, the positional accuracy so much sought after by robot manufacturers tends to be lost. But this does not mean that electrical drive systems are always less appropriate than hydraulic systems. Many of the problems of accuracy with electric motors have diminished. What is more, the choice will be made for the simplest device which can perform satisfactorily.

The hydraulic piston actuator system has its advantages, being simple, reliable and the least expensive means of turning power into motion. But if dynamic performance is required with reasonably large loads, then the choice shifts to hydraulic motors. These are an expensive but efficient way of using energy to achieve better performance. Overall, hydraulic motors are superior to electric ones largely due to the fact that energy is more easily stored in an accumulator for an hydraulic system, being released when activity is required. Because there is no easy way to store sufficient electrical energy, electrically driven robots tend to be underpowered, which results in a very slow machine for heavy loads over large movements.

To offset these advantages for the hydraulic system there is the possibility of the danger of fire in some applications. This precludes the use of conventional petroleum based hydraulic fluid and demands the more expensive non-flammable fluids, such as phosphate ester or water glycol. Kochhar and Burns identify problems with the maintenance of hydraulic systems, particularly sealing difficulties and leaks (Kochhar and Burns, 1983). They also identify problems with performance changes with temperature variations. On the other hand, electrical drives would be less favourable where the environment presents an explosion hazard.

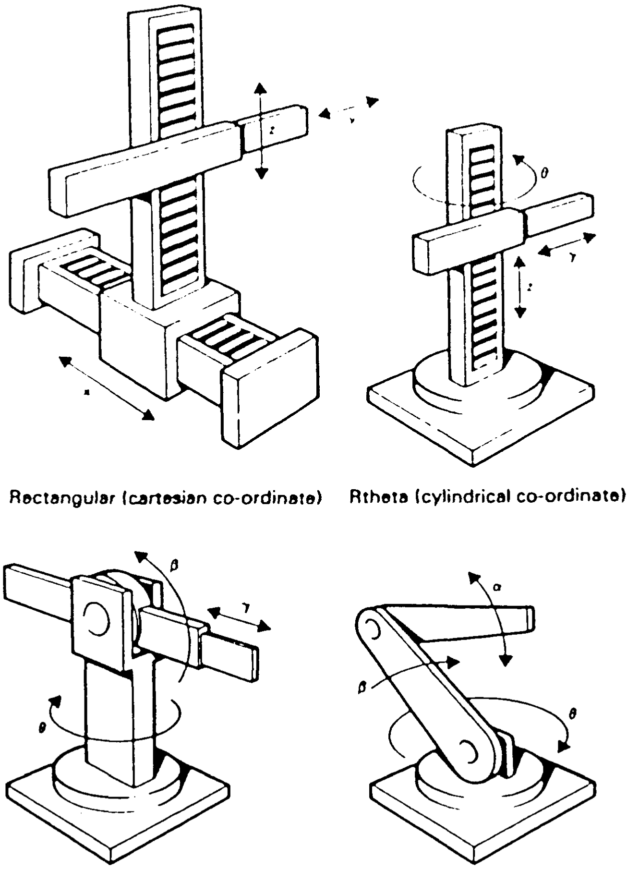
The advantages of hydraulic systems disappear as one considers smaller robot size and as the need for a powerful thrust and dynamic performance disappear. For this and for financial reasons, it is common to find the smaller robots operating with electrical drive systems (Engelberger, 1980).

Mechanical design and configuration

From a mechanical point of view, the industrial robot is a fairly conventional device. The drive system, and the tilting, swivelling and articulating movements use techniques which are all well established in other machinery. Indeed, one robotics company emphasises that their robots use machinery familiar to any machine maintainer. The claim of advanced technology for robots rests on the control system, which ensures instructions are repeated faithfully and consistently, even providing some form of sensory awareness to the robot. Nevertheless, the manipulator, or the 'business end', is an important part of the robot and needs to be described.

One can make a distinction between three groups of the manipulators on industrial robots: those with telescopic motions, those with linear motions and those with articulated motions. The possible configurations these provide allow robots to have differing spatial coverage. Four of the most common configurations of robots are shown below in Figure 1.1. These are Turret (or spherical co-ordinate), Articulated (or jointed arm), Rtheta (or cylindrical co-ordinate) and Rectangular (or cartesian co-ordinate). (Industrial Robot Specifications, 1984). Three of these configurations contain telescopic motions, two linear motions and three articulated motions. Telescopic movement, as a result of rising, falling, extending, retracting and swivelling, covers a volume that is basically cylindrical - or forming part of a sphere if there is tilting motion included (such as in the Turret configuration). An articulated arm can cover a volume which is roughly spherical (if it's pivots are oriented horizontally).

The Rtheta configuration is similar to the motions of a radial drill press. All positions at the extremity of the arm describe a portion of a cylinder. The Rectangular configuration covers a box shaped volume, with the height, width and length fixed by the extent of the robot movement in the three axes. The coverage of the robot arm is obviously dependent upon the various lengths of the parts of the arm and with three degrees of freedom, the robot arm can move so that its wrist can be placed at any point within a given volume fixed by the arm configurations (see Figure 1.2 below). A human arm is capable of a total of six degrees of freedom including the motions of the wrist. As Figure 1.3 shows, a robot's wrist is also capable of 3 axes of motion. It is not always necessary for all three of these to be available for a particular task and a total 5 degrees of freedom on a robot arm is common.



Rectangular (cartesian co-ordinate) Rtheta (cylindrical co-ordinate)

Turret (sperical co-ordinate) Articulated (jointed arm)

Figure 1.1 Four Common Robot Configurations (Industrial Robot Specifications, 1984)

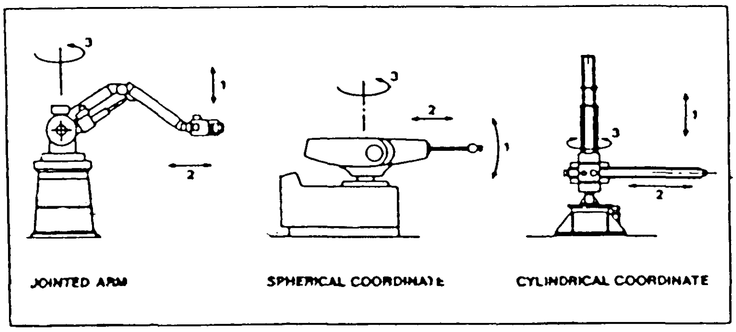


Figure 1.2 Main Axes of Motion for Robot Arms (from Industrial Engineering, 1981)

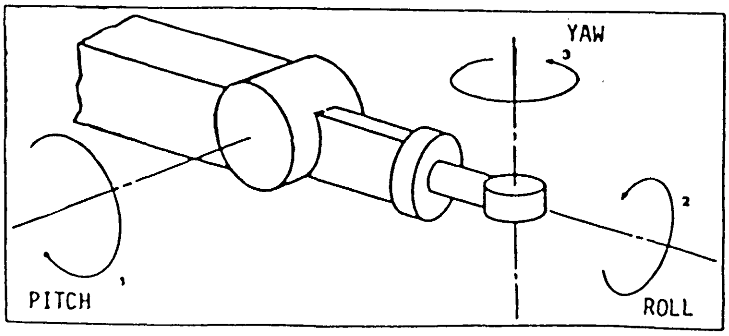


Figure 1.3 Axes of Motion for the Robot Wrist (from Industrial Engineering, 1981)

Programming methods

There are a number of different teaching or programming methods for robots. These can be grouped into four categories (MTTA, 1982).

(1) Manual lead-through or manual teaching

The robot arm is led manually through its motions and the rest positions of the arm are recorded. More complex controls (i.e. continuous path control) store the complete contour through which the robot moves. Sometimes the motions can be played back at a faster or slower speed than recorded.

(2) Master slave or slave mimic

The robot is taught by the programmer moving a separate and possibly scaled-down version of the robot arm - the 'slave mimic'. The robot may be activated during this and follow the motions of the 'slave mimic' as it is moved by the programmer. Continuous path control is required here for recording the complete contour.

(3) Teach pendant or power-teach mode

The robot is always powered on for this type of action with a teach pendant (containing all the necessary controls to take the robot through the programme motions) to control the robots actions. In addition, time delays or manipulative activities can be included in a programme.

(4) Computer or off-line programming

The robots programming is assembled without the need for the robot to move. The robot may be powered on and moving as the instructions are added to the programme, but this is more likely to be the case at the stage of subsequent alterations or refinements to the programme.

The end-effector

The types of robot hands used can vary greatly according to the task to be performed and are even sometimes interchangeable. There are a number of different types of hands, or more accurately end-effectors (a term used to cover hands, grippers, pickups and tools which are put on the end of the robot wrist). The type of end-effector will depend on the task to be performed. Typical ones are:-

a) Mechanical grippers of various sizes (for different sized objects).
b) Spatula or platforms for lifting and transferring a part.
c) Scoops and ladles for fluids.
d) Electromagnetic pick-ups.
e) Special tools - such as routers, spray guns or welding tools.

Robot performance

Robot performance can be measured in terms of maximum arm speed (angular or linear), maximum payload, accuracy and repeatability. The first two parameters are quite common concepts, but it is usual for people to think of the final two as identical. Yet the accuracy and the repeatability of a robot are quite separate. Accuracy relates to the robot's ability to return to a taught position within its established working area. Repeatability relates to the robot's ability to return repeatedly to a position. Thus repeatability is more important than accuracy although if a robot has good repeatability but is not accurate, it is of little use in many applications.

For the robot designer, two separate requirements exist which are to some extent negatively correlated. In designing a robot system, dynamic performance is needed along with accuracy, or repeatability. But to achieve high accuracy in a repeated action, there is some sacrifice of the speed at which the motion can be performed. Present developments of robots are pushing back the limits of this constraint on design, but the limitation nevertheless still exists. For the designer, the constraints of a specified repeatability with differing payloads and elongation of the arm complicates the task of designing a control system. What is more, dynamic performance can often have little to do with the maximum 'slew rate' of the arm (the maximum speed the arm can turn in an arc) since for most actions required, this maximum speed is never reached. The accleration rate becomes the overriding criterion of performance. Though it can be said that mechanically, the industrial robot breaks no new ground, mechanical aspects greatly complicate the task of designing an adequate control system.

Summary of robot characteristics

A series of characteristics can now be summarised (along the lines suggested by Engelberger, 1980) of features which can be expected of the design of an industrial robot:-

1) A hand - capable of gripping and releasing.
2) An arm - capable of moving the hand in 3 planes.
3) A wrist - allowing articulations, for the hand/wrist to be aimed at any point in space.
4) Sufficient power to lift a set weight.
5) Positioning of the hand repeatedly to within a specified distance of a point in space (for example, 0.1 mm).
6) Manual controls, so that a person can operate all the robot limb functions.
7) A built-in memory, so that the robot can be taught a series of actions.
8) Automatic systems which enable the memory to control operations.
9) The capability to move at some speed - usually at least as fast as a human worker.
10) A library of programs (in more complex robots) allowing the robot to be switched back to a previously taught program.
11) A requirement for reliability (mean time between failure - MTBF) in the actual working environment - given as at least 400 hours by Engelberger.

INDUSTRIAL ROBOT SYSTEM DESIGN AND APPLICATION

The aspects of system design and application are considered together here as the two are highly interlinked. The discussion below shows how the application shapes the requirements of system design.

Along with the features of an industrial robot summarised above, there is also a need for signal inputs and outputs, to and from other plant and machinery which form part of a robot system. There are a number of interlocks used for safety and sequence control purposes, some of which are of general use and others more specialised (Engelberger, 1980):

1) Mechanically operated limit switches - of use where the position of a part is crucial to the robot sequence - the part triggers the switch thus moving the robot on to the next part of its cycle.
2) Microswitches - of use in conjunction with end stops to act as limit switches, or to sense weight of parts (on a pallet, for instance).
3) Photo-electric devices - useful so long as an object is opaque; it can sense the presence or absence of an object by the interruption of a beam of light.
4) Pressure switches - used to measure the pressure in air lines or hydraulic feeds.
5) Vacuum switches - used if a robot is also using a vacuum pickup unit. It ensures that the robot will not move until a vacuum is indicated, showing that the object has been picked up.
6) Infrared detectors - used for detecting heat - for instance in foundry applications, they can show if an object has been picked up.
7) Signals from other electronic control systems - this is very important in any robot/machine system. It might be Numerically Controlled (NC) machines, other robots, or a master controller/computer. This is extremely useful in any complex sequencing problem.

Such interlocks ensure that the robot can stay in sequence with the rest of the process and with other machines.

Warnecke and Schraft include such sensors within the boundary of a robot even though these sensors are part of the communication between the industrial robot and the external system, (Warnecke and Schraft, 1982). They identify five subsystems of a robot - the measuring system, the control system, the drive system, the kinematics and the sensors. They also specify the communication between the separate parts of the robot and with the production and orientation equipment which completes a robot system. Figure 1.4 shows these relationships between the subsystems of the robot and other equipment. Their schematic representation of the functional structure of a robot system has inputs and outputs of information, materials and power to represent the activities of the system.

The production and orientation equipment in a robot system depends on the application and on the complexity of system design. At the bare minimum, a robot requires a part on which to work before a production system is formed. More sophisticated system designs would include some structure to support and hold the part in position, sensors to ensure correct alignment, other equipment capable of movement, control interlocks to ensure the

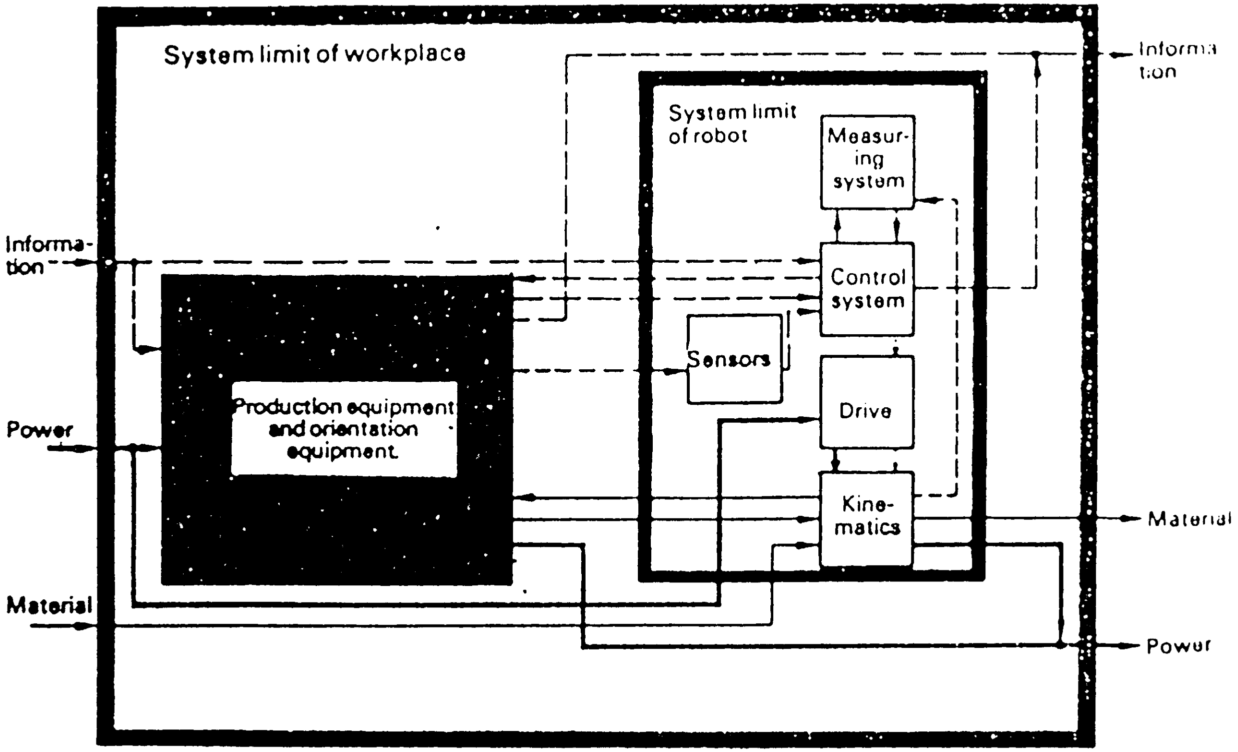


Figure 1.4 Schematic Representation of Functional Structure of an Industrial Robot System (from Warnecke and Schraft, 1982)

sequencing of production, and even vision systems which allows interactive behaviour from the robot system. The more complex the robot production system, the greater would be the need for an overall controller in addition to the robot's own controls.

As an example, in arc-welding applications the robot requires a weld torch on the end of its wrist and welding equipment to supply the welding wire, current and CO_2 gas mixture to shield the weld from the atmosphere. The pieces of metal to be welded together are generally held by a support structure whilst the welding takes place. This support structure may be capable of movement to present the part to the welding torch and also be able to move the part away after the welding is completed. Both types of movement would need to be controlled to maintain the correct sequence and so control interlocks could be present. These interlocks would take the form of limit switches or positional sensors linked with the software of the robot controls. The support structure, or jig as it is commonly called, may also have positional sensors on it to inform the robot whether the parts are correctly positioned before the welding begins.

If this robot system forms part of a larger production process, an overall controll may be necessary. Communication between this controller, the robot and the other equipment would be necessary to ensure that the sequence of operations within the robot system synchronises with that of the overall process. Furthermore, a complex task such as arc-welding could utilise vision systems, as the technical press has advocated (for example, Machinery and Production Engineering, 1985). The control of the arc-welding process is considered a complex affair due to the great number of variables involved. These variables include: maintaining electrode height; tracking the direction of the seam; maintaining correct electrode wire feed rate and maintaining the robot arm motion at the correct rate. To achieve better control, a vision system would need to communicate with the robots controls and the controls of the welding equipment.

Astrop categorises the application areas of industrial robots into three groups of increasing complexity (Astrop, 1982):-

a) parts handling
b) parts processing
c) product building.

The category of parts handling is similar to materials handling tasks. Parts processing includes examples of welding, spraying and other forms of transforming parts. The third category of product building could also be termed assembly applications. Astrop stated that the order of these is not only of increasing complexity, but also of decreasing frequency of examples. What is more, the complexity of the application can be expected to be related to the complexity of system design.

Robot systems are complicated further by the introduction of physical safeguards. The simplest of these is a fence around the periphery of the robot system, which often allows parts in and out of the system. More sophisticated safeguards could be some form of interlock on a gate in the fencing, photoelectric guarding, pressure sensitive safety mats within the fencing or some other sensing device. Each of these would be connected to the robot production system controls to facilitate an interruption to the operation. There could be an emergency stop for all equipment including the robot or a control signal to interrupt the process. These safeguards will be considered in Chapter 3 in the discussion of the literature dealing with robot safety.

Tools for the end of the arm of the robot (end-effectors) are specific to the particular application of a robot. As Engelberger states, the end-effectors are not as flexible as the robots and may be considered as part of the special tooling requirements of the task (Engleberger, 1980). The associated equipment for production or orientation in a robot system (see Figure 1.4) is also more specific to the particular application than to the robot itself. Thus the inherent flexibility of the industrial robot becomes constrained within a production system. Notwithstanding this constraint on the flexibility of an industrial robot it is still possible to 'uproot' the robot and set it down in a completely different context, with a different application and different associated equipment.

Hartley considers the British experience in his overview of robotic production (Hartley, 1983). He deals with the requirements of robot production systems in a range of applications. Examples are given for spot-welding, materials handling, arc-welding, spraying, assembly and several miscellaneous tasks. Miscellaneous tasks include such diverse tasks as deburring, applying sealant, and drilling holes in an aircraft panel.

The Inbucon Report on Industrial Robots in Japan, U.S.A. and the U.K. (Inbucon, 1982) also illustrates its discussion of robots with nine case studies. These systems differ considerably in their complexity and in the extent to which other equipment is included in a system.

Other applications have been reported in the technical press. Several publications have produced numerous articles on robot systems with the expressed aim of improving awareness of robot capabilities (for example, editions of the Industrial Robot, Manufacturing and Production Engineering and Production Engineer).

These articles and the examples given by Hartley and Inbucon show that robot system design varies considerably both between applications and within them. The decisions of management in each company have produced quite different layouts and associated equipment even for highly similar tasks. The systems also differ in their level of complexity. The level of flexibility is also considerably different from one system to another. Some systems identify parts as they enter the system and select automatically the correct programmes for the robots and other equipment. Other systems would need to undergo major redesign to accommodate a design change in the processed parts.

THE CURRENT USE OF ROBOTS

Surveys of Robot Use

Interest in the spread of robot use through British Industry has been shown over a number of years. An annual survey was started in 1980 by the British Robot Association (BRA). The results of these surveys form the most consistent record of the increase in robot use and of the common types of applications in Britain. Each set of annual figures is produced from questionnaires sent to the robot suppliers in the U.K. A strict definition is applied of what constitutes an industrial robot (see above). The results of the surveys are presented in the form of an overall total number of robots for the end of the year, the numbers in a range of applications, those installed in each category of application in that year and information on the origin of the robots. As these surveys have become better established, more information has been provided in the technical specification of the robots and their geographical distribution in the U.K. Figure 1.5 below gives a graphical representation of the overall figures for each year. Figures before 1980 are estimates from the BRA. This graph shows a rapid increase, with a 655% increase from 1980 to 1984. However the percentage increases are diminishing each year. In 1981 the percentage increase on the previous year was 92.2%, in 1982 this was 61.6%, in 1983 this was 52.2% and in 1984 this was 38.7%. Although the number of robots installed each year is increasing, the increase is not proportional to the number installed at the beginning of each year.

The figures for each year were derived from sales figures of U.K. and known foreign suppliers. This approach to the collation of statistics has a number of consequences. Little is said of the potential for productive use of the spread in different industrial sectors. The BRA is also unwilling to divulge the number of each robot design installed each year,since this information is commercially sensitive to the supplier companies. However, the statistics do produce a series of "snapshots" of robot use in Britain.

The BRA statistics provide information on the main application areas for industrial robots in each year. Initially, the range of applications had 13 categories (Industrial Robot, 1981). The number of categories increased to 19 at the end of 1984 (Industrial Robot, 1985). All the categories present in 1980 remained throughout and 6 were added - 4 of these in the final year. The 4 new categories given in 1984 (forging, glueing/scaling, laser cutting and water jet cutting) are included in the 'Other applications' categories in this discussion. Thus fourteen categories are considered here.

Two broad categories can be considered, covering a majority of the robots in use - Tools Handling and Materials Handling. Tools Handling includes such applications as surface coating, spot welding, arc-welding

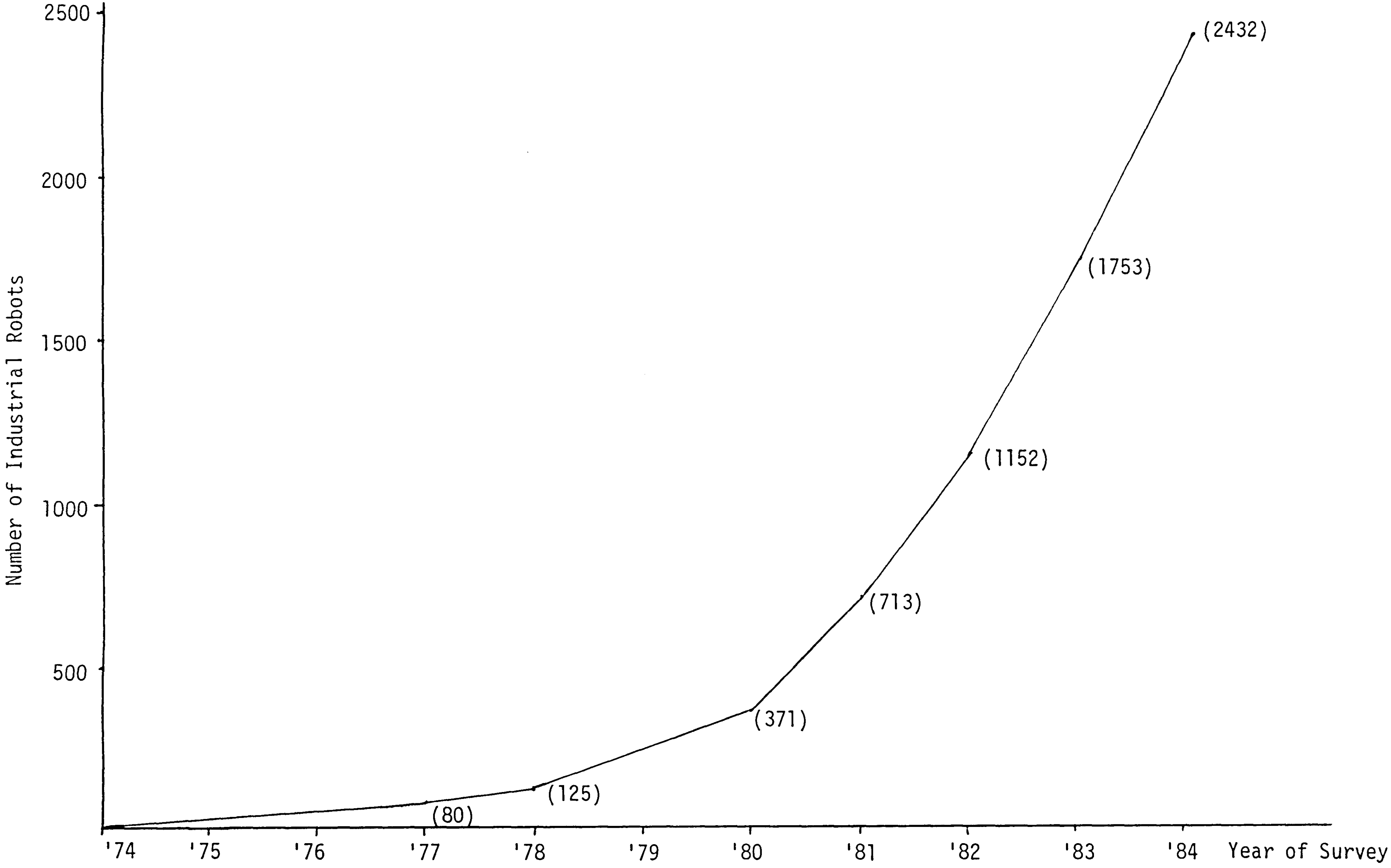


Figure 1.5 Total Number of Robots Installed at the End of Each Year (BRA Statistics)

and grinding, fitting or deburring. Materials handling is a broader grouping, including injection moulding machine loading, machine and press tool servicing, palletising, investment casting and other examples of handling parts or materials. Besides these two broad groups there are the robots involved in assembly, and education or research. Any other applications are combined in the 'other' category. Table 1.1 shows the percentage of the total in each of the categories for 1982 to 1984 and the annual total at the bottom of each column.

Table 1.1 shows that there has been a slight shift in robot usage. The most dramatic change has occurred in assembly applications. Their proportion of total numbers has risen threefold in two years. This resulted in assembly being the fifth largest application category at the end of 1984. Changes in the other categories have been less rapid. Surface coating has had a sizeable drop, showing its diminishing importance in the overall figures.

Three categories dominate each years figures, namely spot welding, arc welding and injection moulding. The first two of these maintains a nearly stable proportion in each year, but injection moulding shows a slight increase. The only other category to exceed 5% of the total robot population (besides the other category) is Machine Tool Servicing, which has seen a slight drop in importance. Thus the clearest information to be derived from Table 1.1 is that, notwithstanding some minor changes, robot applications in Britain have been dominated by a handful of categories.

Information on the geographical distribution of robots have been supplied by the BRA for 1983 and 1984. These show that certain areas like the West Midlands and the South East have a high concentration of robots. The Industrial Robot (March, 1985) points out that certain other areas, such as Central England, East Anglia and the North East have relatively high concentrations because of the presence of car manufacturers in these areas (in Oxford, Essex and Merseyside respectively). Scotland and Wales show larger increases in numbers of robots than other areas. In 1984 Scotland had the largest increase at 105% on the previous years total of 53, making a total of 109 robots at the end of the year. The Industrial Robot considers this the result of investment in electronics and electronic assembly in Scotland (Industrial Robot, 1985).

	End of 1982	End of 1983	End of 1984	
Surface Coating	10.8%	9.5%	7.3%	Tools Handling
Spot Welding	21.6%	19.9%	19.4%	
Arc Welding	13.6%	13.3%	14.0%	
Grinding/Drilling/ Fettling	1.1%	1.5%	1.8%	
Die Casting	3.1%	2.2%	1.6%	Materials Handling
Injection Moulding	14.5%	15.7%	16.9%	
Machine Tool Servicing	9.6%	9.4%	8.8%	
Press Tool Servicing	2.3%	2.7%	2.4%	
Investment Casting	1.0%	0.8%	0.6%	
Inspection/Tests	1.3%	1.7%	1.7%	
Palletising, Packaging	3.3%	3.8%	4.2%	
Assembly	2.8%	5.9%	8.2%	
Research/ Education	3.3%	4.6%	5.0%	
Other	11.5%	8.8%	8.1%	
Totals	(1152)	(1753)	(2432)	

Table 1.1 Percentages of Robots in Each Application Category

(From BRA, 1982 and 1983 and The Industrial Robot, 1985)

The BRA statistics for the end of 1984 were the first set to include an analysis of the industries adopting robots. Table 1.2 shows the totals in each industrial sector for 1984 and the percentage increase on the previous year. This shows that the automotive industry is by far the largest robot user. However, the largest increases in robot use occur in two of the sectors which are minor robot users. Also worthy of particular note is the increase in the electrical and electronics industry. An 85.3% increase was recorded in 1984, giving over 10% of the total number of robots at the end of 1984. This increase made the electrical and electronics industrial sector the third largest user of robots in the U.K.

International Comparisons

Interest in the statistics produced by the BRA has been shown by a range of publications. Of greatest interest in these reports has been the comparison with robot use in other countries, especially by Germany, U.S.A. and Japan. A report on the statistics for 1982 made the point that as many new robots were installed in West Germany in 1982 as the total number of robots in the U.K. (U.K. Commline, 1983). In 1984, Labour Research emphasised the high percentage increase in the number of robots in Britain alongside a report from Germany on possible job losses (Labour Research, 1984). The IEE made strong comparisons between the U.K. and Germany, stating that for a long time West Germany has been the yardstick against which U.K. industry has measured itself (IEE News, 1984).

1983 was the first year that the percentage growth rate of the U.K. robot population exceeded that of West Germany. However, Technology reported that the figures from the BRA were deceptive (Technology, 1984). British robot manufacturers had achieved only half the penetration of the home market of their West German counterparts. The British market was also shown to be less than half that of West Germany, with only a handful of companies accounting for most of the British output. On the manufacturing side, British industry was seen to be heading for collapse. A year later, this magazine (now renamed New Technology) reiterated this view. In an article on the statistics for 1984, the point was made once more that

	Total in Dec. 1984	Percentage increase on 1983 figures
Energy/Water Supply	42	68.0%
Metal Manufacture	15	7.1%
Metal Goods	206	40.1%
Mechanical Engineering	162	50.0%
Electrical/Electronics	252	85.3%
Automotive	885	29.0%
Aerospace/Shipbuilding	86	28.4%
Food/Drink Pharmaceuticals	18	125.0%
Timber/Paper/Furniture	14	180.0%
Rubber/Plastics	381	52.4%
Other Industries	371	20.8%
Overall	2432	38.7%

Table 1.2 The Distribution of Robots Between Industrial Sectors (The Industrial Robot, 1985, p. 33)

the British rate of robot installation was well behind that of West Germany (New Technology, 1985).

Japan, U.S.A. and West Germany have been the three largest user countries of robots since the beginning of the 1980's. Sweden was also a relatively large user before this decade. The number of robots in Japan and U.S.A. outstripped all other countries from very early in the history of robot use, being comparable only with the total number of robots in Western Europe. In 1982, the BRA estimated that U.K. was fifth in the 'league table' of robot users, behind Japan, U.S.A., West Germany and Sweden. U.K. had 1152 robots at that time, Japan had 13000, U.S.A. had 6250, Germany 3500 and Sweden 1300. In 1983, the U.K. had slipped to fifth place behind the four above and Italy. In 1984, the position was almost unchanged, with France above the U.K. and Sweden below. Table 1.3 shows the annual totals for 1982-1984 for these countries and for a few others below the U.K. The order is organised according to their placing in 1982, or in the case of Spain, Australia and Finland, their placing when they first appear in the table. This table shows that, irrespective of the definition of robot used, Japan's figures are far in excess of other countries. The U.K. robot population is comparable with other European countries. In Table 1.3, it is clear that we do not appear to be as successful at robot adoption as France, Italy or West Germany. The growth rates of France and Italy have meant that their totals have increased faster than the U.K.'s. Only Sweden appears to be performing worse, after a more rapid initial adoption of the technology. However Sweden is somewhat unique in that its industrial sector is much smaller than other European countries. In contrast to its placing the table of robot populations, Sweden had the second highest ratio of robots to industrial workers in the world in 1984 (Industrial Robot, 1985).

	1982	1983	1984
Japan	13,000*	16,500*	64,000*
U.S.A.	6,250	8,000	13,000
Germany	3,500	4,800	6,600
Sweden	1,300	1,900	2,400
U.K.	1,152	1,753	2,423
France	950	1,500	3,380
Italy	700	1,800	2,700
Belgium	350	500	859
Spain	-	400	-
Australia	-	300	-
Finland	-	120	-

*The figures for Japan are not on the same basis. A 20% increase occurred between 1983 and 1984 (Industrial Robot, March 1985, pp. 30-35), not a 388% increase as the figures above suggest. This discrepancy is explained by the change in the definition of equipment included for Japan.

Table 1.3 International Comparisons of Robot Use

The Difficulties of Survey Data Collection

The collection of statistics on robot use in the manner described above has a number of problem areas. Complete coverage of all robot installations cannot be ensured. Indeed the BRA estimated a total of over 2600 for the end of 1984, but did not receive 100% returns from the suppliers they approached (Industrial Robot, 1985). It would also be difficult to cover those robots bought directly from a supplier outside the U.K., since these suppliers would not necessarily be questioned.

The choice of questions of robot suppliers tells us little about the potential users of robots. Even though some statistics on the use of robots in different industrial sectors was included in 1984, little can be gathered of the concentration of robots or the differences in the diffusion of one application when compared to another. An example of the variations in diffusion is the difference between spot and arc-welding applications. Spot welding is largely concentrated in the automotive industry with a large number of robots doing near-identical tasks adjacent to each other. Arc-welding applications can be found in a larger number of industrial sectors, commonly with only a few robots in a factory. Comparisons of robot use in different countries also suffer from this difficulty. The relative concentration of robots in certain industrial sectors such as the automotive industry is not highlighted by comparisons of total numbers of robots.

One of the most important limitations of such data collection is the rate at which it becomes out-dated. The robot market has been recognised as quite unstable (Technology, 1984, New Technology, 1985). Companies are constantly in the process of experimenting with the use of robots, perhaps discarding or re-locating them should they prove unsuitable for the initial application. Robot suppliers are also in a state of fluidity, with licences being held for foreign-made robots for a few years, before being passed on to another interested company. For example a Japanese designed arc-welding robot was marketed originally by a company selling other arc-welding equipment. This company did not sell sufficient robots to satisfy the robot manufacturer and so the licence was taken elsewhere in Europe.

The last five years has also seen a number of British companies move into robot manufacture. At best these have met with mixed successes.

Some have closed down their operations, but even those which have continued have not captured a sizeable proportion of the robot market.

Information supplied on the tasks for which robots are purchased is problematical, especially when robots are bought by a user with no prior experience of robots. One cannot say that a robot being used experimentally to develop a process or one used for training on an application has the same task as a robot being operated automatically and continuously. Nevertheless, it is likely that robots being used in the former manner will be recorded as performing the more productive latter task. It is also likely that a company experimenting with robots will try to evaluate the robots use in a number of tasks, any one of which could be the nominal task for which it was purchased. Furthermore, the classification adopted by the BRA for the applications is of limited explanatory power. In a number of cases, for example, it may be difficult to separate general handling of parts from assembly. Similarly, holding a part for deburring is essentially no different from deburring a static part with the robot holding the tool. Yet the two are unlikely to be classified as the same.

These points set limitations on the confidence which can be placed in any survey of industrial robots use in Britain. Even so, one can state that the major applications of robots are surface coating, spot-welding, arc-welding, injection moulding and machine tool servicing and assembly. The exact placing of Britain in any international comparison cannot be given with complete confidence, but one can be sure that Britain's rate of increase in robot installation is lagging behind some of its European counterparts.

In-Depth Studies of Robot Adoption

These problems of the collection of statistics of robot use suggest that a more in-depth study is likely to be fruitful. With the present robot numbers and range of users this would be very difficult, but an earlier study can be reviewed here. R. Zermeno-Gonzalez carried out an extensive study of most of the robot users in 1978 and 1979 (Zermeno-Gonzalez, 1980). It is worth noting immediately that the total covered was 200 - 8.2% of the robots in 1984 - and only 110 robot users. The work was carried out at the Technology Policy Unit, Aston University as part of a research programme into the development and diffusion of robots in industry.

The research involved identifying potential users and then questioning them on their use of robots. Zermeno-Gonzalez identified a significant number of failed applications and robots whose prime purpose was development or training. He was also able to draw some conclusions about past and future trends in robot use. The conclusions drawn by Zermeno-Gonzalez are naturally of only limited use today with such a massive increase in robot use since 1979. However some of the trends noted at that time have continued since.

Zermeno-Gonzalez considered the invention and development of robots to be a combination of two separate trends in modern machinery development. Industrial robot design achieves a shift towards more versatile automation and is produced in the form of standardised off-the-shelf machines. The versatility of the robot affects the need for flexible peripherical equipment - that is, the more versatile the robot, the more rigid, or dedicated, the rest of the machinery can be.

Overall, the direction of change in robot design has been one of increasing sophistication. There has also been a quite separate trend of designing robots for specific applications. The use of a less versatile but off-the-shelf robot (i.e. specialised to some extent to a particular task) has often been the preferred choice to a general-purpose robot. Of course this option depends strongly on the ability of the particular section of the robot market to sustain a specialised design. So far this has been carried out in the areas of die-casting and injection moulding, spot-welding, surface coating, arc-welding and assembly.

In one respect the British scene is markedly different from the other countries which are major users, in that the number of robots per firm is low (between 1.69 and 2.07 in the period studied by Zermeno-Gonzalez). Zermeno-Gonzalez found only 2% of user firms had more than 10 robots. As one can see from Table 1.4, the distribution is very heavily weighted to the lower end of the scale:-

No. of Robots Bought by a Company	% of Companies
10	1.9%
5-9	2.9%
2-4	21.9%
1	73.3%

Table 1.4 The Distribution of Company Use of Robots in 1979
(Taken from Zermeno-Gonzalez) Table A, p. 128, Vol. 2

Though Zermeno-Gonzalez's study was based on a far smaller number of robots than the present population, a similar size distribution exists today. There are now a couple of companies with more than 100 robots (BL and Ford) and a few with more than 10 (Flymo, for example); there is then a considerable gap before the majority of users are encountered. In other major user countries, the spread of robots by companies is more even.

The "low level of intra-firm diffusion", along with the result from interviews Zermeno-Gonzalez undertook, led to the conclusion that "robot adoption was still largely an experimental activity" (Zermeno-Gonzalez, 1980, p. 139). He felt that robots were adopted for new systems in new industries and firms. A very important factor in the successful pioneering of applications was the presence of an enthusiastic management team. He found that an environment conducive to innovation, such as that found in firms in the high technology area of industry, was important for successful pioneering work.

The research into the development and diffusion of industrial robots was continued at the Technology Policy Unit, Aston University by a further research project from 1979 to 1982. This considered the process of robot adoption in detail, gaining an understanding of the inhibiting and facilitating factors (Fleck, 1982). The same robot population was taken as a base and technical, organisational, economic and labour aspects of robot adoption were investigated with a sample of the robot users. The findings of this research reinforced some of the findings of Zermeno-Gonzalez, in particular that the car industry plays a crucial role in the diffusion of robots and as such constitutes a special case. The research project also found that in a large number of cases (44%), initial failure was experienced with half of them (22%) abandoning robots altogether. An important finding relevant to the research presented in this thesis was the importance of competence in robotics as well as in the process to be roboticised for the successful development of robotic systems.

It was also clear from this research that organisational changes would occur with robot introduction. The organisational structures were found to shift from one appropriate to the management of people to one for the management of machines. James Fleck concluded that the unit of measurement should not be the robot in isolation, but should be the robotic system. The findings supported the view expressed above that the robot system is closely tied to its application, whereas the robot on its own is much less so. Whereas the industrial robot can be thought of as versatile and flexible, with universal applicability, the robot system is more dedicated to the task for which it was designed.

PRODUCTION RELIABILITY

The requirements for machine reliability and system availability have already been touched upon, as have the problems faced by some robot users. This section considers studies of industrial robot system performance and of reliability of similar micro-electronically controlled production equipment.

Studies of Robot Systems

Studies of production problems with robot systems are rare. The majority of technical literature on robots, including articles in the technical press, deal with the benefits of robot use but do not discuss details of the possible difficulties which could be faced by a robot user. However a large number of robot users have faced problems in the past, as the TPU has found (see above).

A rare example of discussions on unsuccessful applications or initial problems attempts to show that industrial robots suffer drawbacks just like any other machinery (Production Engineer, 1985). In this article, three robot users discuss their problems with robots.

The first, a factory manager with Clares' Equipment, pointed to problems with associated equipment. At one time, this company was experiencing a reject rate in excess of 10% of processed parts. The problems were alleviated partially when the inadequacies of workpiece fixturing (i.e. jigs) were identified. The usual downtime on a robot system at one time was four days, showing the problems that the suppliers were having with a new technology. To improve production further, it was found that the accuracy of all the machines supplying components to the robots needed to be improved dramatically. However, despite these initial problems, the numbers of robots in Clares' Equipment's factories rose to 14, with all but the first three justified by capital investment returned within three years. An interesting problem at Clares' Equipment was the knock-on effect of the purchase of robots on production both upstream and downstream of robot production. New investment was needed in other areas to provide parts at sufficient rates and quality for the robots and to take the parts completed by the robots.

The second user was Hoover Universal (UK). Their purchase of special-purpose robots for robotic welding created reliability problems. They found that the robots' motors overheated and that mechanical parts were of low quality and in some cases they distorted under load. The Managing Director identified the cause of the low volume production of special purpose robots: "there is simply not the volume production for the robot manufacturers to get their own quality levels right" (Production Engineer, 1985).

The third user in the article was VS Engineering, a supplier and commissioner of numerous robot systems. Their experiences have shown that the introduction of robots creates its own problems particularly in production management. For example, there is a demand for skilled labour of a type in short supply, in-house maintenance skills become more important, management do not always perceive correctly the capabilities of robots, parts of necessary quality and consistency are not always available and the work-rate of robots can create problems. It is commonly assumed that robots work at a far higher rate than humans. However, the the Managing Director of VS Engineering stated that robots rarely match the peak rate of a human operative although they can work at a steady rate all day. The cost of a robot system is also underestimated frequently by robot users. The cost of a robot - at £30,000 to £50,000 - can end up as only being one third to one quarter of the total cost. The rest of the expenditure is on integrating, controlling, training and documenting for robotic production, and the purchase of new machinery to work alongside the robots.

These reports of production difficulties are a welcome addition but they are really only anecdotal accounts of users' difficulties. We know little of the percentage loss of production and no comparison is possible between the three users above. An extensive search for more rigorous work on robot system production problems succeeded in uncovering only one study in Japan. The report on production difficulties is 'second hand' in that the study is quoted in another article (in Sugimoto and Kawaguchi, 1985). The original study (K. Sato, 1982) probably contained more information than is given in the secondary source, but efforts to obtain the original have been unsuccessful. Therefore the report given by Sugimoto and Kawaguchi must be relied upon.

Sato presented a table of frequency of robot problems. This is reproduced below as Table 1.5.

Problem	Frequency %
Faults of control system	66.9
Faults of robot body	23.5
Faults of welding gun and tooling parts	18.5
Runaway	11.1
Programming and other operational errors	19.9
Precision deficiency, deterioration	16.1
Incompatibility of jigs and tools	45.5
Other	2.5
Total	(204.%)

(The percentages come to more than 100%. Clearly there is an overlap between the categories.)

Table 1.5 Frequency of Robot Problems (from Sugimoto and Kawaguchi (p. 70, 1985)

Only one category of problem is defined by Sugimoto and Kawaguchi. Runaway is given as an unreproducible erroneous action caused by short circuits, noise or similar interference. Sugimoto and Kawaguchi consider that at 11.1% of incidents, this is quite a major cause for concern. The lack of clear definitions for the other categories is a slight problem, since it is unclear what is meant by some terms (such as 'deterioration'). Faults of the control system could be hardware or software failures or both. It is not clear which type of events are categorised as which type of problem, or rather, as which group of problems (since the total is well over 100%).

Mean times between failures for robots are also given from Sato. The mean times are presented in a form of groups of failures between time intervals, and so it is in the form of a distribution. Table 1.6 reproduces this table. Sugimoto and Kawaguchi conclude that the Mean Time Between Failures (MTBF) for robots is rather small and point out that 75.1% of robots had an MTBF of 1000 hours or less. Few robots managed over 2500 hours MTBF. This distribution is approximately a log-normal distribution. They conclude that "it should be fully recognised that robots have not yet attained adequate reliability" (Sugimoto and Kawaguchi, p. 91, 1985). However, no information about the sample size or time period is given to allow the MTBF's to be judged in terms of their population base.

Studies of Machine Tools

Because of the general lack of good data on robot production and reliability, it is useful to consider a similar technology, that of conventional and computer numerically controlled (CNC) machine tools. The Machine Tool Industry Research Association (MTIRA) carried out a survey of conventional machine tools in 1974, providing statistics on breakdowns and average downtime (Stewart, 1977). In all, 9410 metal cutting machine tools in 15 engineering workshops were covered, but very few CNC machine tools were included in this survey. Downtime figures as a percentage of production time varied from 0.6% to 4.4% with an average of 2%. Mechanical breakdowns involved more downtime than electrical breakdowns;

MTDF (hours)	Frequency
Under 100	28.7
100 - 250	12.2
250 - 500	19.5
500 - 1000	14.7
1000 - 1500	10.4
1500 - 2000	4.9
2000 - 2500	1.2
Over 2500	8.5
(Total)	(100.1%)

Table 1.6 Mean Time Between Failures (MTBF) (from Sugimoto and Kawaguchi, 1985)

though the numbers of electrical and mechanical breakdowns were roughly equal, the mechanical breakdowns accounted for 80% of lost production. Stewart admits to the limited meaning of the average downtime figure of 2%, since it is an agglomeration of figures for a range of machine tools. Utilisation of machinery is shown to be much lower than that accounted for by breakdowns, in the range of 60-80% of full production.

A subsequent survey by the MTIRA is also reported by Stewart. This considered 191 CNC machine tools with an average age of 5.5 years distributed between 14 companies (each with at least 9 CNC machine tools.) This survey found that average downtime was 7.6%, much higher than in the case of conventional machines. A problem with identification of the reason for failure was found, since with this more complex machinery, it was considerably more difficult for maintenance staff to recognise clearly the reason for failure. Repairs were thus conducted on a trial and error basis rather than by a more systematic investigation. This may explain partly the greater downtime with the supposedly 'better' technology.

A study of one particular make of computer numerically controlled (CNC) machine tool - from Alfred Herbert Ltd. of Coventry - has been reported (Keller, et al, 1981). Field failure data on 35 machine tools during their first year of use is analysed. The times to failures were fitted to a Weibull distribution and also to a log-normal distribution. The log-normal distribution was found to have a marginally better fit to the data with mean times to failure of 430.5 hrs for the CNC system (i.e. the controls), 950.5 hours for the hydraulic systems and 278.5 hours for the mechanical system using the log-normal distribution. Repair times were found to constitute about one third of the mean downtime of the machine tools overall, which were about 25 hours for each of the components (CNC, hydraulic and mechanical systems). The availability of CNC machines was found to be between 82% and 85% of the total available production time (extracted from the Weibull distribution and log-normal distribution respectively).

A further study of machine tools reliability has been carried out by D.J. Bennett (Bennett, 1978). The data collected in this thesis comes mainly from the records kept by the manufacturers' own service engineers. Repair time and failure rate data is obtained from four companies. Bennett finds that a log-normal distribution was a good approximation for the repair time. The average downtime is 8.8 hrs., representing 2.5% of operating time. This figure conceals considerable variation, with machine availability varying from 76.6% to 99.9%. An overall mean value for the MTBF is given as 140 hours.

There is clearly some variation between the findings of different studies on machine tool reliability, but it is also clear that some common characteristics emerge. Electrical failures are of shorter duration than mechanical or hydraulic failures. The availability of machine tools vary somewhat, but are in the range of 82-98%, with two surveys giving values near 98%, one with a value of 92.5% in a third and 82-85% in the fourth. A log-normal distribution appears as a good approximation for the results in each of the studies.

SUMMARY AND CONCLUSIONS

This chapter has set the scene for the thesis by describing the design of industrial robots and the production systems in which they are used. The spread of use of industrial robots and the range of major applications have been considered as well as information on the production reliability of industrial robots and similar industrial equipment.

Three parts of robot design, the controller, the power supply and the manipulator and a further three characteristics provide an adequate description of an industrial robot and show the range of variation in this type of automation. The controller of an industrial robot has been categorised into four basic types by two characteristics (servo or non-servo control and by point-to-point or continuous path control). These two characteristics are linked, since continuous path control also requires servo-control as well as a large memory to be fully effective. However the vast majority of robots are simpler than this and have some form of point-to-point control.

The power supply has been categorised by three types of power sources: electrical, pneumatic and hydraulic: these may coexist on the same robot for different articulations. The choice in power supplies appears to be moving towards electrical sources, in part because of improvements in the design of motors.

The mechanical design of a robot appears to be largely conventional, since ways of producing controlled motion have been developed for similar equipment. Four basic configurations arise from the combination of three separate types of motion (telescopic, linear or articulation). The four configurations provide a range of coverages which, by virtue of three separate axes or degrees of freedom, occupy a specified volume. When 3 degrees of freedom are also available on the robot hand, the tool at the end of the arm can achieve any orientation at any point within the limits governed by the extent of movement in each degree of freedom.

The further three characteristics of an industrial robot are its end effector, its repeatability or accuracy and its programming method.

A dramatic increase in the use of industrial robots has occurred in the U.K. since 1980. However, the rate of increase is decreasing with a slight shift in the proportions of different application areas. The main changes are an increase in the use of industrial robots for assembly and a decrease for surface coating. Three application areas dominate, that is spot-welding, arc-welding and injection moulding, with the automotive industry dominating as the largest user. There is a wide range of complexity and flexibility in system design and application areas, which has implications for the need for interlocks and complex sequencing.

International comparisons of industrial robot use placed the U.K. behind some of its major competitors. There were also signs that robots were being introduced into industry in other major industrialised countries at a greater rate than in the U.K.

In-depth studies of industrial robots have identified a significant number of failed applications and a low average number of industrial robots in each factory. Robot use also seems to be largely an experimental activity with success dependent on an environment conducive to innovation (for example in a 'high technology' industry). Success at industrial robot application has been shown to require competence in both robotics and the process to be 'robotised'. The robot system is constrained by the application, a finding which supports the view adopted in this thesis - that the correct unit of study for industrial robots is not the robot in isolation, but the complete system in which it operates.

Production reliability studies on robots show that robots are not some form of universal panacea to cure production problems and indeed often create their own production problems. A Japanese report showed robots to have a mean time between failure of less than 1000 hours for three quarters of the robots studied with studies of similar machinery also showing a low reliability.

CHAPTER 2

HEALTH AND SAFETY LEGISLATION, ORGANISATION AND STRATEGIES

INTRODUCTION

This chapter considers the means of ensuring health and safety at work. It begins with a review of the context of health and safety at work in Britain, including relevant legislation, philosophy and the institutions of inspection and enforcement.

Research into the pattern of accidents and their causes or explanations, including multidisciplinary approaches to the analysis of serious accidents is then described. The chapter concludes with a summary of a framework of strategies for the management of safety.

THE CONTEXT OF HEALTH AND SAFETY AT WORK IN BRITAIN

Health and Safety Legislation

There are two major Acts of Parliament relating to health and safety of factories in Britain today, the Factories Act 1961 and the Health and Safety at Work Act 1974. Both of these have a wide application in industry. In addition, a large number of Regulations on specific problems with machinery, substances or articles at work exist.

A description of the legal context for robot safety in the U.K. is provided by R.J. Barrett (Barrett, 1985). In this article, he refers to the Factories Act and the Health and Safety at Work Act, as well as giving examples of other regulations which might apply in particular circumstances. Robot paint spraying may involve consideration of the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations, while robot grinding could involve the Abrasive Wheels Regulations. If the robot systems were in factories, they would also be subject to the Electricity Regulations. Barrett does not present these Regulations in detail but rather comments that areas of safety legislation which appear to be relevant should be considered. These Regulations apply more to the application than to the robot system and so cannot apply generally to robot production systems.

By contrast, the two major Acts of Parliament are applicable to robot production systems in a more general sense. The Factories Act is specific in nature, giving a list of requirements applicable to factories, whereas the Health and Safety at Work Act (HASAWA) is more widespread in terms of those it protects and in terms of the allocation of duties. The HASAWA also places the emphasis for the assessment of risks and for the implementation of appropriate safety measures on manufacturers, suppliers and users according to what is "reasonably practicable". These two Acts are considered below in more detail.

Factories Act, 1961

The Factories Act 1961 is extensive, covering areas of health and welfare of employees in factories as well as their safety. The important sections for a consideration of machine safeguarding are Sections 12 to 16. Sections 12 and 13 are concerned with prime movers and transmission machinery, which in the opinion of the HSE (Barrett, 1985), present little problem when robots are considered. Section 14 is the most relevant, in that it deals with dangerous parts of machinery. Section 14 subsection (1) requires that "every dangerous part of any machinery ... shall be securely fenced unless it is in such a position or of such construction as to be as safe ... as it would be if securely fenced" (HMSO, 1961). Sub-section (2) allows for an alternative safeguarding method to a fixed guard in the form of an automatic device. Consideration of the applicability of this section has been found to revolve around what constitutes a dangerous part and secure fencing. Barrett quotes an Appeal Court decision to explain these concepts. "A part of the machine is dangerous if it is a reasonably foreseeable cause of injury to anybody acting in a way in which a human being may be reasonably expected to act in circumstances which may reasonably be expected to occur" (Lord Guest, 1962, Close v Steel Company of Wales (AC 367) (Barrett, 1985). Thus the test of applicability becomes one of reasonable foreseeability. Secure fencing is that which achieves protection from the reasonably foreseeable actions. Clearly this provides an almost absolute duty once a dangerous part is identified. Barrett also refers to specific Regulations which illustrate exceptions (for example the Woodworking Machine Regulations). Sections 15 and 16 of the Factories Act also provide for exceptions for certain operations such as maintenance or adjustment. These exceptions are covered by the Unfenced Machinery Regulations, 1938. Barrett considers examples of actions with robot systems which would fall within the remit of these sections. He provides the example of close observation for welding robots. However, to this consideration is added the caveat that it is important to establish immediate necessity rather than mere convenience for the observation.

Health and Safety at Work Act

This widely applicable Act has been described as the "son of the Robens Report" - the Royal Committee of Inquiry established in 1970 to review the provision made for the health and safety of people in the course of their employment. The Committee of Inquiry were also to report on any changes that were needed. The Robens Committee concluded that the existing statutes and statutory instruments on health and safety at work were somewhat haphazard. The emphasis had been, they felt, on an over-reliance on "negative regulation by external agencies" (Robens, Lord, 1972). It recommended a new and comprehensive Act giving general principles of responsibility, supported by regulations, codes of practice and guidelines on specific matters. They also recommended one national authority for health and safety at work controlling a unified inspectorate.

Section 2 of this Act deals with the general duty of employers to ensure, so far as is reasonably practicable the health, safety and welfare of employees at work. The general duties extend to "providing and maintaining plant and systems of work which are so far as is reasonably practicable safe and without risks to health" (HMSO, 1974, Sect. 2). Section 6 places a duty on anyone "who designs, manufactures, imports or supplies any article for use at work to ensure, so far as is reasonably practicable, that the article is so designed and constructed as to be safe when properly used" (Sect. 6).

The Act goes on to state that it may be necessary in carrying out this duty to arrange for the examination and testing of equipment and to make available adequate information. An employer must prepare a written statement of the safety policy and bring this statement to the notice of employees.

The employer also has a duty to those not in his employment. Outside contractors, their employees and the general public whether within or outside the workplace are to be safeguarded. Employers are required to carry out their undertaking in such a way as to ensure that so far as is reasonably practicable they do not expose people not in their employment to risks to health and safety. The standards of protection given should be similar to those given to employees. People in control of premises have similar duties, with the addition of duties regarding the emission of noxious or offensive substances into the atmosphere.

Employees also have duties under this Act, namely to take reasonable care for the health and safety of themselves and other persons who may be affected by what they do or fail to do at work. They must also cooperate with the employer to enable any duty on an employer to be carried out. Furthermore, all people have a duty not to interfere intentionally with or misuse anything which has been provided in the interests of health, safety or welfare, such as fire escapes, perimeter fencing or fire extinguishers.

Overall philosophy of health and safety legislation

The overall philosophy of the Health and Safety at Work Act reflected the concerns of the preceding Committee of Inquiry chaired by Lord Robens. It was designed to give those who create the risks and those who work with them the primary responsibility for acting to prevent accidents and illness. This has been described as a move towards self-regulation within a structure of specific regulative law (Dawson et al, 1983). Dawson et al state that an essential feature of self-regulation would be that it manifests itself differently in different contexts. This difference between factories is implicit in Barrett's commentary on health and safety law. "Inspectors of Factories are always prepared to help by discussing the legal issues affecting installations, but the responsibility for ensuring safety remains with those who design, manufacture, import, supply and use robots" (Barrett, 1985, p. 5).

The Health and Safety Commission and Executive (HSC and HSE)

To enforce the duties on people in a self-regulating legal framework, the HASAWA created the HSC, and its operational arm, the Health and Safety Executive (HSE). The Commission's role was to be one of general direction and policy making, whereas the Executive was to deal with day-to-day operational matters. The HSE brought together 6 previously separate Inspectorates - the Factory, Mines and Quarries, Explosives, Alkali and Clean Air, Nuclear Installations and Agricultural Inspectorates. The scientific and medical support staffs were also included and went to form the Employment Medical Advisory Service (EMAS).

The actions of inspectors have been described by two representatives of the HSE who, in keeping with the overall philosophy of the Act, have indicated that the inspectors are concerned with the management's policy for health and safety organisation to carry out this policy, arrangements for safe systems of work and other similar matters (Green (Ed.) 1982). The HSE does not consider it the role of inspectors to solve problems for management (Green (Ed.), 1982, p.1).

The Act gives extensive powers to the inspectors. They have the right to enter premises at any reasonable time, to make investigations and examinations, to take measurements, photographs and samples, to take possession of articles, to have potentially dangerous articles dismantled and tested, to require people to answer questions, to issue prohibition and improvement notices and to initiate prosecutions. If some person is contravening health and safety legislation or has contravened the law in such a way as to make it likely that it would happen again, then the inspector may issue an improvement notice. Prohibition notices are issued when an inspector considers that there is a risk of serious personal injury. If the risk is imminent, the notice takes effect immediately and prohibits the work activity.

The HSE states that it is the intention to prosecute if the notice is not complied with (Green (Ed.) 1982, p. 21). Prosecution can be of individuals or corporate bodies, or both. Most offences under the HASAWA can be tried either at a magistrates court or at a higher court and carry the possibility of up to 2 years imprisonment (see Selwyn, 1982, for a list of offences and maximum penalties). Below is a simplified representation of the legal framework which applies to health and safety legislation (Figure 2.1).

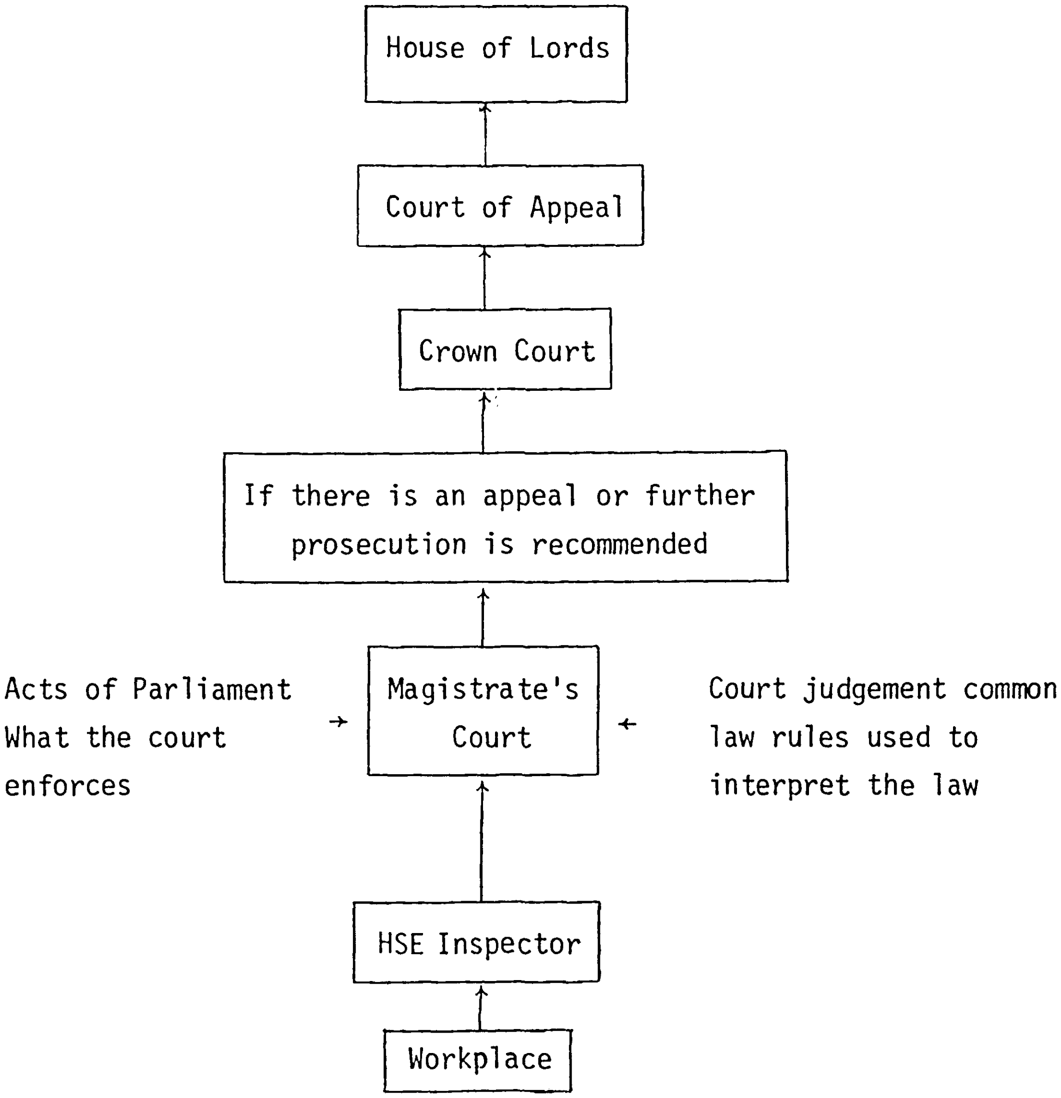


Figure 2.1 The Health and Safety Legal Framework (from Eva and Oswald, 1981)

The HSE can effect changes in the behaviour of person by other means than resorting to pressure from inspectors or prosecution. For example, the HSC can submit proposals for regulations to the appropriate minister. The Act does specify some areas for regulation, such as rules for handling and storing of particular substances, requirements for monitoring various aspects of the working environment and standards for noise. The HSC can also publish approved Codes of Practice. Though these do not lay down legal requirements, they have the same role as the Highway Code in traffic offences. They are admissable in evidence if relevant to a case of a breach of any requirement of the Act. The onus of proof is then shifted onto the persons who do not follow the guidance to show that they have fulfilled requirements satisfactorily by some other means.

In 1978, the Safety Representatives and Safety Committees Regulations came into effect. These allowed recognised trade unions to appoint safety representatives to represent employees in consultations with an employer over health and safety matters. The trade unions were then to inform management of the appointed worker safety representatives (HMSO, 1977). The duty this imposes on the employer is one of consultation, not of negotiation or agreement (Selwyn, 1982).

The Role of the HSE and the HASAWA

The HSE was formed to fulfill the enforcing duties of a safety philosophy which emphasised self-regulation. It was not intended that inspectors would be the primary enforcers of good health and safety practices. A general consensus of common interests and aims was assumed amongst the workforce and management. From this consensus would arise the driving force for improving health and safety conditions within each factory. Where no consensus arises and no common decisions are taken to improve health and safety, the executive role of the HSE comes into play. Inspectors are then needed to ensure that minimum standards are met.

Clearly, a general lack of consensus in factories implies a greatly increased workload of the HSE and makes it the main force for health and safety improvements.

Different interests within the factory set different weight by health and safety matters, making it impossible for a consensus on this where none exists on other industrial matters. As a Research Officer for one Union (NALGO) has stated, "Health and Safety is an important element of the terms and conditions of employment of working people and consequently trade unions will seek, through collective bargaining, to reach joint agreements on health and safety standards" (The Safety Practitioner, 1984). Thus health and safety is seen as an element in industrial relations, and not something over which consensus can easily be reached. The different role required of the HSE in the atmosphere of a general lack of consensus needs to be borne in mind when considering the discussion about the way in which the HSE carries out its role as an inspecting body.

A lot of discussion has revolved around the interpretation of the phrase "so far as is reasonably practicable" which appears frequently in the Act. The HSE has attempted to provide assistance on the interpretation of this in guidance on the Act. The guide explicitly states that reasonable practicality is not to be a reflection of the profitability of a company. "The comparison (or risk and costs) does not include the financial standing of the employer. A precaution which is reasonably practicable for a prosperous employer is equally reasonably practicable for the less well-off". (HSE, 1980). Other writers have been concerned with this issue. Eva and Oswald point out that "reasonably practicable" means that the cost of injury or disease to the worker is balanced against the costs of improvements to the employers (Eva and Oswald, 1981, p. 46).

Distrust of the judgements in courts has also been evident, with judges being seen to take the side of the employer in the evaluation of costs versus the benefits. (TUC, 1975). The Inspectorates have also been criticised for their handling of enforcement. It is claimed that most visits to firms are short with some rarely visited. The staffing levels of the Inspectorates are considered largely to blame for this lack of inspection. Enforcement is often not seen as a great threat to employers. (Eva and Oswald, 1981). Eva and Oswald quote the average for 1977/78 as £99 (compared to a maximum of £1000). Though this has since improved, fines are still well below the maximum allowable (in 1979 the average fine was £186) (Technology, 1983).

While bearing these criticisms in mind, it is important to remember that for a technological development such as the use of robots in industry, the HASAWA is extremely useful. Though there may be bureaucratic inertia, it would be difficult to obtain the necessary unified approach to the health and safety problems of robotic systems by other means. The universality of robots, being applicable to a large number of industries, would have been an enormous headache to health and safety inspectors in the separate inspectorates in existence before 1974.

SAFETY RESEARCH

Some examples of safety research are reviewed in this section which show the range of issues in health and safety at work. This discussion can be dealt with under a series of headings:- accident statistics, studies of the causes of accidents, analysis of serious accidents and the management of safety.

Accident Statistics

The Health and Safety Executive have collected statistics on accidents at work regularly. These figures come in the form of notifications of dangerous occurrences and reports of notifiable accidents. Of particular importance to a study of robots are the figures for manufacturing industry. Table 2.1 presents the figures for fatalities and notifiable accidents for 1973-1977 in Manufacturing Industry, which show a fairly constant rate of 4.0-3.5 deaths per 100,000 people at risk and about 3500 accidents.

No discussion of official accident statistics would be complete without a consideration of the difficulties of considering a fully comparable time-series and the under-reporting of accidents. Definitions of notifiable accidents have not remained consistent. Dawson et al have considered these issues in relation to an analysis of the effects of legislation upon accident rates (Dawson et al, forthcoming publication). They conclude that it is difficult to separate the role of legislation from other factors influencing the level of accidents. Technical and organisational developments, such as changes in employment levels, systems of work and training or skill levels could have as great an impact, and may even be more important.

Problems with under-reporting in official statistics are also recognised by Dawson et al. Comparisons between industrial sectors are hampered by the variations in under-reporting, estimated as of the order of 25% in manufacturing and 50% in the construction industry. Changes in the requirements for reporting accidents have also exacerbated the problem of under-reporting. Two changes are highlighted, the introduction of Regulations on the Reporting of Accidents provided for in the HASAWA and which became operative in 1981 and the changes in claiming of industrial injury benefit as a result of the Social Security and Health Act (1983). Neither of these two changes are of direct relevance to the period 1973-1977 given in Table 2.1, but they show how legislative changes can affect the content of statistics. The period covered in Table 2.1 is characterised by a larger number of statutes under which accidents could be reported. Dawson et al refer to the Explosives Act

	1973	1974	1975	1976	1977
Fatalities	236	254	196	175	179
Rate/10^5 at risk	4.2	4.5	3.7	3.4	3.4
Accidents	209699	199090	184324	181065	187261
Rate/10^5 at risk	3710	3520	3490	3480	3590

Table 2.1 Statistics for Manufacturing Industry (1973-1977)
(from HMSO, 1980)

(1975) Regulation of Railways and Railway Employment (Prevention of Accidents) Acts (1871, 1900 and 1975), Mines and Quarries Act (1954), Agriculture (Safety, Health and Welfare Provisions) Act 1956, Factories Act (1961) and the Offices, Shops and Railway Premises Act (1963), all of which provided for the reporting of accidents. Not only were their definitions of reportable accidents different, but the possibility of dual counting could not be excluded. It was only with the advent of the Notification of Accidents and Dangerous Occurrences Regulations (1980) that finally a unified set of statistics was provided for all those covered by the HASAWA. However, it was itself affected by the Social Security and Health Act (1983). Dawson et al conclude that 'As a consequence, official statistics on accidents at work are an unreliable data base from which to draw conclusions about accident causation" (Dawson et al, forthcoming publication). This suggests that it would be worthwhile to look at research into accident causation and not to concentrate only on accident statistics.

The Causes of Accidents

Heinrich carried out one of the earliest studies into the causes of accidents (Heinrich, 1931). His research led him to consider an accident sequence as analogous to a row of 5 dominoes. The first of these represented the person's social environment and background, the second the fault of the person, the third an unsafe act or hazard, the fourth an accident and the final one the injury. Each of the first four were necessary before an injury could occur. When the first 'domino' (social background and environment) fell and the 2nd domino was also present (fault of person) then it would fall also. This in turn would knock over the 3rd domino (unsafe act or hazard) if it were present and so on until the fifth domino fell. If one domino were missing (say an unsafe act or hazard) then the accident sequence would not propagate beyond this stage. Though this model is limited by its imagery to a purely linear accident causation, it has undoubted power in showing how an accident has a series of steps before it is realised. Later researchers have emphasised more the multi-causality of accidents.

Heinrich's research also led him to postulate a heirarchy of frequency for various accident categories, which he stated in the form of a triangle. He suggested that for each disabling injury, 29 minor injuries occur. Far more no-injury accidents (300) occur for each disabling injury. This is represented below as Figure 2.2.

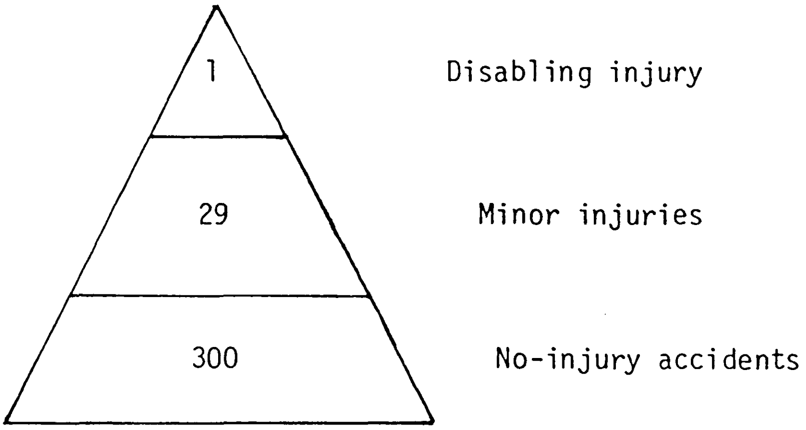


Figure 2.2 Heinrich's Triangle of Accident Frequencies

It is possible to disagree with the exact ratios given by Heinrich, but nevertheless his presentation is once more a powerful illustration of a basic concept.

A more recent study of accidents was carried out by the Factory Inspectorate in 1974 (Department of Employment, 1974). This was reported by Atherley in a review of safety strategies (Atherley, 1974). The Inspectorate carried out a study on a random sample of 621 accidents. The Inspectorate looked to see which accidents could have been prevented by reasonably practicable precautions and those which could not. They found that circumstances in which the accidents occurred were diverse and roughly half the accidents appeared to be preventable by reasonably practicable means. Of these reasonably preventable accidents, the Inspectorate concluded that the measures required were nearly equally under the control of workers and management. This showed the role of management and workers in maintaining physical safeguards, devising and using safe systems of work and monitoring performance. It also showed the importance of involving workpeople and securing their greater participation in the routine details of accident prevention.

Edwards has undertaken research supported by the HSE which included a study of the causes of accidents and the attitudes towards their causes (Edwards, 1981). She found that attitudes prevalent in the factories studied did not reflect the true causes. There was a predisposition to think of accidents as either the result of machine failure or human error. The former could be designed out to some extent, whereas the latter was treated as unpreventable (except if equipment could be made "idiot-proof"). The implication was that the latter cause was the obverse of the former since the people appeared to take the view that if machinery did not fail, the only remaining cause of a hazard (and thus an accident) was error on the part of a person.

Edwards tried to encourage the use of a more systematic analysis of the causes of accidents in the plants she studied. Her conceptual model of accident causation had four basic elements - software, hardware, environment and 'liveware' (people) (S.H.E.L.). The interaction of the four components produces the potential for accidents with no simple initiating cause being placed on any one component of this model.

A psychological approach to the causes of accidents is taken by Kay (Kay, 1971). Two quite different operating states of a person are identified.

(1) The environment controlled or stimulus response (S-R) mode. In this mode, the person reacts to signals and waits for another signal before initiating another response. Performance is intermittent, with measurable time gaps between stimulus and response.

(2) The preprogrammed mode. In this,one response triggers the initiation of the next response, with a smooth and apparently continuous succession of actions. Further signals occur but it appears as though they are anticipated and the person can respond without interrupting the smooth flow of actions.

These two operating states are very different. The first derives from inexperience whereas the second is strongly related to learning and to skill levels. Kay considers that the act of switching from one state to the other makes a person highly vulnerable to an accident. If a person is operating in pre-programmed mode, the act of switching to S-R mode when an unexpected signal is received creates a marked delay, removing the chance of reacting fast enough to take remedial action. Kay considers "an outstanding feature of many accidents is that a person has to switch from operating in a pre-programmed mode to an environmentally controlled (S-R) mode. Efficiency drops at the very point where most is demanded of it" (Kay, 1971, p. 117).

Rasmussen makes a similar point in his review of human error analysis and prediction (Rasmussen, 1978). "An operator will only make conscious observations if his attention is alerted by an interrupt from the subconscious processes. This means that he will only deal with the environment consciously when his subsconscious, automated, or habitual responses no longer will control the environment adequately" (pp. 362-363). As a result, "he may more readily accept the improbable coincidence of several familiar faults in the system rather than the need to investigate one new and complex fault of low probability" (p. 363).

Rasmussen also considers the role of human operators in rapid error correction. Because of our capacity to correct for our own mistakes, there is a distinct difficulty in assessing the reliability of human actions. Any collection of data on human error may contain information on the number of opportunities for error, but would not "give information on the total frequency of errors committed, but rather the frequency of errors which are not immediately corrected by the operator himself" (p. 376). As Rasmussen states succinctly, "The probability of selecting the wrong key on your key-ring is high; however, the probability that you should not succeed in entering your house for this reason is nil" (p. 369). As a result, the accurate prediction of human failure rates for any task for a complete safety analysis is highly problematical. This is so when a human action is necessary in response to a machine failure, but is even more difficult to ascertain when the initiating event of an accident stems from human action itself.

Multidisciplinary Approaches to the Analysis of Major Accidents

A high proportion of safety studies and safety research has quite rightly concentrated on the more risky enterprises of mankind. Accidents of major consequence are usually considered from a technical standpoint (See Green (Ed.), 1982). In other words, the analysis considers the outcomes of discrete machine failures and human actions on the operation of the relevant systems. Such analysis can be very useful in identifying equipment failures and their effects but are limited by the exclusion of certain aspects which have been recognised to influence accident causation. Chapter 7 considers some techniques and their limitations more fully.

Two organisational theorists have taken a different approach. They attempt to show that factors such as organisational behaviour and other socio-technical factors are of importance alongside purely technical details.

Turner (1976 and 1978) considers the origins of disasters, by concentrating on the events which lead to them. Turner makes the point that there is a thin line separating a disaster from an accident, particularly since an accident to some people could be a disaster to others. Turner points to failures of communication in the sequence of events leading to a disaster, which allow the problems involved to accumulate unnoticed. These failures along with misunderstandings and ambiguities did not all contribute to the disasters he studied. Some of these problems were only revealed incidentally afterwards. These difficulties in communication are caused by what Turner calls a "variable disjunction of information" (Turner, 1976), that is, the amount of information needed for the problems of complexity was far in excess of what could be generated or attended to. Therefore the need to be selective in information handling imposes problems on the organisation, causing it to make decisions which are later reflected in the events leading to the disaster. Several symptoms are noted by Turner, particularly 'organisational exclusivity' and 'the decoy problem'. The former term refers to the difficulty of transferring information recognised as pertinent outside to within the principal organisation. The latter term concerns the correct perception of and action for a hazard, but with attention distracted from the problems which eventually cause a disaster. This concept could also be considered as an unanticipated consequence, where certain actions produce effects other than those intended.

How the analysis of disasters pertains to ordinary accidents is not specified clearly by Turner. He does say, however, that "accidents are produced as a result of the combination of misinformation or misunderstanding with sufficient energy to produce an undesired transformation. Disasters are accidents which are more surprising or more alarming than usual ..." (Turner, 1978, p. 184). One can infer that Turner made the connection between his analysis of the causes of man-made disasters and that of accidents, the main difference being the amount of potential energy accumulated in the system under consideration.

Perrow concentrates his attention on a sociological analysis of the organisation of high-risk technologies (Perrow, 1984). He concentrates on technologies such as nuclear power, petrochemicals, aircraft and the use of recombinant DNA, where the potential for disasters is high. His is an organisational analysis of system failures and accidents, identifying the characteristics within the structure of the organisation which contribute to accidents. In this work he uses a definition of an accident which differs from the conventional view of injury to a person or damage to equipment. He divides systems into smaller sets, the subsystem, the unit and the component. Accidents are then failures which progress to cause a disruption of the output of the system or a subsystem. Incidents are those failures which are limited to parts or a unit of a system. Perrow is therefore more concerned with the effect of a failure or a series of failures upon the output of the system.

Perrow develops the concept of a "normal accident" or system accident in his analysis, that is, one which involves the unanticipated interaction of multiple failures. These accidents are 'normal' because the systems are designed so that multiple interactions of failures will occur in an unpredictable manner. The source of the accident is not different from other accidents, but the multiple interactions have a dramatic effect on the outcomes. Perrow uses two features of organisations and systems to consider the propensity of a system to have system accidents, that is the complexity of the interactions within the system and the degree of tight coupling. At the opposite end of the measuring scale for these two features are the linearity of the system and the degree of loose coupling. These terms are defined, but quite deliberately used fairly loosely. They are tendencies of the systems rather than fixed states.

The two dimensions of Perrow's analysis can be explained further by his development of the characteristics of each. Complex interactions involve unfamiliar, unexplained or unexpected sequences, and are either not visible or not immediately comprehensible. Linear interactions on the other hand are those which are in expected and familiar sequences. Even if unplanned, their sequence is quite visible. Tightly coupled systems are those with little time to respond to changes or perturbations, with more time dependent processes, invariable sequences and little slack, buffers or redundancies except those built into the design. Loosely coupled systems have alternative methods of production, slack in the resources available, possible delays in processing and the possibility to alter the order of sequences. For both dimensions it is the degree to which one extreme predominates that decides the features of a particular system. It is therefore possible to have four combinations:-

(1) tight coupling and linear interaction (e.g. Dams, some continuous processes like drugs or bread manufacture),
(2) loose coupling and linear interactions (e.g. most manufacturing and single goal agencies like the Post Office),
(3) loose coupling and complex interactions (e.g. Universities and R & D firms)
(4) tight coupling and complex interactions (e.g. nuclear power plants, aircraft and chemical industries).

Perrow places these on a 2 x 2 grid with examples scattered within each of the four boxes according to his own judgement (see Figure 2.3). To a large extent, the placing of a type of technology is decided by the requirements of that technology, although Perrow recognises the possibility of carrying out some "technological fixes" to move the technology along one of the dimensions of the grid.

The types of systems susceptible to system accidents in Perrow's analysis are those with complex interactions and which are also tightly coupled. With his experience as an organisational theorist, he realises that complexity requires decentralisation to handle the unexpected problems that occur, whereas tight coupling requires centralisation to handle the

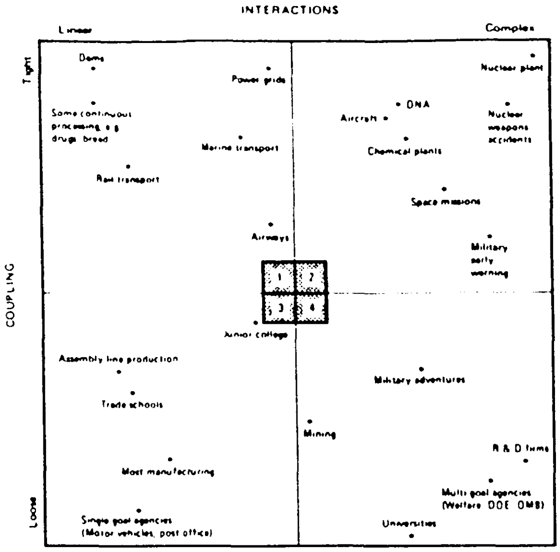


Figure 2.3 Interaction/Coupling Chart
(from Perrow, 1984, p. 97)

lack of time and invariable sequences. This internal contradiction within the organisation is in addition to the risks of the technologies. These circumstances place demands upon people and system design which are impossible to meet, thus leading to system accidents. A failure may have unexpected and multiple interactions, but unless the time available to react to those effects of the failure is too short, the problem can be handled before it progresses to the system level. In complex, tightly coupled systems, this time is not usually available.

Although Perrow takes a different approach, he identifies a number of similar problem areas to Turner. The decoy problem, of heeded warnings which produce an understanding of the problem (later shown to be false) is noted. Also highlighted is the difficulties of information transfer when the amount of information required exceeds the capacity to process it. Neither author considers manufacturing industry directly, presumably because it is not known for large scale accidents. However, Perrow places the majority of manufacturing industry in a position of loose coupling with linear interactions on his chart. Though he has not directed his analysis explicitly to manufacturing industry, it would seem to follow from his analysis that automation could push manufacturing industry towards tighter coupling and more complex interactions. The sequence of operations would become governed by the ability to change the operation of pieces of automation. The interactions of automated equipment may not be fully understood or expected, especially following a failure of a part of the automated production system.

The Management of Safety

Most research into safety has concentrated on the events leading up to an accident. This can take a purely technical stance or be more broadly based and include the behaviour of people in organisations (for example Turner and Perrow in the previous section). On the other hand, studies of how strategies are developed to deal with health and safety need to take a broad focus. It is possible to concentrate on technical matters in safety strategies (see Atherley, 1974) but a study must still consider the prevention of accidents by the influence of people's actions.

Atherley provides several early examples of health and safety strategies (Atherley, 1974). The narrative on these strategies relates almost exclusively to technical solutions to problems. There is a recognition of other influences such as socio-economic factors in ensuring safety and particularly the exclusion of certain people from certain work tasks, but the emphasis in his narrative is on technical solutions to health and safety problems.

Atherley also classifies four types of safety strategies - essential, prerequisite, adjunctive and collateral (Atherley, 1978). Essential strategies are directed at the hazard in order to bring about its elimination, reduction or restriction. Atherley sub-divides essential strategies into pre-accident and post-accident strategies and concentrates his discussion on technical controls, for example the use of dust respirators. Pre-requisite strategies are necessary as a condition for the effective introduction and implementation of essential strategies and include many organisational considerations, like the level of commitment, supervision and training. However Atherley is quite clear in stating that "in the absence of essential strategies, they cannot in themselves strike at danger" (Atherley, 1978, p. 393). Adjunctive strategies are subordinate to essential strategies, and include medical examinations and monitoring. Collateral strategies exist in parallel to or alongside those strategies directed at hazards and are directed at behaviour not the hazard. Atherley illustrates his explanation with the example of the beneficial effects of compensation upon safety. Thus, in his classification of four types of safety strategies, Atherley sees an important role for organisation issues, but in a subordinate role to the mainly technically based essential strategies.

A study of safety strategies appears to this author to lend itself to a multi-disciplinary approach, considering the technical and organisational influences in the decision making processes which are at the root of any safety strategy. The development and application of safety strategies can be called loosely the management of safety.

Dawson et al have considered the steps involved in safety strategies (Dawson et al, 1982 and 1983). The framework they developed is considered here in some detail as it is applied in the analysis of the empirical study.

Dawson et al consider hazard control as a sequence of possible actions. A hazard is defined as the potential for loss or harm to people and/or things (Dawson et al, 1982). If that potential for harm or loss occurs, then the hazard can be said to have been 'realised'. Following hazard realisation, the consequences of the realisation will become apparent and the hazard will continue, but with its characteristics (such as the probability of recurrence and severity of consequences) affected by this realisation.

For Dawson et al, actions to improve health and safety at work are directed at the process of hazard realisation, of which there are two major types of action:-

(1) Anticipation - where actions are taken prior to hazard realisation.
(2) Reaction - where actions follow the hazard realisation.

Since realisation does not necessarily remove the hazard, the reaction to any hazard will embody some forms of anticipation of future possible realisation. However, before these interventions can be applied, the hazard needs to be identified. Once identified, the choice is made about whether the risks involved are acceptable. If they are not, then three possible forms of actions are available:-

(1) Elimination of the risk by acting upon the probability of occurrence or the effects of consequences.
(2) Containment of the hazards by reducing the probabilities of realisation.
(3) Mitigation of the consequences of the risk of hazard realisation.

These are represented by Dawson et al in the form of a diagram representing the sequence of hazard control options, reproduced here as Figure 2.4.

As the diagram shows, a variety of different and complementary control actions are possible. Mitigation of possible consequences is represented

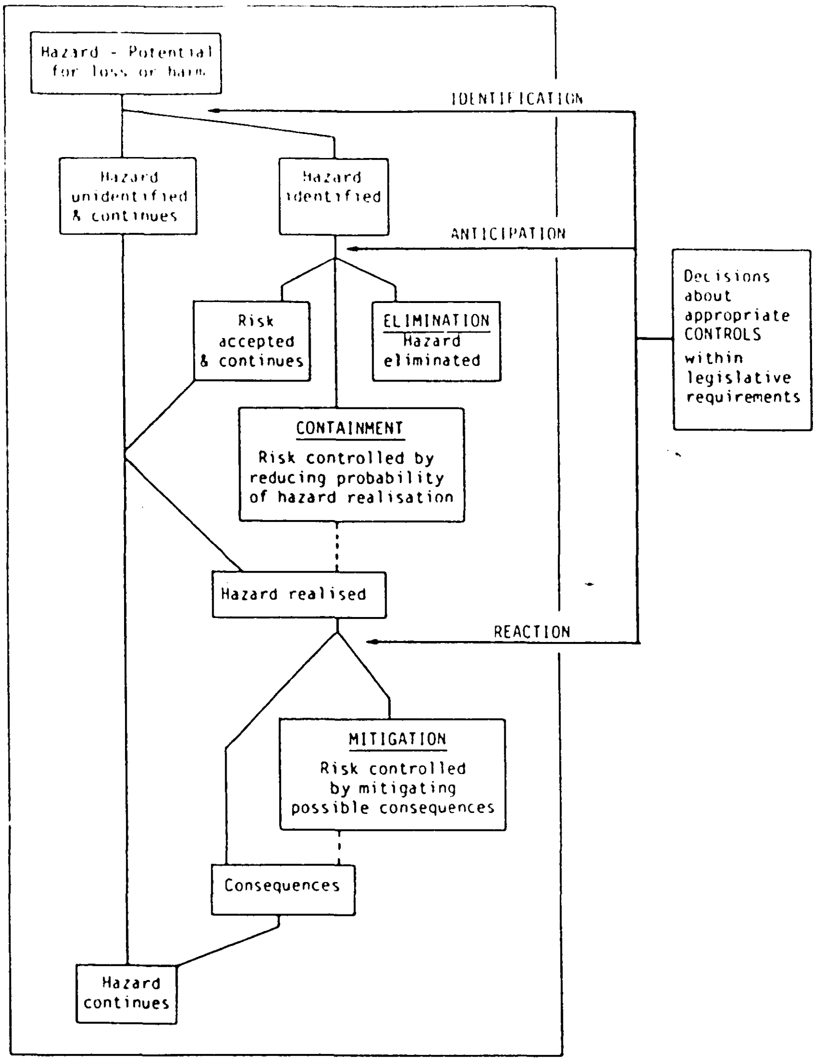


Figure 2.4 Hazard Control Options
(from Dawson et al, 1983)

as being part of the reaction to the hazard, but there are two forms of mitigation - of actual consequences and of likely consequences - of which only the former is truly a form of reaction.

The Identification stage can be seen as the first in the anticipation of the hazards. An evaluation of the safety issues can be made and decisions formulated upon what should be done.

A variety of strategic options can be used, based around the three key areas of elimination, containment and mitigation. Elimination of risk involves acting on the probability of occurrence and the consequence of hazard realisation, either jointly or separately. Typical examples of this strategy are changing machinery or plant design or using alternative raw materials.

Containment of hazards is aimed at the probability of hazard realisations. Dawson et al state that a large part of what is called preventive activity in health and safety would fall within this category of action. Typical examples are the provision of protective clothing, training, safeguards such as fencing or other limitation of the hazard by for example,working practices which restrict the hazardous activity.

The Mitigation of Likely Consequences will typically take the form of such things as evacuation procedures, provision of fire fighting equipment, means of escape and first aid facilities.

As these examples show, the focus of a strategic option can vary between acting upon people, on hardware available within the system or on the interactions between the two. Training is one area which clearly falls within the focus on people, whereas options which act upon equipment by excluding some forms or enclosing equipment are clearly acting upon hardware. The use of equipment to remove the necessity of interaction, the development of systems of work and other operating procedures or the development of evacuation procedures act on the interactions between people and hardware.

Where no anticipation occurs, consideration of the hazards which may arise is missing. This does not mean that no strategies will develop, but that they would be a fortuitous by-product of other considerations within the organisation.

Decisions on health and safety issues are rarely taken in isolation within an organisation. Dawson et al emphasise this point: "Local strategies to control hazards through elimination, containment and mitigation must then be understood within the context of the organisation in which they originate" (Dawson et al, 1983, p. 438). They state that complex organisations are composed of a number of different interest groups with a number of objectives besides health and safety. The different groups, of which corporate management, plant management, technical specialists, first line supervision and workforce safety representatives are considered to be the most important, may have different views on acceptable levels of risk. Clearly, the sources of power and influence of the various key interest groups are critical to the extent corporate attitudes and responses reflect their views.

These key interest groups may be able to change the proportion of scarce resources available to health and safety as well as affect their overall availability in the organisation. The use of scarce resources and the perception of the importance of health and safety relative to other priorities will be deciding factors in the judgements over costs and availability of resources for health and safety. The three main types of scarce resources considered are:-

(1) technical and specialist knowledge
(2) capital and revenue finances
(3) time for line management to participate in health and safety strategy development and implementation.

The process of producing a strategy for controlling hazards is clearly not complete at the stage of deciding what is to be done. One also needs to look at the development and implementation of the strategy. Once the strategy is in operation, monitoring in the form of detection and investigation of its operation will take place, to be followed by the evaluation of the monitoring and possible adaptations. These stages in the organisational process are described by Dawson et al as Technical Controls. Another set, referred to as Motivational Controls are more general in nature and are used to develop and maintain a safety awareness along with a commitment to maintain Technical Controls. Technical controls are to be applied at the point of risk, whereas Motivational Controls apply throughout the organisation. Three principal elements are identified as the core of the motivational control system:-

(1) the general objectives, culture and atmosphere of the organisation
(2) the definition of responsibility and authority of personnel
(3) the mechanisms of accountability and performance measurement.

SUMMARY AND CONCLUSIONS

This chapter has considered two major Acts of Parliament and their relevance to ensuring health and safety with industrial robot systems. The underlying philosophy of health and safety legislation was shown to be self-regulation within a structure of specific regulative law. Within this overall philosophy, the role of inspectors from the Health and Safety Executive has been more of education and advice rather than enforcement of punitive law. Inspections are meant to investigate the steps taken by managers in handling the health and safety issues in their factories.

This approach of the Health and Safety Executive creates some difficulties. In particular, the expected role of inspectors is difficult to achieve since it derived from a view of a general consensus on health and safety. The reality is much more a reflection of negotiations between conflicting views held by different interest groups. Nonetheless the unified approach made possible by the advent of a combined inspectorate has a number of advantages for a technology which cuts across normal industrial sector boundaries, as is the case with industrial robots.

A brief view of accident statistics and consideration of the difficulties of obtaining an accurate time series with a common data base led to the conclusion that their use for analysis is limited and that more can be gained from concentrating on research into the causes of accidents. This directed attention to the role of different elements in accident causation. Heinrich emphasised a linear causation model, whereas Edwards considered multicausality involving the interaction of four basic elements of any system. The Factory Inspectorate concentrated on the role of management and workpeople in divising, using and maintaining means of accident prevention.

Consideration of the role of human behaviour in accident causation identified the way in which a continuous succession of familiar actions leads a person to be ill-prepared to respond to a sudden unforeseen action. This switch between what Kay referred to as 'preprogrammed' and stimulus-response mode can be a significant reason for the propagation of a dangerous condition into an accident.

Studies of the causes of major accidents highlighted the problems of the transfer of information and the implications of complexity and tight coupling of systems. Systems susceptible to system or normal accidents (in the terms used by Perrow) are those with complex interactions and which are also tightly coupled. Consideration of the relevance of this finding to industrial robots led to the conclusion that robots would move manufacturing industry towards tighter coupling and more complex interactions.

The studies of the causes of accidents presented in this chapter suggested that a technical approach to the study of safety strategies would be inappropriate and that a multidisciplinary socio-technical approach was required. A framework for the analysis of safety strategies was presented which concentrates on the various stages of application and considers the organisational requirements of scarce resources, the role of key interest groups and the influence of motivational controls for safety. This framework allows a multidisciplinary approach to the analysis of safety strategies. The effectiveness of a safety strategy can also be assessed. It will therefore be applied to the analysis of the robot systems in the empirical study presented in this thesis.

CHAPTER 3

ROBOT SYSTEMS: HAZARDS AND GUIDANCE

INTRODUCTION

This chapter is concerned with the safe use of industrial robots. First, the benefits and the hazards of robots are considered by looking at surveys of robot accidents and hazards and at authoritative statements. The guidance on safe robot use which has originated from the growing awareness of the hazards of robots is then considered in some detail. The approach and emphasis of current guidance is discussed in terms of the implied focusses for safety strategies.

THE BENEFITS AND HAZARDS OF ROBOT USE

The Benefits of Robot Use

The claims of benefits of robot use are not limited to improvements in production engineering and management. It is a common theme of a number of books and articles written on the subject of industrial robots that the main effect of robots on health and safety is a positive one. For example, industrial robots are endowed with the ability to remove workers from hazardous environments by taking over unpleasant tasks in the workplace. Engelberger takes this view in stating that the main effect of robots in the area of safety has been to remove people from hazards (Engelberger, 1980). By doing so, he asserts, robots may well be said already to have saved human life.

The Inbucon study (INBUCON, 1982) also takes this view in its description of nine case studies of robot applications. It refers to improved health and safety conditions in several cases as a result of the substitution of a robot for which previously was a dangerous job for a human.

The same claim has also been stated in the USA (Heroux and Munson, 1979) by senior engineers with the robot manufacturer, Unimation. They outlined the benefits that robots were already bringing about in various processes. They named press-loading, spray painting, furnace tending and other hazardous jobs, where the use of robots had reduced the risks to workers' safety and health. The exposure to toxic materials, the loading/unloading of hot parts and the lifting of heavy loads had also been reduced or removed by the introduction of robots.

A paper at the 4th British Robot Association Annual Conference by M.P. Kelly of BL Technology referred to the social obligation companies should have to remove operators from hostile environments (Kelly, 1981). He went on to elucidate a number of processes which presented hazards for workers. Fusion welding, he considered, was an obvious hostile environment, in which a robot could also bring the added benefits of good, consistent, quality welds and greater speed. Resistance welding, a major application of robotics in the automobile industry, presented hazards for workers, but the main advantages here of automation were in improved quality of the welds. Undersealing of cars was considered an extremely hostile environment, the work having to be done in confined spaces from below the body of the car, with unpleasant substances. For paint spraying and adhesive bonding, hazards arose from the choice of compounds used. The latest adhesives had an associated risk of dermatitis, and the use of polyurethanes in paint spraying would be made possible by automating the process as it was too dangerous to be carried out by a human.

In addition, articles have appeared in various journals advocating the adoption of automation on the grounds of reducing the hazards for the workforce. As an example, an article in The Engineer in 1978 advocated the adoption of robots for arc-welding, on the basis of the result of a questionnaire sent to ship welders in Sweden (The Engineer, 1978). The article's theme is that the hazards of arc-welding would be greatly alleviated by robot application, if not completely eliminated.

In different parts of the world there have been moves to promote the use of robots in order to improve industrial safety. In W. Germany, the "Humanisation of Work" programme initiated by the government has supported the use of automation in dangerous workplaces. Two studies of the effects of robot introduction as part of this programme have shown some benefits in health and safety but some increases in mental or psychological stress and strain (von Gizyiki, 1980, Wobbe-Ohlenburg, 1982). The second of these studies found that though extreme stress may be decreased, other new stresses may arise.

In East Germany, robots have been seen as part of an attempt to reduce manpower requirements. Industrial robots are advocated for the elimination of hazardous or monotonous work according to an analysis of the requirements of various tasks (Otto, 1979).

In Japan, several papers at successive International Symposia on Industrial Robots have emphasised the use of industrial robots to improve the quality of working life. One of the most recent of these goes furthest in promoting robots for safety reasons (Hasegawa and Sugimoto, 1982). Specific dangerous jobs are mentioned, such as foundry work with associated occupational deseases from inhalation of dust, hearing difficulties, and vibration injuries, forging with its very high accident frequency rate (quoted at over 8 times the manufacturers mean value), the disposal of high level radioactive waste and ship painting.

The Health and Safety Executive in Britain has noted the benefits which could arise from the use of automation, particularly whilst reminding users of the possible dangers. "It would be quite wrong to ignore the benefits which robots bring with them including the possibility of removing the need for operators to place their hands between the platens of presses and die-casting machines or work in toxic/inflammable atmospheres" (Barrett, 1985). More generally, the advantages of programmable electronic systems (p.e.s.) have been promoted by the HSE in the context of their safe and proper use. R. Bell, HM Senior Electrical Inspector points out the wish of the HSE to encourage the use of p.e.s.'s in certain areas and gives a short list of advantages (Bell, 1982):-

(a) Better information of the process being carried out may be supplied and hence the controllability will be improved, along with the safety.

(b) Some deficiencies in sensors and signals may be overcome.

(c) Diagnostic programs could be adopted, giving warnings of impending problems and suggesting solutions.

(d) As an extension of this diagnostic function, a running log could be stored so that it could be retrieved, in the event of an incident, for investigation.

(e) There is the potential to provide safety interlocks of almost any degree of complexity.

(f) The output from sensors may be used to derive parameters which previously were too complex.
(g) The p.e.s. may enable operators to be moved from hazardous or hostile environments.
(h) Better control information could be provided. For example, actual conditions could be compared with expected conditions during start-up, steady-state or shut-down.

A similar list of advantages also appears in another two HSE publications. (HSE, 1981 and HSE,1984a).

It would be wrong to assume that this view of advantages by the HSE means that hazards of p.e.s.'s are not important. Indeed they place far more emphasis on the problems of p.e.s. use in these publications.

The attitudes of those people who state only the positive effects of robot introduction have been summarised by Stowe (1983). Two complementary statements are normally given:-

(1) Robots are considered as a safety device in themselves, removing workers from hazardous environments and relieving them from monotonous, tedious and dirty jobs. The reliability and low accident rate of robots reinforces this attitude.
(2) Robots are considered no different from other high-speed industrial machines, involving no high risks. Any risks there are can be eliminated by the use of fail-safe design, interlocks, personal protective equipment and a good safety attitude. Because no new hazards exist, there is no need for special safety standards for robots.

Stowe comments that the advent of industrial robots places the safety professional in an ironic position. The safety professional can hail the robot as a safety device but at the same time must consider the hazards arising from a new piece of production equipment. Thus, no matter how true the attitudes summarised above may be, "it behoves the safety professional to investigate the hazards associated with robots to determine what unique safety issues, if any, need to be addressed" (Stowe, 1983). Thus his inclination as a safety professional is to doubt the claims of the benefits of this technology and to assess the hazards. This author agrees with this cautious approach to the benefits of industrial robots and the following section considers the published evidence of hazards associated with robot use.

The Hazards of Robot Use

There has been a growing public discussion of the possible safety problems and hazards of industrial robot use. This concern has been particularly noticeable since the beginning of the 1980's and is evidenced by the number of conferences, symposia and seminars at which robot safety has been a major subject. The annual conferences of the British Robot Association and the International Symposia on Industrial Robots have both had a substantial proportion of papers on industrial robot safety. The I. Prod E. and I. Mech. E. have organised seminars on the subject of industrial robots which have included issues of safety. In addition, one seminar on safety guarding was organised jointly by these two Institutions in conjunction with the Zinc Alloy Diecasters Association (I. Mech. E./I. Prod. E., 1984). Besides these, there has been a two-day seminar on Robot Safety, organised by the University of Nottingham and Ford Motor Company Ltd. (University of Nottingham, 1982), a joint HSE, I. Mech. E., I. Prod. E. seminars and Robot Safety in November 1985 and an International Colloquium on safety with automation at which robot safety played a major part (ISSA, 1985). Papers from some of these conferences have been revised and included in a book on Robot Safety (Bonney and Yong (Ed.), 1985). This book also contains a few exclusive articles. It is quoted from frequently in this chapter because it represents perhaps the most up-to-date collection of publications on a major subject of this thesis.

The various publications have produced a number of independent assessments of the hazards of robot use. Some of these assessments are based on surveys of accidents and hazards with robots. These surveys are a very useful source of information and are considered here before other publications on hazards.

Survey data

Two countries, Japan and Sweden, have provided figures on accidents and near accidents. One survey was carried out in each of these countries near the end of the 1970's. In Sweden, Carlsson et al reported on a questionnaire survey sent to the Swedish Metal Workers Union (Carlsson et al, 1979). Twenty-one branches of this Union were questioned, who reported 15 accidents. Seven accidents were reported for both 1976 and 1977 and one during the first half of 1978. By extrapolation to the whole robot population in Sweden, the figure of 2.5 accidents per year for every 100 robots installed in Sweden was derived. The data did not provide information on the number of persons working with robots and so it was not possible to calculate accident rates for periods of work. The types of accidents were commonly cases of trapping of the worker, when the worker was inside the barrier around the robot system. Clearly, it was possible in some cases to enter the robot's area of operation with the robot powered on. Information on incidents which did not lead to accidents was not considered satisfactory and therefore was not reported. A study visit by the National Board of Occupational Safety and Health is also reported by Carlsson et al. Although no accidents had occurred, a number of incidents were reported. Examples were given of a robot arm moving at speed to an end-stop as a result of a valve failure, a worn electrical cable causing a robot arm to drop and of another robot making an unexpected motion during programming.

Sugimoto (1977) reported on a survey undertaken by the Research Institute of Industrial Safety in Japan. Eighteen accidents were included in this survey and a table of causes was produced. This table is reproduced below as Table 3.1.

Table 3.1 shows that relatively few accidents occur during normal operation (about 10%). The greatest risks derive from working within the robot's area of operation, carrying out tasks like programming or adjustment.

A problem arises immediately one considers this table in detail, as the categories of causes are very unclear. Some categories refer to movement by equipment, others to the presence of persons within the work area and others to failures. Clearly it is possible for all three of these types of causes to occur simultaneously in an accident. For example, Sugimoto states that a common cause of erroneous robot movement during adjustments was a problem with the robot's control. It seems likely that a judgement has been made as to the major contributory factor to each accident and this factor has been given the title of 'cause'. Another limitation of this survey is the absence of information on the base from which the figures are drawn. The number of robots, robot users or the period of time covered are not given.

Later studies in both Sweden and Japan have followed up this work and have produced clearer results. In Sweden, the Occupational Accident Research Unit in Stockholm analysed 29 accidents with robot systems during 1979, 1980 and 1981 as part of larger survey of accidents with control systems (Backstrom and Harms-Ringdahl, 1984). They found that their study obtained a frequency of 1 accident per 100 robots per year. However they readily admit to missing data, making this figure a substantial understimation. Considerable disagreement between their findings and Sugimoto's was produced. Whereas Backstrom and Harms-Ringdahl found that 60% of the accidents occurred when the operator made a correction on the robot or the part being processed, Sugimoto's figure for this is interpreted as 17%. Difficulties in comparing surveys are highlighted by this discrepancy. Not only are the representativeness of each survey's sample open to question, but also there appears to be a difference in the categorisation methods. Thus differences between the two surveys cannot be considered significant.

A more complete analysis of accident data is given by Carlsson (Carlsson, 1985). This report draws on a data base of the National Board of Occupational Safety and Health in Sweden. It identified 36 accidents in the period from 1979 to 1983, showing that 7 or 8 accidents requiring the injured person to be "sick-listed" occurred each year from 1976 to 1983. This report provides summary tables of the robot type, the event and activity, the industrial sector in which each robot worked, the types of workers injured and the types of injury. These tables show that pick and place robots were by far the most frequently involved in accidents. Welding, painting and coil-winding applications had only one accident each. The activity of the injured person is particularly interesting and so this table is reproduced as Table 3.2. Adjustments in the course of operation and repair or programming were the most frequent activities involving accidents. Unfortunately, information on the sample base, such as the proportion of each type of robot and task studied is not given.

The two columns in Table 3.2 are for the two types of events, those involving contact with moving machine, parts or materials and other events.

Type of Cause	% of Occurrence	Absolute Number
Erroneous robot movement in stationary work	5.6	(1)
Fault in another machine during stationary work	5.6	(1)
Erroneous robot movement during programming	16.6	(3)
Fault in another machine during programming	16.6	(3)
Erroneous robot movement during manual control	16.6	(3)
Unauthorised person within work area	11.2	(2)
Human error during installation, adjustment and repair	16.6	(3)
Other cause	11.2	(2)
Total	100	(18)

Table 3.1 Causes of Accidents with Robots (from Sugimoto 1977)

Activity	Contact with moving machine, part of material	Other
Adjustment in the course of operation	14	-
Movement up against robot	1	1
Repair, programming, etc.	13	2
Miscellaneous	3	2

Table 3.2 The Number of Accidents by Activity and Event Type (from Carlsson, 1985)

Contact is far more frequent when accidents occur. Carlsson states that "it is the manual adjustment of material in proximity to a robot arm, which has no protective screen or guard, that is the most common cause of injury. In other words, the injured person has been working inside the robot's work area". (Carlsson, 1985). The tables also show that exactly one third of the injured were persons who work with the machine in the course of planned or unplanned interruptions or persons who instruct operators. The other two-thirds were other workers, such as operators of the robot systems or people working adjacent to the robot areas. The types of injuries are shown to be predominantly to the fingers, hands, head, head, back or arm. Only 2 injuries occurred to the legs of workers.

A description of each accident is given as an Appendix to the paper by Carlsson. The types of processes and industries are very varied as are the exact course of events. What is striking about the description is the frequent ability of a worker to be close to operational machinery and thus to be struck or trapped.

Nicolaisen also uses information from a survey on incidents and accidents with robots in Sweden (Nicolaisen, 1985). He considers 24 critical situations observed over a period of 14 days at eight workplaces. Some of these resulted in injuries to people or material damage, whereas the majority merely illustrated the potential for harm. It will serve little purpose to quote from this report at length but a few comments on the circumstances of the incidents are useful. An overwhelming majority of incidents (18) involve the robot coming close to or into contact with the person. Nicolaisen comments that in these incidents, there is the possibility or necessity for the work area to overlap with that of the robot. In some of these the safety barrier is within the robot's reach, and involve the robot reaching beyond the safety barrier. The other incidents concern general housekeeping (oil on the floor and positioning of cables) and the interactions of the components of the system. In one of the latter cases, the system went out of control following a break in a cable.

In these surveys of accidents with robots in Sweden, it is sometimes difficult to decide whether each survey is independent, or if they use a common information base. One can be fairly certain that the second Carlsson paper has the whole of the survey of Backstrom and Harms-Ringdahl within its own survey. The accidents reported by Nicolaisen are also likely to be included in Carlsson's paper. However, it is not wholly clear whether there is an overlap between the first Carlsson paper (1980) and the second (1985).

Further Japanese studies provide perhaps the best data on accidents. A Ministry of Labour study of 190 industrial plants in the middle of 1982 when 4342 robots were in use found 11 accidents had occurred in the preceding 4½ years (Ministry of Labour, 1983). Table 3.3 is taken from this report and gives details on the accidents, which include two fatalities. It is difficult to assess the accident rate from these figures, since the number of robots in use in each year is not given. The first year of robot use in each plant is given but the figure of 4342 robots refers to the end of this period (1982). We can see from Table 3.3 that 2 accidents occurred in 1978 (one of which was a fatality), 2 accidents in 1979, none in 1980, 6 in 1981 (including a fatality) and 1 in 1982.

Figures for near-accidents are also provided, showing 37 of these occurred from 1978 to 1982. Thirty-three of these occurred in the final 1½ years. One would expect this increase in hazardous incidents from an increasing robot population. Sugimoto (1985) reports this survey and also a larger investigation by the Research Institute of Industrial Safety, which had obtained data on 350 incidents associated with industrial robots. Sugimoto reports on the causes of accidents in terms of the movement of manipulators and of faults in equipment or by operators. Unnatural movements and repeated movements form nearly 59% of the accidents (30.6% and 28.3% respectively). When one considers unexpected movements, 61.9% are caused by robots and associated equipment and only 38.1% by operator error. Mechanical or electrical problems with equipment are also the major cause of all accidents (81.6% as opposed to 18.4% for operator error).

These surveys show a number of serious accidents associated with robot use, including two fatalities. Japan appears to have a more serious safety problem than Sweden since the accidents in Japan have been worse. However, one needs to remember that Japan's surveys included more robots. There is also a larger robot population in Japan. The frequency of use is high enough to generate a large number of hazardous conditions and it is therefore more likely for some of these to manifest themselves as accidents. In total, 5 fatalities have been reported worldwide, 4 of which were in Japan (Altamuro, 1983).

No.	Year	Situation During Which Accident Occurred	Result	Work Situation
1	1978	A worker attempted to remove an imperfectly worked piece from a conveyor with both hands at which time the operation limit switch of the I.R. (for feed and removal of work material) was tripped and the worker's back was forced against the robot.	Death	During operation
2	1981	When the starting button was pushed following adjustment of the machine (shaving machine) the manipulator of the I.R. (for feed and removal of work pieces) that was in the background extended and the operator was caught between the machine and the manipulator.	Death	During adjustment of related equipment
3	1978	The functioning of the I.R. used in welding went awry during its operation and the worker came into the operating range of the manipulator as a result of which the manipulator flung the worker against the machine.	7 days lost time	During operation
4	1981	The cover of the I.R. (for assembly use) was removed for adjustment of the unit when the worker attempted to pick up a part that had fallen whereupon his hand became enmeshed in the moving section of the industrial robot.	3 days lost time	During operation
5	1979	The worker attempted to retrieve a part needed in the assembly without cutting off the power supply to the I.R. (for assembly use) when he came within the operating range of the manipulator and his hand was caught between the manipulator and the unit being assembled.	No lost time	During operation
6	1979	The manipulator started to function erratically during inspection of the I.R. (for assembly use) and the workers hand was struck by the manipulator.	No lost time	During inspection

(Cont'd)/

No.	Year	Situation During Which Accident Occurred	Result	Work Situation
7	1981	The manipulator functioned erratically when instructions were being given to the I.R. and the worker's body was struck by the manipulator.	No lost time	During instruction
8	1981	When the worker attempted to clean an accompanying equipment that was within the operating range of the manipulators of an I.R. without cutting off the power supply, his hand was struck by the manipulator.	No lost time	During operation
9	1981	I.R. (for assembly use) was being repaired when the manipulators started to function erratically and the worker's hand was struck.	No lost time	During operation
10	1981	The I.R. (for assembly use) was being serviced when a fellow worker accidentally tripped the switch whereupon the manipulator struck the worker's hand.	No lost time	During operation
11	1982	The worker was using an air gun to blow away the cutting scrap from a lathe from which the product machined was transported away by an I.R. when his hand became caught between the manipulator and the piece being finished. Note: these 11 cases of accidents occurred in 6 plants.	No lost time	During operation

Table 3.3 Summary of Serious Acidents with Industrial Robots in Japan (From Ministry of Labour, 1983)

There is one further reservation which needs to be stated about these survey of accidents and near accidents. This concerns the type of equipment included in each survey. The problems of robot definition have already been discussed in Chapter 1, as well as the different stances of the collectors of statistics on robot use in each country. At the end of the article dealing with the most recent Japances surveys, Sugimoto states that about 150,000 robots are in use in Japan whereas the British Robot Association accepts the figure of 65,000 industrial robots in Japan at the end of 1984 (see Chapter 1). This begs the question of what type of equipment is included in the surveys reported by Sugimoto. The population base for any sample is likely to differ from one country to another. International comparisons of accidents are therefore complicated by more than legal and cultural differences in health and safety considerations.

Authoritative statements of robot hazards

With the rapid increase in robot use already seen in the UK and elsewhere, the consideration of a small number of accidents is of only limited benefit. What is more important is the potential for accidents which exists in the growth of the use of this technology. This potential can be understood by consideration of authoritative statements on the hazards associated with robots. These have been developed from the surveys but reflect the possible hazards as well as those that have been realised as accidents. Sugimoto and Kawaguchi note that although experience gained from past accidents may be hepful, there has been very little data available which identifies accidents involving robots clearly. However, they use the cases of accidents reported in surveys to conclude that the accidents "demonstrate clearly that robots have arms powerful enough to kill human workers, whilst suggesting some accident potential operation patterns peculiar to robots" (Sugimoto and Kawaguchi, 1985). Since insufficient data is available, Sugimoto and Kawaguchi attempt to evaluate hazards of robot systems using the surveys as illustration of these hazards. They begin by considering what would constitute the danger area within a robot system. They state that robots are different from conventional machinery where the danger zone is usually inside the machine. With a robot the danger area extends to the whole space within the reach of the robot arm. This could also extend further should the robot lose control of a workpiece held by it.

Sugimoto and Kawaguchi assess the hazards of robot use first in terms of the types of actions requiring interactions between machinery and workers and secondly in terms of energy available in a robot system to cause hazards. For each activity involving contact with robots, they identify hazards which in part are peculiar to robots.

For moving and installation work Sugimoto and Kawaguchi state that robots are occasionally extremely unstable structures. Some robots cannot stand upright until they are anchored to the floor with bolts. With any other type of machine this would be very unusual. Thus there is a definite possibility of being hit or trapped by an unstable robot.

Sugimoto and Kawaguchi state that the preparation and adjustment of a robot for productive use often needs to be done from above the floor with the person exposed to the hazards of falling as well as cuts, scrapes or an electric shock. For some of the final tests, such as adjustment to the controls, the robot has to be fully operational with the worker in an exposed position. There is also the possibility of human error in the loading of programmes into the robots' controls.

When programming, workers must enter the robot operating zones and cannot do their tasks if the power to the robot is disconnected. Thus the worker(s) and the robot are in close proximity with the robot in an active state. The robot is capable of powerful and sudden movements under these circumstances, particularly if a slow speed for the robots motions is not used by the programmer. Sugimoto and Kawaguchi state that the hazards are greater for the more complex robots which are programmed by a hand-held teach control or by direct movement of the arm. What is more, the act of programming on a step-by-step basis is likely to be accompanied by mental fatigue. The attention of the programmer can wander from the task and the robot could move without the person being wholly aware of it. Errors are also more likely under fatiguing circumstances. Simpler programming methods such as the movement of a pin on a pinboard control are less dangerous since they safeguard against abnormal operation of the robot.

Testing the robots operation and performance can be done mostly at a low speed, with no work piece, or as in the case of arc or spot welding, with no electric current flowing to the robot's tools. But a worker checking on the robots path will need to be very close to the end of the moving robot arm to determine the accuracy of the motion. This is particularly so for complicated tasks such as arc welding. The work piece or the electric current would have to be present to check how the robot performs the whole task. The worker is then brought into close contact with the robot whilst it is operational, even if moving at a slower speed than normal.

Sugimoto and Kawaguchi emphasise the need to confirm that there is no dangerous condition within the operating zone of the robot during production "A careless or haphazard approach to the set-up procedures is an invitation to disaster" (Sugimoto and Kawaguchi, 1985, p. 88).

During automatic operation, hazards are posed by the process, the robot and tasks which the operator has to do to complete the operations of the system. Those hazards directly linked to the robot include the possibility of the robot arm or a part held by the robot coming within reach of the worker. Sugimoto and Kawaguchi consider unexpected halts and starts as particularly hazardous events. They categorise robot halts into seven groups.

(1) Emergency halt with the use of the emergency stop button.
(2) Temporary halt using the pause button on the robot controls.
(3) Malfunction halt due to a detection of an abnormality.
(4) Runaway halts for machine failure.
(5) Condition wait halts for sequencing of robot actions with associated machinery.
(6) Work termination halts at the end of a work programme.
(7) Apparent halts due to fixed point position control.

Among the means to stop robots are (in decreasing order of stringency): cutting off the power completely, cutting off the drive and oil pressure pump power supply, cutting off the power supply for servo control and pauses. Robots differ in their design philosophy, so that it is not possible to say which type of halt has which means of preventing motion. However, the more 'severe' halts (emergency halt or malfunction fault) can be expected to have the most stringent means of stopping the robot. The type of halt and the means by which the halt is achieved are important since a worker may come within reach of the robot during any investgation and correction of a problem. Sugimoto and Kawaguchi state that accidents caused by a sudden, unexpected starting are quite possible under such circumstances. The problem of assuming erroneously that the robot is at rest is also highlighted. Accidents could occur if the process was halted by the failure in the sequencing of associated equipment, whereby its correction would cause the robot to start moving rapidly once more.

During repair and maintenance, workers often have to be within reach of the robot. This could be in a very tight space and with the worker in an awkward position. A distinction is drawn between normal maintenance and maintenance to eliminate a malfunction. They consider the risks from unexpected robot movement are greater under circumstances where a problem has already interrupted the robot's operation.

Sugimoto and Kawaguchi consider the accidents likely with robots also in terms of the form of energy released. They speculate that accidents would arise because the energy of the robot system would be converted or channelled into a form capable of injury. They recognise that the application of the robot would be very important in any identification of sources of energy as well as the mode of operation at any time. Potential energy is available within a system in the form of physical potential energy or from an electrical potential difference or from high pressure devices. The major source of 'positional' energy is given as the toppling of a robot or other falling items of machinery. Electrical energy can arise from the power to an electric robot or to the tools (such as as arc-welding torches). The continual movement of the robot arm causes cables to wear leading to exposure of the wires. Even if a worker does not receive a shock, there is the possibility of power failure or short-circuit which could cause erroneous action of the robot. It is also possible for fires or explosions to occur. High pressure may be present in an hydraulic or pneumatic circuit. These also can be subject to worn or frayed cables, resulting in a catastrophic loss of power. The resultant 'whip' of a broken hose could injure a person, or any motion caused could lead to injury. For example, a gripper could open as a result of a break in a pneumatic hose causing the robot to drop a part or throw it some distance.

Other causes of dropped or thrown parts are classed under mechanical energy sources. The abrupt stopping or collision of the robot arm could result in the release of the part being held. The main source of hazard from mechanical energy is given as the ability of the robot to move at high speed. The interactions of the robot with other equipment increases the risk of a worker being pushed or trapped by machinery.

Other sources of energy are those associated with applications, such as chemical, biological, thermal energy or radioactive materials. The use of a robot can multiply the hazards first by creating extra hazards which also increase those of the application (such as presenting a source of combustion or explosion in an explosive atmosphere or near combustible materials) or secondly, by increasing the spread of the hazards (such as spreading dangerous chemicals over a wider area, or tipping hot or very cold material onto a worker).

These two dimensions of robot hazards (interactions and available energy) are presented by Sugimoto and Kawaguchi in the form of a table. This is reproduced here as Table 3.4. Those hazards which are thought to have a strong relationship with robot use are marked by crosses. The other hazards are marked by circles.

Malfunctions of the robot which lead to the possibility of accidents are given some consideration by Sugimoto and Kawaguchi. They list a number of accidents where the robots had moved suddenly in a way they were not meant to. These forms of unexpected start are different from cases of motion which a worker had not foreseen but were nonetheless correct. Common causes of these malfunctions are given as electrical noise, problems with pressure or servo valves, encoder-related problems, printed circuit board malfunctions or abnormalities and errors traceable to misjudgement or erroneous operation by workers.

Sugimoto and Kawaguchi use their analysis of robot hazards to create a Fault Tree Analysis (FTA) of robot accidents. They present this as a qualitative illustration of the causes of accidents by potential, kinetic, or thermal radiation. No attempt is made to quantify the possibility of occurrence of any of the tree's branches. This is understandable, since each branch contains much which is dependent on human actions. This is to be expected since hazards are so intricately linked to human interactions with the elements of the robot system. Nor is an attempt made to include the hazards associated with applications or with other equipment

		Robot Related Work with Potential Danger							
Energy Source	Type of Accident	Transport & Installation	Grading	Programming	Test Running	Starting	Work Attendant to Automated Equipment	Maintenance to Eliminate Malfunction	Maintenance and Repair
Potential Position	Collision with robot	0	0			0			0
	Fall	0	0	0	0		0	0	0
	Hit by falling object				X	X	X	X	
	Hit by toppling robot	0			0	0	0	0	0
Electric	Electric shock		0	0	0	0	0	0	0
High pressure	Rupture			0	0	0	0	0	0
Mechanical	Hit by thrown object				X	X	X	X	X
	Collision & hit	0		0	X	X	X	X	X
	Caught between robot & other object	0		0	X	X	X	X	X
	Cuts,scapes, tears	0	0	0	X	X	X	X	X
	Caught in robot		0	0	0	X	X	X	0
	Cuts		0	0	0	0	0	0	0

(Cont'd)/

		Robot Related Work with Potential Danger							
Energy Source	Type of Accident	Transport & Installation	Grading	Programming	Test Running	Starting	Work Attendant to Automated Equipment	Maintenance to Eliminate Malfunction	Maintenance and Repair
Chemical & Biological	Explosion								
	Contact with dangerous and harmful substances								
	Exposure to sonic wave strain	0	0	0	0	0	0	0	0
Thermal	Contact with very hot or very cold object								
Radioactive	Exposure to ultraviolet or infrared rays								
	Exposure to radioactive rays								

Table 3.4 Robot Hazards (from Sugimoto and Kawaguchi, 1985)

0 - type of work which can be expected to result in an accident with robots

X - type of work in which a marked accident relationship exists with robots in a robot system. In this form, an FTA has illustrative power only and serves little more purpose than the detailed explanation of the hazards. Given the difficulties of introducing human actions into a quantitative prediction analysis (see the discussion of Rasmussen's work in Chapter 2) it is difficult to see how it would be possible to carry out a complete quantitative safety analysis of a system which has so many diverse and frequent interactions between workers and machinery.

Sugimoto and Kawaguchi present similar hazards to other writers, but provide a more detailed summary of the risks in all work activities. Other writers concentrate upon the characteristics of industrial robots which present the hazards described above.

Spur and Duelen concentrate upon the amount of contact personnel must have with the equipment in an individual robot system (Spur and Duelen, 1981). They accept that it is impossible to exclude workers completely from contact with robots since workers are required within the robot systems for certain functions. High risk activities are those which bring workers into close contact with the operational robot. Thus, providing and testing programmes, setting up and maintaining the robot system are classed as high risk. The risk is further heightened if the purpose for being in the system is such that the robot's motions are large enough to exceed the strength and reaction time of the worker. By comparison, the risk associated with automatic operation should be relatively low, since personnel are meant to be outside the working area. They conclude that it is the large volume of movement, the high rate of motion, the large masses and the ability to programme the path and rate of motion without restriction which cause accidents with robots (Spur and Duelen, 1981).

Percival distinguishes between impact hazard and trapping point hazards. Although both are included implicitly in the assessment of Sugimoto and Kawaguchi, Percival separates the different causes. Impact can occur with a moving part of a robot or with parts or tools carried or manipulated by the robot. Rapid, unanticipated movements in a linear or rotary direction could cause this. The release of a part at speed is also given as a possible source of impact. Trapping can occur between a fixed object and a robot arm or between parts of the robot arm itself. Associated equipment can also present independent trapping hazards. Percival draws similar conclusions about the hazardous characteristics of robots by stating that "the major new hazard (of robots) is the working envelope of the robot which increases the complexity of guarding arrangements. Unpredictable action patterns, the ability to move in free space and the possibility of reconfiguration all distinguish a robot from other automated plant" (Percival, 1984, p. 21).

The guidance provided by the MTTA (MTTA, 1982) shows close agreement to Percival's perception. This is not unexpected, since Percival played a major part in the preparation of the guidance as Manager of the Quality and Standards Division of the Machine Tool Industry Research Association. A short introductory description on the hazards identifies impact and trapping points as the major types of hazard and considers control errors, unauthorised access, human error, problems with the power source and mechanical hazards as the major sources of the potential for an accident.

It has not escaped the notice of some authors that the characteristics which make industrial robots hazardous are very much the same as those which provide the benefits of production. This paradox of the use of industrial robots has been noted by Hasegawa and Sugimoto (1982). They have commented that from "the standpoint of effectiveness and flexibility of job, the more degree of freedom, broader operational area, higher moving speed and bigger power the better. But from a safety outlook, these merits may be demerits" (Hasegawa and Sugimoto, 1982).

Nicolaisen derives some sources of hazards which he considers would become more prevalent as industrial robot use and technology develop (Nicolaisen, 1985). The increased range of applications will thus increase the hazards. First the wider use of small and medium-sized machines will mean greater and more frequent contact between people and robots. Secondly, complexity will increase resulting in a larger set of functions and also more likelihood of failures. The types of complexity considered relevant by Nicolaisen are more complex programmes, collaboration between robots, the greater use of sensors, the use of tool changing systems and the possibility of robots with mobility. Thirdly, the energy potential within the system will increase with more dynamic performance characteristics for the industrial robots, higher-speed tools and the use of tools such as lasers and water-jet cutters. Thus Nicolaisen recognises the periods of close contact between human and robot, the complexity of interactions and the amount of potential energy available within the robot systems as sources of hazards and foresees these as increasing in their frequency. Once more, benefits for production are identified as associated with increased hazards.

The National Engineering Laboratory has considered the causes of collision hazards with robots which once more emphasise the characteristics of rapid and unrestricted robot arm motions. This work was commissioned by the Health and Safety Executive (Hunter, 1981).

A large position change between points which are taught or programmed results in an increased risk. It is often difficult to visualise the locus of each of the robot joints, or indeed any points in the mechanism. Embedded software in the robots controls decide the articulation of the arm, whereas the programmer/teacher fixes the locus of the tool on the end of the robot arm (end-effector). In point-to-point control, even the end-effector is unlikely to move in a straight line over large position changes, since each axis operates independently. It is however possible to specify a straight-line subroutine on some of the new, more advanced robots. Although the path of the axes of the robot arm is repeatable once programmed, it cannot be predicted away from the robot.

Large position changes are likely to occur for several reasons, some of which are not obvious at first to an inexperienced onlooker. For instance, the movement between the end of the programme and the initial position in that programme could be large. Should the robot programme be substituted for another one already in the memory, the new initial position could also require a large movement. Finally, following the resumption of automatic work after repair or teaching, the robots motion could be dangerous,in that other objects may lie between its position on resumption and the initial position in the programme.

Further publications from the Health and Safety Executive have concentrated upon the safety assessment of the generic group of programmable electronic systems (p.e.s.) (Bell, 1982, Bell et al, 1983, Daniels et al, 1983 and HSE, 1984a). Each of these publications is more concerned with providing guidance on safe use, but also contains some statement of the hazards, or disadvantages, of the use of p.e.s.'s. The most extensive of these gives seven disadvantages (HSE, 1984a):

(1) A p.e.s. or its programme may contain faults caused by errors in design. Because of the difficulties in testing a p.e.s. fully, errors may remain undetected until a particular set of conditions cause a failure. There is then a distinct possibility of a dangerous condition resulting.

(2) A fault may be introduced into the programme, or data stored in the memory of the p.e.s., as a result of some transient fault or disturbance.

(3) The failure modes of a p.e.s. are significantly more complex than for conventional control systems and are not always predictable.

(4) Modern electronic digital devices operate at very low voltages and currents and are more susceptible to electrical interference.

(5) Because of the relative ease of re-programming a p.e.s. and the rapid and continuous development of hardware technology, the 'experience phase' with any specific system is limited. Data for reliability or safety integrity purposes is therefore limited.

(6) Even when the safety requirements are relatively simple, the linking of the safety to a p.e.s. will mean that an assessment would need to consider the p.e.s. in depth.

(7) The relative ease with which a p.e.s. can be re-programmed also means that particular attention has to be paid to minimise inadvertent programme changes and deliberate unauthorised changes. These problems are exacerbated because of the difficulty of software assessment after a change has been made.

These 'disadvantages' of p.e.s's are relevant to robot systems and their operation. However the publications in which they appear suffer from not dealing in detail with hazards for the many different types of p.e.s.'s, including robots. The publications are also limited by their concentration on safety integrity, that is "primarily concerned with failures that lead to an unsafe state" (HSE, 1984a, p. 11) rather than safety. We can see from the list of seven disadvantages that in only the last one is anything other than faults with equipment considered. The hazards of human-machine interactions are thus only partially covered. It would be wrong to consider that hazards with any equipment arise only from the failure of that equipment in an unsafe manner, since accidents do not always rely upon equipment failures. Unsafe practices and the ommission of reasonably practicable means of safeguarding are recognised as major contributions to accidents (see Chapter 2) and are issues related to safety rather than the narrower topic of safety integrity.

This presentation of the hazards of robot use has provided many points which lead one to agree with the conclusion drawn by one safety practitioner, namely that "robots introduce a unique combination of hazards" (Stowe, 1983). However, one should not necessarily conclude that robots are the major source of accidents in a factory which uses them. For example, Carlsson concludes from a consideration of industrial robot accidents that robot that related accidents comprise a small proportion of all accidents involving machines and devices (Carlsson, 1985). Relatively brief periods of sick leave result from the accidents he reviews. He considers that the type of injuries warrant more concern, since a high percentage of accidents involved injury to the head. Nevertheless, the surveys presented here show that there is a significant potential for harm with actions requiring close interaction between workers and industrial robots being the most hazardous. An analytical assessment has developed from these survey results and has specified the sources of the hazards and the characteristics of industrial robots which give rise to these hazards. Industrial robots have therefore been shown to have the capacity to add appreciably to the hazards of the process for which they are used.

The implication of this conclusion for all the authors discussed above is that safety strategies are required to deal with safety problems which are identified. Most of the authors proceed to provide some suggestions or guidance on this matter. This guidance is the subject of the next section of this chapter.

GUIDANCE ON SAFETY STRATEGIES FOR ROBOT SYSTEMS

A framework for considering safety strategies developed by Dawson et al has been presented in Chapter 2. The guidance on the safe use of robots is considered below in terms of each of the areas of this framework.

The Identification of Hazards

In essence, the presentation of the hazards of robot use serves the purpose of aiding the identification of hazards for any potential user. Thus the preceding section chronicles some of the available information. It should not be considered that the publications on robot hazards or robot safety are restricted to those which only safety specialists are likely to read. Several attempts have been made to introduce the concepts of robot hazards to a wider audience. An example of dissemination of information appears in Robotics Today, a magazine designed for those interested in all aspects of robotics (Robotics Today, 1983). The numerous conferences dealing with robot safety have also served the purpose of bringing hazards of robot use to a wider public.

Kilmer has developed a three hazard level model of robot systems (Kilmer, 1985). This distinguishes between the high risk area near the robot and the lower risk elsewhere. The three levels are measured in terms of the detection of a person intruding into the system:-

Level I - perimeter penetration of the workstation
Level II - intruder detection within the workstation
Level III - intruder detection very near the robot.

This identification of differentiated hazardous areas is used by Derby et al (Derby et al, 1983). They also expand on the three levels to distinguish two areas within the system's perimeter:-

Level I - workstation perimeter
Level 2A - area within the workstation but outside the reach of the robot
Level 2B - area within the workstation and within the reach of the robot
Level 3 - a small volume surrounding the robot arm which moves with the arm.

Clearly, Level 3 has the highest level of hazard, Level 2B is more hazardous than Level 2A and so on.

The Health and Safety Executive have produced a document dealing directly with hazard identification with robot systems. (R. Barrett et al, 1981). It attempts to establish a method of risk assessment for any robot system. The authors state that the selection of safeguards and other safety features should be based on this assessment. The paper outlines how the installation should be considered in its various modes, i.e. programming or teaching, normal working and maintenance. Each mode should be examined for its designed and aberrant* behaviour. Several factors will have a bearing on the risks involved, such as:-

(a) the frequency with which access to the danger area is required,
(b) the foreseeable risk and severity of injury should an interlock fail, taking into account:
    (1) the method of working
    (2) the likely need for access
    (3) the action of parts safeguarded by interlocks
    (4) the characteristics of the machine.

The hazards liable to lead to injury need to be determined, for each of the modes and for 'designed' or 'aberrant' behaviour in each mode. It is then necessary to consider any recognised means of guarding such machinery. However, the authors accept that it would be unlikely that available standards would cover the possible hazards. The safety framework suggests consideration of what could establish a reasonable standard for a particular application, for example whether fixed guards or interlocking guards are appropriate.

Problems are foreseen when analysing for aberrant behaviour, since such conditions may only exist on failure of part of the machine system (for example, the control system). Failure modes can be complex and hazards may be hard to identify. However, the authors state that reliance should not be placed solely upon the digital programmable system, unless a detailed assessment has been carried out.

Any safeguarding interlocks required for one mode of operation must be compatible with the requirements for the others, from both a functional and a safety integrity point of view. The use of emergency stop control buttons, though not mentioned in detail, should be considered and adequate safety integrity of their operation ensured.

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*'Aberrant' robot behaviour is defined by Barrett et al as "any unconvenanted movement of the machine system caused by a malfunction of the control system" (Barrett et al, 1981, para. 26).

Documentation is considered essential throughout, covering "the analysis, decisions and systems of work etc., relating to hazard analysis, risk assessment, safety integrity assessments, maintenance requirements etc. The need for such documentation cannot be over emphasised" (Barrett et al, 1981, para 27(15)).

The whole of this framework is presented in the form of 6 flow-diagrams giving detail on the questions to be asked in the analysis. Normal working, with high risk, aberrant behaviour, programming and maintaining are each considered on a separate flow diagram.

This framework is similar to the other publications of the HSE, in that it emphasises ~~safety integrity rather than other publications of the HSE, in that it emphasises~~ safety integrity rather than other aspects of safety. It also concentrates on considerations of hazards controlled by physical safeguards, that is strategies focussing on hardware. Hazards which would require strategies focussing on people or their interaction with machinery would be difficult to fit into the flow-chart presentation given in this publication.

The other publications on programmable electronic systems (for example, Daniels et al, 1983 and Bell et al, 1983) have culminated in a draft consultative document on guidance on the safe use of programmable electronic systems (HSE, 1984a). This document provides an assessment technique to be used for p.e.s.'s. It has already been stated that this document does not deal directly with industrial robots, but with the generic group of all p.e.s.'s, and as such, the suggested methodology is generally applicable. There are two elements to the assessment technique, one quantitative and the other qualitative. Part I gives a general introduction, a discussion of the advantages and disadvantages of the use of p.e.s.'s and some general guidance. Part II of this document concentrates on an exposition of both assessment techniques and Part III has a worked example of the application of the techniques.

The quantitative assessment presented by the HSE uses risk or hazard analysis techniques (fault tree analysis (FTA), failure mode and effect analysis (FMEA), failure mode, effect and criticality analysis (FMECA), and failure logic diagrams). A detailed presentation of the theory and application of reliability analysis is given as a basis for the development of the assessment. The probability of failure on demand, the overall failure rate and unsafe failure conditions can then be found for any system. The qualitative assessment is more diverse because of the wide range of applications. However, the document states that the frequency of probability of many events is impossible to quantify accurately and for these a qualitative approach is preferable. The suggested methodology assesses whether all reasonable measures have been taken to reduce the probability of a hazard. The assessment should take place at each phase of the specification of the design. The advice is given that attempts to assess a system at a late stage would be less effective. Checklists are provided for each relevant area:-

(a) safety requirements specification
(b) systematic failure causes
(c) common cause failures in redundancy systems
(d) software.

The emphasis on safety integrity in the published work of the HSE is particularly apparent in terms of the hazard assessment methodologies presented here. The scope of the document is "to provide guidance for the safe application of digital programmable electronic systems (PES's) which have safety function or, in the event of their failure, would have safety implications" (HSE, 1984a). In other words it is concerned with the safety integrity of equipment, the ability of equipment to perform safely when required so to perform. It appears to this author that this stated aim excludes a large area of safety implications for p.e.s. application, namely their use for controlling equipment and thereby having safety implications. The safe use of industrial robot systems requires an assessment of the hazards of man-machine interactions, rather than merely being concerned with failures which could result in unsafe conditions. Clearly, for p.e.s's whose function is related to safety, their failure necessarily has safety implications. Thus the two concepts of safety integrity and safety are more tightly linked for p.e.s.'s with safety functions.

The quantitative hazard assessment in this document is presented in a manner which would suit the specialist. It is highly unlikely that a small company introducing robot systems would have the skill or knowledge to apply the techniques and guide figures correctly. However, it would appear that the qualitative assessment presented in the p.e.s. document has more relevance for industrial robot systems than the quantitative assessment. Indeed, Barrett presents such a list in his presentation of robot safety (Barrett, 1985).

The questions to be asked are presented in a different form by Barrett, but have the same purpose as in the draft consultative document. Barrett considers that the safety requirements of robot use will become apparent with the answers to these questions. Eight different areas are covered - the robot system environment, the location, hazard assessment, robot specifications, programming by the manufacturer, programming by the user, aberrant behaviour and general considerations. Hazards are identified in each area, but particularly in the third - human interactions with the system - where questions are asked concerning personnel requiring access to the robot, the tasks associated with the system and the personnel for each one, stored energy, the preparation of a list of potential hazards including malfunctions, and the effect of losses of or interruption to power to the system. In effect, the hazards identified above are considered in relation to one system through the application of this checklist.

Barrett considers that the process of going through this checklist will answer the overall question of "Is there a reasonably foreseeable risk of injury associated with aspects of robot use" (Barrett, 1985) and thus lead one to deciding on the need for particular safety strategies.

The Development of Strategies

Throughout the guidance on strategic options, there is an acceptance that "each robot installation is different, each presents unique application problems" (Sugimoto and Kawaguchi, 1985). It is therefore impossible for all the safety requirements to be stated explicitly or to be satisfied by anyone other than the user and designer of the complete robot system. As Percival states, "each installation should be taken on its merits and (the safety requirements) based on an assessment of the risks involved" (Percival, 1984). The guidance is provided for both robot users and suppliers and an implicit assumption throughout it is that the responsibility for the safe use of robot systems rests with users and suppliers. It is ultimately their actions within the context of self-regulation of health and safety at work which is most important.

The development of strategies is presented here in a form compatible with Dawson et al's framework for safety strategies. The strategic options are considered in terms of both their focus (on hardware, people or their interactions) and their effect (elimination of hazards, containment of hazards or mitigation of likely consequences). The guidance is separated initially into the three categories of effect and within these by their focus. Throughout, one document dominates the discussion. This is the most authoritative document for guidance on safeguarding industrial robots in the U.K., produced by the Machine Tools Trade Association (MTTA, 1982). This document occupies a position of importance in the absence of any specific publications by the HSE. It has already been stated that relevant publications from the HSE have dealt with the subject of robot safety as part of the wider issue of p.e.s. safety. Though these publications offer some guidance on ensuring robot safety, it is necessarily of a general nature. The MTTA publication goes into more detail on the specifics of the requirements of industrial robot production systems. However, it does not fulfill the role of an Approved Code of Practice. One reason for this is the lack of Trades Union input in its formulation. It is largely a collection of experiences of companies who were using robots extensively in 1982. Nevertheless, it has gained a position of importance as a statement of the best industrial practices with robot systems.

Britain does not have a standard for robot safety. However, the MTTA guidance can be considered to form the basis on which a future British Standard will be produced. Together with guidance from other countries in the forefront of robot use, it is also likely to play an important part in the development of an international standard.

Elimination strategies

Elimination strategies focussing on hardware concern the spatial relationship and design of equipment, with exclusion of equipment considered hazardous. This exclusion is advocated for robot systems in a number of articles. Publications by the HSE consider this an important part of system design. The draft consultation document (HSE, 1984a) and the more general publication on Microprocessors in Industry (HSE, 1981) both consider the selection of equipment to remove hazards. Electrical disturbances or interference is considered by both publications, with the earlier publication advising the use of specially designed filters with a possible back-up supply. Screening of electrical interference or the use of a separate supply in exceptionally 'noisy' environments is also suggested. The draft consultative document goes into more detail on the options available to eliminate interference. Apart from filtering, other means of elimination include screening of signal cables and sensitive equipment, the introduction of suppression devices, the careful selection of power sources and the use of optical isolators or fibre optics. The robot's memory should be as far as possible of a form which is incorruptible. The HSE advises the use of Read Only Memory (ROM) or some form of Programmable ROM as part of a larger set of design considerations. The p.e.s. may also be a source of ignition in certain environments, and the HSE advise the installation of a non-hazardous area if possible or the adoption of explosion protected equipment or production technique if proximity to an explosive atmosphere is unavoidable. W. Stowe suggests the use of an hydraulic robot, the use of non-flammable liquids for lubrication, hydraulics, and having only the robot arm in the hazardous area (Stowe, 1983).

Nicolaisen has highlighted equipment design as a form of elimination of hazards. He gives a number of areas where design will reduce the probability of the robot not working properly (Nicolaisen, 1985). Among these are the use of reliable hardware, tested software, brake action with power failure, adequate solidity and protection against environmental influences for the programming unit (or teach pendant).

Dr. J. Hunter suggests the incorporation of a facility in the robot controls which would prevent switching from manual to automatic controls if this would result in a large position change as the first subsequent movement (Hunter, 1981).

H. Akeel suggests the design of robots as a means of eliminating hazards, (Akeel, 1983). He considers six elements of intrinsic robot safety. These are:-

(1) Mechanical hardware
(2) Electrical/electronic hardware
(3) Control system algorithms
(4) Control system software
(5) Operational system software
(6) Operational practices

The first five of these are concerned with the operation of equipment, but not all are truly elimination op~~era~~tions. The three software elements (considered as part of the hardware for the purpose of the safety framework, since they involve instructions to machinery and not to people) are means of containing the hazards. The sixth element, the operational practices, focusses on people and are a means of containment. Nevertheless the two hardware elements provide means of eliminating hazards. Mechanical considerations in the design such as the elimination of pinch points, built-in hose and cable routes, smooth design lines and covers for the drive mechanisms eliminate some of the hazards. The inclusion of intrinsically safe electrical circuits and isolated input/ouput signals are also possibilities.

The incorporation of fencing around the robot system can be seen as a hazard elimination option. Since people cannot enter the system, they are not exposed to any of the hazards which might be within. W. Stowe suggests the use of fencing for this reason (Stowe, 1983). Such fencing has to be designed for maximum reach of the robot and maximum speed of the material carried by the robot. Also the fencing must be capable of stopping a part loosened from the robots's gripper or end-effector. However, the hazards are still present within the system and are not eliminated for those workers who have to enter the system for certain tasks. Fencing therefore acts primarily as a source of hazard containment.

Elimination strategy options which focus on people deal with the selection and restriction of access to the robot system to certain well skilled and authorised personnel. The MTTA guidance refer to an exclusion of all inadequately trained persons from working with a robot (MTTA, 1982). The HSE's draft consultative document advises that only authorised and competent personnel should have access to the means to alter the software of a p.e.s. Dr. J. Hunter suggests that it should not be possible for unauthorised personnel to reset a robot in order to recover from a fault if this could result in a large position change (Hunter, 1981) while Percival states that programming should be restricted to qualified programmers because of the high hazard level. J.W. Russell also agrees, stating that only trained and authorised personnel should be allowed to operate or work on robots (Russell, 1983). The effect of such an exclusion is to eliminate all hazards of robot use from a large number of people, even if there remains a core of workers still exposed to the hazards.

Containment strategies

It is unlikely that all hazards with a system are either eliminated or that their consequences are below the threshold for further actions to contain hazards. As a result it is usual for containment strategies to dominate the range of options. This concentration of options is very evident in the guidance provided for robot safety. Three areas are clearly apparent, one for each focus for the strategies. Physical safeguards are a strategy option which focusses on hardware, the provision of training and information focusses on people and systems of work and operating procedures focus on interaction of people and machinery. Each of these is presented in a separate section below.

Physical safeguards: The guidance on physical safeguards can be further divided into six topics. These are fencing, interlocks, additional or secondary safeguards, safety features in the robot design, control or software features and other safeguards.

1) Fencing

In a general article on safety aspects of robots and FMS, Percival discusses why the move towards close proximity fencing in the last 15 years, encouraged by the HSE, cannot be applied adequately to robot systems (Percival, 1984). "The very nature of the robot with its envelope precludes close-proximity fencing" (p. 180). The benefits of close-proximity fencing - the considerable reduction in space between machinery and fencing preventing access - cannot be accured for robot systems. Percival considers users and system supplier must return to the original idea of distance guarding

The MTTA guidance on safeguarding robots applies either fixed guards or distance guards to robot systems (MTTA, 1982). Fixed guards are meant to remain permanently in position once installed and thus provide no means of access. The guidelines give the recommended openings in fixed guards for a number of distances from a danger point, as provided by British Standard 5304: 1975 (the standard for safeguarding machinery). Distance guards are similar to fixed guards but may have a door to allow for access. The choice of material for the fencing is left to the installer, with the MTTA stating that it must be of a "material adequate for their purpose but with due consideration to handling requirements ... e.g. maintenance and adjustment" (MTTA, 1982, p. 10). A range of options are given, including metal lattice, welding wire and solid material. The recommended height is given as 2 metres.

Almost without exception other guidance also suggests the use of fencing, although some are aware of its role in maintaining only a perimeter. For example, Robinson considers that the concentration on the safeguarding of the perimeter of the robot system has resulted in the area with the fencing becoming "the neglected zones" (Robinson, 1985). He contests that the experience of accidents with robots shows that the dangers of working within the perimeter are not covered by such safeguards as fencing. Nicolaisen also points to this limitation of the use of safety fencing and considers that some safeguards directed at those activities required within the fencing (fitting, programming, maintenance, inspection and repair) are needed (Nicolaisen, 1985).

The MTTA guidelines appear to anticipate these limitations by stating that the principal objective of fencing is to prevent access to the robot when the automatic cycle is capable of being initiated. The guidelines recognise the need for access and therefore suggest that consideration should be given to the need for access, its frequency and the foreseeable risk and severity of injury.

2. Interlocks

The MTTA guidance views interlocked access gates as a natural adjunct to fencing of the robot system. A locked access door which has not been interlocked to the system would satisfy some of the requirements of safety. However access would still be possible whilst automatic operation could occur if the key to the access gate were available. The MTTA guidance advises that the interlocked guard should prevent the automatic cycle when open, but closing it should not restart the robot cycle. (One should add here that such an interlock should also not start the cycle of any other equipment in the robot system).

The MTTA guidance gives 2 further criteria for the interlocking:-

a) until the interlocked guard is closed, the robot cannot operate (except if specifically stated otherwise for a task such as setting),

b) either the interlocked guard remains locked closed until a dangerous movement has ceased or, where overrun does not create danger, opening the guard causes all movement to stop.

Thus the interlock stops movement by its opening and continues to prevent it until it is closed. Where necessary to ensure that the gates cannot be opened until machines are at rest, it is advised that the interlock should incorporate some form of time delay. The recommendation is made that an interlocked access gate should be provided where frequent access within the robot system is required.

The interlock can be any combination of mechanical, electrical, hydraulic or pneumatic parts, but must fail to safety. Four types of interlocks are given:-

(i) mechanical interlocking
(ii) dual-control system interlocking with cross-monitoring, or power-system interlocking
(iii) dual-control system interlocking without cross-monitoring
(iv) single-control system monitoring.

It is recognised amongst other authors that interlocks offer an improved safety strategy. Stowe recognises the role of interlocks (and other additional safeguards) in providing sequence control and preventing undesirable or extended movement (Stowe, 1983). Russell states that interlocks prevent unintentional access by operators or passersby (Russell, 1983). Van Deest presents interlocks as a standard safeguard of robot systems (Van Deest, 1984).

Thompson considers the role of safety interlocks systems in some detail (Thompson, 1985). He considers the use of limit switches, plug and sockets and key systems in greater detail than the MTTA guidelines and gives examples of commercially available types. He states that the more complex key (such as the Lowe and Fletcher System) and plug and socket systems are suitable only where access through the guarding is infrequent. The reason given for this opinion is that their operation is time consuming and thus highly disruptive to the production process. Thompson does not advise such a system for access to load or unload parts. By implication, he suggests that limit switches are preferable when frequent access is required.

3. Additional Secondary Safeguards

For any additional safeguards to be effective in preventing hazardous occurrences, they too must be interlocked with the operations of the robot system. Such additional or secondary features are sensory devices that detect the entry of a person within a robot system. The two most common forms advised for robot systems are electro-sensitive safety devices and pressure-sensitive matting.

Electro-sensitive safety devices have recently been the subject of an updated British Standard (BS 6491 Part 1: 1984). This gives their specification for general requirements. The HSE has produced an accompanying Guidance Note for this British Standard (PM41) which deals exclusively with the use of photo-electric safety systems to protect persons from dangerous parts (HSE, 1984b).

The MTTA guidance suggests that trip devices should only be used as secondary forms of safeguarding. It recommends that they should be designed so that the machinery cannot be set in motion unless the device has been reset manually.

Photo-electric guarding is given a short chapter in the recent book on Robot Safety, written by a major user of both robots and photo-electric guards. This article was initially an internal report within Ford (Europe). It deals with technical details of the operation, installation and examination or testing of photo-electric guards and suggests the use of photo-electric guards not only to safeguard the operator, but also to limit the motion of a robot (Ford, 1985).

Pressure sensitive matting is also accepted generally as a beneficial secondary safeguard. The MTTA guidance recommends that this type of safeguarding may be appropriate as a safety device to augment a conventional guard. The guidance also stresses that it should not be possible to step over or otherwise circumvent a pressure mat and thus allow a person to be in a hazardous position.

Graham sees the role of pressure senstive matting as part of an integrated system, with some combination of software provisions, fixed guards, perimeter interlocking and photo-electric devices to secure an adequate level of safety (Graham, 1985). Graham shows that pressure sensitive mats have been used extensively in industry and provides several examples of robot applications. The advantages put forward are that they are durable, reliable and can operate in adverse environments.

Other safety devices have been suggested by a few authors. Nicolaisen discusses the use of the detection device developed at the Institute for Production and Automation (IPA) in Stuttgart (Nicolaisen, 1985). This device operates on contact with another object and is essentially an 'anti-collision' device, bringing a robot to an emergency stop in the event of contact with a person. Robinson also refers to a similar device to protect a worker within the most dangerous zone of a robot system - adjacent to the robot arm (Robinson, 1985).

Meagher, Derby and Graham propose the use of an advanced sensory system based on programmable electronic control. (Meagher et al, 1983 and Derby et al, 1985). The authors see that this highly complex sensory system offers substantial benefit but admit that there would be problems with its introduction. "A great deal of work remains to be done before such a system could be introduced on the factory floor" (Meagher et al, 1983).

4. Robot Design

A large number of safety features have been suggested to improve robot designs. Those concerned primarily or exclusively with control or software features are dealt with in the next sub-section. This subsection deals with guidance on the physical design features of a robot which could contain hazards.

Safety features on the teach pendant, for example the incorporation of teach restrict and a 'deadman's control' are suggested widely. However the selection of slow programming speeds, that is teach restrict, is felt by some authors to be a matter of discretion for the programmer. It is thus a matter of procedures for the interaction of people with machinery. Other authors consider that teach restrict should be a matter of hardware. Van Deest suggests that the robot speed should be restricted to about 30 cm/s (Van Deest, 1983).

The 'dead-man's control' is so named because of the need to keep a button depressed in order to contine sending its command signal. Releasing a motion button on a teach pendant with a 'dead-man's control' would result in the robot stopping immediately. The MTTA guidance considers that this is a very useful feature, irrespective of whether programming is of the manual lead through type, with a 'master slave' arm or with a teach pendant. Stowe also considers this a useful feature, and makes a further point that the operation of the dead-man's control should be linked to the other equipment in the robot system as well as the robot (Stowe, 1983).

A number of quite general features of robot design receive approval. The need to ensure that the robot is mounted securely on the floor is stated by several authors, including the MTTA guidance and Russell (Russell, 1983). This can be seen as a recognition of the hazard of toppling of the robot, highlighted by Sugimoto and Kawaguchi (see above). The need to ensure that the robot does not reactivate automatically on the restoration of power and that the gripper does not release parts in the event of a sudden halt by the robot are also mentioned by Russell.

A great deal of agreement exists on the need to 'design-out' any sharp edges on a robot (e.g. Nicolaisen). Stowe's guidance on this point is to guard all sharp edges and pinch points (Stowe, 1983). Russell goes along with Nicolaisen in suggesting the inclusion of cushioning on the robot arm. Other suggested features are check valves and limiters to ensure pneumatics or hydraulics do not operate at too high a pressure (Russell, 1983) and shear pins at critical positions to cause the system to collapse rather than to cause harm (Stowe and Van Deest). Stowe also discusses the correct selection of the robot for the task, with a sturdy base, adequate gripper and sensing devices to ensure that the part is correctly oriented for the task(Stowe, 1983).

5. Control or software features

The MTTA guidance considers the robot controls in a general way, saying that there should be ample clearance between the controls and other machinery and that near each START control there should be a STOP control. START controls should also be shrouded, gated or positioned so that they cannot be operated unintentionally. The HSE's discussion document (Microprocessors in Industry) advises that controls and software should be designed so that programmers will be re-entered at a safe point especially after any necessary resetting (HSE, 1981).

An example of the German approach to guidance considers the matter of controls and software somewhat differently (Spur and Duelen, 1981). Spur and Duelen recognise that much can be done by programme structure and by control monitoring. In particular they state that movement can be monitored accurately by considering position and acceleration. Percival and Van Deest also see the benefits to safety of diagnostics within the control software (Percival, 1984 and Van Deest, 1984). For Percival, fault diagnostics will decrease the frequency and duration of periods of access within the system. Van Deest sees diagnostics as part of the sequence control for the operation of the system, with additional benefits for safety. Meagher et al suggest a complex control device for safety sensing. The safety computer would make decisions on the need to induce an emergency stop.

Akeel suggests software features to ensure intrinsic safety for robots (Akeel, 1983). Among these are means of responding to excessive 'following error' (that is, the distance at any moment between the control's stated position and the arm's actual position), emergency response to abnormal velocities, the imposition of limits on the robots working envelope and interlocks through the software to the systems sensors or limit switches. Russell also considers similar safety provision in the robot's software (Russell, 1983). In addition Stowe proposes the simulation of the movements and processes performed by the robot using computer assisted design techniques (Stowe, 1983). This is higly similar to work undertaken by Nottingham University to utilise a CAD package for robot production simulation - the GRASP package (Yong et al, 1985). This CAD package can incorporate machine tools and system interactions, as well as a basic human model.

6. Other safeguards

Other safeguards are mostly of a more general nature and are not specific to just robots or robot systems. For example, the MTTA guidance considers work lighting as a basic element of safety. In particular, the guidance states that lighting should be adequate for programming the robot and if necessary, local lighting should be provided in areas of regular maintenance. Lighting should meet the requirements of the relevant British Standard (BS2771), and, where appropriate, comply with the Factories

Act 1961. Warning signs should also be placed on the fencing of the robot system with an indication, if applicable, that unauthorised access is prohibited. These signs should comply with BS 5378 (Safety signs and colours, Part 1: 1980 Specification for colour and design).

A 'power-on' light is suggested to inform workers that a robot system is in an operational state. Stowe states that a warning or flashing light should announce the lack of motion as "dwell time". This could be backed by audible warnings. Russell is also aware of the need to identify pauses in the robot's actions. The MTTA guidance also suggest that the robot system floor should be marked out (with black and yellow hatched lines). This marking should inciate the complete envelope of movement in a horizontal direction of the robot and its largest anticipated workpiece.

Fixed stops to the robot's motion are also suggested by a number of authors. The MTTA suggest this as one method of restricting robot motion during access and also say that if this were used, floor marking could be restricted similarly. Russell and Van Deest also advise the use of fixed stops. However, Stowe points out some negative aspects of the use of physical restraints of this kind for the robot. In his opinion, such limiters to motion as posts "merely add more(trapping) points to a system inherently crowded with them" (Stowe, 1983, p. 33).

The positioning of the controls has also received some attention. The HSE's draft guidelines on the safe use of p.e.s. (HSE, 1984) advises that the p.e.s. should be located where casual interference is avoided. Van Deest considers the placement of the controls and their layout as important factors. Russell also states that the robot controls should be located outside the danger area.

Robot tools are advised to be considerably over-designed by Stowe (with a 40% safety factor) (Stowe, 1983). Russell also considers the action of tools and suggest the provision of mufflers to contain the air noise levels if tool action is exceptionally noisy.

Two authors have provided guidance by describing systems with their safeguards. These have provided examples of systems in which physical safeguards for the containment of hazards have been used to the near exclusion of all other measures (Linger, 1985 and Potter, 1983). Linger presents the safeguarding philosophy developed at IVF in Gottenburg (the Swedish Institute of Production Engineering Research). He proposes a set of detection devices - 'contact mats', infra-red sensors, photo-electric sensing devices and camera image sensors. The signals from these detection systems are processed through a controller, which first signals the robot controller to stop and then applies a brake if the robot controller does not act rapidly enough.

Potter provides five hardware options for a system, along with several additional safeguards such as sensors, photo-electric guards and pressure sensitive matting. These five safeguarding options all involve hardware means. The first three are variations on the fencing and interlocked access gate design and the final two concern the restriction of the motion of the robot either by a 'handcuff' applied to the robot or a motion limiter. The former of these two devices locks the robot in a static position while a person enters the robot system. The robot is allowed to work in one section of its complete working area and is prevented from entering the other by the limiter device. If the robot should move over to the other sector for any reason than an emergency stop condition would result.

Both of the last two authors above suggest implicitly by their presentation of system design that the safeguarding of the robot system can be achieved by purely hardware means for containment purposes. Although there is a concentration on hardware in the other guidance, ~~there is a concentration on hardware in the other guidance~~, there is also some role provided for other focusses.

The provision of training and information: Far less guidance is provided on training and information than on physical safeguards. The MTTA guidance has only a small paragraph covering training. As something of an anachronism, it states that training is "perhaps the most important safeguard of all". If this is the opinion of the MTTA it is surprising that so little is said on the subject. Nowhere is a detailed specification of the content of training presented and the needs of training are given a brief, almost cursory consideration.

The MTTA guidance provides some advice on the subject areas of training. The training should cover suitable systems of work (considered below) and make workers fully aware of the operation of the control system and the consequences of failure. A particular point is made of tuition on the possible effects on safety of a failure to follow the correct procedures.

The HSE state that personnel training is essential and proceed to provide a similar set of general guidance of training content (HSE, 1981). Elsewhere the HSE have stated that a reserve of adequately trained personnel and refresher courses should be provided. Line management and safety staff should also be given special safety training to aid their monitoring duties (HSE, 1984). Russell also sees the benefits of initial and periodic training in the operation and maintenance of the robot (Russell, 1983). Van Deest states that a range of personnel should receive training (Van Deest, 1984). He reasons that this training can best be supplied by the robot suppliers' representatives at the robot manufacturers or suppliers facility. They will then be able to provide a complete training programme. Van Deest's advice seems to overlook an aspect of robot system operation, namely the crucial area of the equipment's instructions. The training provided by the robot suppliers' facility would be unlikely to encompass this and would more likely consider the robot in isolation.

The guidance on the provision of information is equally sparse. The MTTA guidance merely refers to the need for the robot supplier to provide sufficient information for the correct installation, operation and maintenance of the robot. Akeel develops the concept of intrinsic robot safety to include instructions on the robot (Akeel, 1983). He considers it the responsibility of the robot designer to provide information on the procedures for operating the robot safely.

A more extensive list of information is provided by Robotics Today in a report on a Robotics Industries Association seminar on safety (Robotics Today, 1985). It is reported that the Manger of PRAB Robots , F. Leipold, described information which should be provided by a robot manufacturer to a user:-

(1) Information on safe unloading and moving
(2) Installation information
(3) Information on the operating limits of the robot
(4) Information on any precautionary conditions for use
(5) Operating instructions
(6) System drawings
(7) Information to permit proper maintenance and repair, including a spare parts list.

Systems of work and operating procedures:- Considerable agreement exists on suitable steps to ensure safety in the interactions of people with machinery. This section is subdivided into guidance on safe systems of work, which are formal structures for the interactions of people and machinery, and on operating procedures, which are activities undertaken during interactions.

1. Safe systems of work

The MTTA guidance considers that a safe system of work is an enhancer of physical safeguards, ensuring that those hazards are not sufficiently contained by physical safeguards are controlled by a formal system of work. "Although most interlocking systems, by the nature of the hazards involved, provide a primary means to ensure safety, consideration should also be given to enhancing the overall level of safety by the use of a safe system of work" (MTTA, 1982). The MTTA guidance continues by stating that there is a definite need for correct documentation and access procedures. It is not sufficient to trust oral instructions. Percival also emphasises precise written access procedures for all activities - setting up a task, programming, maintenance and emergencies (Percival, 1984). This documentation and procedures may involve an even more formal system, a permit to work system (PTW).

The MTTA guidance provides details of the content of a PTW system. It states that it effects proper control of personnel by formalising the actions. Formal steps are required for those doing the work, from those responsible for the work and from those authorised to sign such permits. A PTW document should contain a number of details:-

(1) the work to be done
(2) who will supervise
(3) who is to carry out each section of the work
(4) the safety precautions which have been taken
(5) a time limit, if necessary, within which a check needs to be carried out to see if the working environment is safe
(6) the procedure which should be followed before the PTW is cancelled.

The person responsible for the work should sign a statement showing that the tasks and precautions are understood. The need for flexibility in the structure of different PTW systems is recognised in the guidance. For example the MTTA is not specific on the duration of each PTW, giving either each separate occasion or each working shift as suitable. Van Deest also suggests the establishment of procedures for each type of activity with the robot system (Van Deest, 1983).

2. Operating procedures

Operating procedures are provided by a number of authors for each stage of robot system interactions. However these procedures are mainly quite general in their specification.

The MTTA guidance states that any procedures should also take into account the operation and safeguarding of any associated machinery within the robot system. It also recommends a number of steps for general access, with others for certain tasks. The appropriate power off switch or isolation shall be used, noting that this may cause the arm to droop. Then a personal danger tag should be placed on the isolator or stop button, and this interrupt switch or button should be locked off where practicable. The interlocked gate should then be opened and means taken to ensure it remains so. Maintenance safety pins, locks or jacks should also be fitted. After the task is complete, the system should be returned to the original condition by the reverse procedure until the danger tags are removed and the system is reactivated.

The HSE states that "effective operational and maintenance procedures should be adopted" although these procedures are not given in detail (HSE, 1984a, p. 41). The HSE makes the point that procedures should take account of the assumptions concerning human behaviour in the safety integrity assessment they advise in this document. The capabilities of personnel and their level of understanding should also be borne in mind when designing procedures. Formal procedures should also be instigated to collect data on failures and problems so that appropriate action can be taken and procedures amended accordingly.

Stowe gives some general advice on special procedures for certain tasks, such as hot work or welding, and the need to ensure proper protective clothing. Inspections of workpieces are also suggested, to ensure tool wear or fatigue is recognised before catastrophic failure (Stowe, 1983). Russell matches the HSE with advice to report all unusual robot motions so that they can be investigated and corrected.

Programming practices are one of the main concerns of guidance on operating procedures, since it is clearly recognised that this activity presents some of the more intractable problems of safe robot use. The MTTA guidance recommends the selection of 'teach restrict' mode for the robot, if available, or the use of a reduced robot speed before entering the robot system. Consideration is also given to the possibility of programming the robot with the programmer in a safe area or at least outside the sweep of the robot arm. It is recognised that this may not be possible in all cases, but would be a preferable procedure for programming. On-line programming via a computer is considered a hazardous exercise if the robot is operating at normal speeds at the same time and therefore the guidance states that this should always be performed outside any fixed fencing and by trained operators.

The HSE identify the teaching operation for robots as one which requires special procedures (HSE, 1984a). The HSE also provides some advise on programming procedures (HSE, 1981). Programmes should be well documented and all documents updated after any amendments. The HSE also suggests reduced speed for programming motions to avoid hazards with the addition of a simulated 'dry-run' to check the programme's structure.

Hunter identifies several procedures to reduce the possibility of variations in robot motions and large position changes when programming (Hunter, 1981). Account must be taken of the divergence of the end of the robot arm from a straight line during motions between points and also of the positioning of the articulating joints. Particular care is required over the return path from the end of one program cycle to the beginning of another. If several programmes are present in the memory each connection between the programmes should be checked so that the paths of the robot that would result are collision free. After programming (or carrying out of maintenance) the robot should be guided under manual control to a position which does not offer the possibility of large arm movements on resumption of the programme.

Percival also draws attention to documentation of programmes (Percival, 1984). He states that programmes should be written carefully, checked and tested, identifiable during operation and in storage and amendments made to all copies of the programme.

Stowe advises the use of low speeds for programming but includes the novel suggestion of programming with full extension to the robot arm at each occasion of human interface during the automatic cycle (Stowe, 1983). Although he does not state it explicitly, one can presume that this is to minimise the need for a person to enter the robot's reach.

Russell suggests the presence of a second person throughout periods of programming. This person could then react in a hazardous situation to limit the extent of injury.

Maintenance procedures is the second-most frequent area of concern with operating procedures. The MTTA guidance makes a point of stating that during maintenance, any movement of the robot should be made with teach restrict selected and with non-essential workers outside the fence. The point is made that total reliance should not be placed on the indications of the controller system. Some additional means of identifying safe conditions should be used. General 'housekeeping' procedures are given (keeping areas clean and clear from obstructions). Any possible corruption of the programmes should also be checked. When hydraulic pressure systems are used, the guidance recommends that some means of dumping any stored energy be used.

The HSE advise that a maintenance document be prepared which is clear and capable of being readily understood by maintenance personnel (HSE, 1984a). This should specify when and how mainenance procedures should be carried out. Procedures for making the system safe after maintenance are also suggested. Modifications should be checked to see if they have any unexpected consequences on software or hardware performance. The HSE also recommends that programmes incorporating error detection routines be used.

Emergency access procedures are briefly discussed in the MTTA guidance. The procedure for access differs from normal access in that the emergency stop circuit is activated and not the process interrupt switch. Normal operations such as loading also require procedures and are given some consideration by MTTA. The guidance on this states that the operator should have good visibility of the robot's movements, and it is desirable that information on the status of the robot is at hand at all times.

Mitigation strategies

Means to mitigate likely consequences of hazard realisation for robot systems is advised only in terms of the provision of hardware. This takes the form of emergency stop buttons or trips. The MTTA guidance describes a suitable design for an emergency stop, using hardware based components so that the robot will be stopped "as quickly as possible" (MTTA, 1982, p. 11). However guidance (from MTTA or other sources) do not provide advice on a suitable length of time between pressing of an emergency stop and a complete halt of the robot.

The MTTA guidance recommends that the emergency stop should not influence the functioning of any equipment which if stopped could endanger the operator of the robot. An example of one such possibility is the releasing of a workpiece from a gripper. The design of an emergency stop should make it impossible to restart the robot until the buttons or switches have been reset manually. Merely resetting the stop devices should not cause the robot or associated equipment to operate. A hand-wired emergency stop on the teach pendant is also recommended.

The guidance also suggests that an emergency stopping system activated by contact between the robot and an object should be considered. Certain circumstances could arise which would make it necessary for there to be a repositioning of the robot or associated equipment when the emergency stop is activated. The MTTA guidance considers that such repositioning could reduce a potential danger in some circumstances. However the means by which this could be achieved safely and the sort of circumstances warranting this are left unspecified. The guidance also warns of the need to make operators aware of the consequence of operating an emergency stop since under some circumstances it could cause the robot arm to droop. However, no remedy to this is suggested.

Van Deest and Russell consider the distance between emergency stops around the perimeter of the system to be an issue of importance (Van Deest, 1984 and Russell, 1983). The system design should allow easy access to an emergency stop device without great distances between them. Stowe identifies the need for an emergency stop to 'freeze' both robot motion and that of the rest of the system (Stowe, 1983). This final point highlights an interesting emphasis throughout the guidance, but which is particularly evident in the advice on emergency stops. The guidance directs itself almost exclusively to the robot and not the rest of the robot system. It seems natural to this author that an emergency stop should prevent all hazardous motion within a robot system, yet most of the guidance is not explicit about this. The guidance on emergency stops is also unclear on the means of operation. As Sugimoto and Kawaguchi noted (see earlier), there are many ways in which a robot can be stopped and also some variations in the design of robot emergency stops. The guidance does not state a preference for a particular means of operation.

Other Elements of Safety Strategies

The guidance on robot safety concentrates on anticipation strategies, to the almost complete exclusion of other elements identified in the framework of Dawson et al. These other elements are considered here under the combined heading of the other elements of safety strategies.

Nicolaisen presents a set of factors involved in improved safety at work which shows an understanding of the process of developing and implementing safety strategies. He also sees the development of a robot system as a process, with a number of stages at which decisions have to be taken. "Before the ... application is reached, important preliminary decisions have already been taken with regard to safety" (Nicolaisen, 1985). He sees the successful development and implementation of safety strategies very much as a matter of correct timing, to ensure the decisions relevant to safety are made at a time when change is possible.

A rare awareness of the problems of implementation of strategies is shown by Carrico (Carrico, 1985). His article is concerned with training and designing for safe implementation but his discussion concentrates on system implementation rather than the implementation of a safety strategy. However, he considers that training and instruction to play an important part in the safe implementation of a robot system.

Some problems with safeguards are discussed by K. Griffin (Griffin, 1983). He also provides some insights into the adaptations undertaken by his company, Hughes Tool Company, Houston. Typical problems were the disregarding by personnel of safety barriers and the failure of physical safeguards causing unanticipated motion. In all these cases, the solution to the problem was to improve hardware features, that is, the physical safeguards on the systems.

GUIDANCE ON ROBOT SAFETY ELSEWHERE IN THE WORLD

A few countries have progressed further with guidance on robot safety than the U.K. (Japan, JISB8433, 1983, W. Germany VDI Guideline 2853, 1984). These guidelines are close to being accepted standards in their respective countries. Although they bear little direct relevance to British use of robots, it is useful to note the similarities or differences between countries. Percival notes that "considering that all the national standards have been produced independently, it is surprising how similar the approaches have been in the different countries" (Percival, 1985). A draft ISO standard also exists, which is largely an amalgamation of other standards and contains major sections from the MTTA guidance (ISO/TC184/SC2/WG3-N1)). Thus, the guidance reviewed in this thesis represents a major part of the content of any future international standard.

DISCUSSION - SAFETY ENGINEERING OR SAFETY MANAGEMENT

The guidance on robot safety concentrates on hardware measures, particularly physical safeguards. One of the best statements of this attitude is given by Percival, who points to "the need to incorporate as many safety features as possible within the design of the machinery itself" (Percival, 1984). This concentration on hardware and the almost completely disregarded elements of implementation, adaptation and monitoring shows that the guidance on robot safety comes firmly within the terms of safety engineering. Engineering solutions to the problems appear to be considered sufficient in themselves. By comparison, issues of safety management do not receive much attention. This criticism goes some way to explain the lack of specific guidance on training and the general nature of guidance on operating procedures.

The concentration of the guidance on hardware is well illustrated by considering the recent book on Robot Safety (Bonney and Yong (Eds.), 1985). It is significant that this contains a large number of examples of systems concentrating on physical safeguards and also has seven chapters describing particular types of physical safeguards. Though some chapters deal with aspects such as training and operating procedures, there is not one chapter that concentrates on one of these and considers the problems and pitfalls in detail. There is also no chapter considering problems of safety strategy development and implementation.

One of the aims of this thesis is to deal with those areas which have been identified as unsatisfactorily covered by the guidance. Safety engineering and safety management can be seen as equally important components of a safety strategy and both are required for a successful development and implementation of a safe robot system. The concentration on physical safeguards suggested by the guidance may be necessary (for example, to fulfill requirements under the Factories Act, 1961) but other focusses can also contribute to a successful strategy.

SUMMARY AND CONCLUSIONS

This chapter has considered the statements made from the point of view of health and safety on both the benefits and the hazards associated with the use of industrial robots. The major suggested benefits have focussed on the substitution of robots for people in dangerous work and improved information and control of processes. However there are also significant hazards so the effect of robots on health and safety cannot be seen to be solely a positive one.

Surveys of accidents with industrial robot systems showed that serious accidents have occurred with robot use elsewhere in the world, including a small number of fatalities. These surveys also showed that certain activities (for example programming) are more hazardous because of the close proximity between workers and operational tools.

Authoritative statements on robot hazards were in general agreement on the features of industrial robots which combine to cause accidents. The possibility of large unforeseen positional changes, rapid motion, large sources of energy (positional, kinetic, electrical, etc.) and the ability to programme movements along any path in the volumetric coverage of the robot arm make certain activities with an industrial robot quite hazardous. Thus the advantages in terms of production scheduling of using an industrial robot are associated with disadvantages in terms of maintaining safety.

Industrial robots have the capacity to add appreciably to the hazards of the process for which they are used. Thus there is widespread agreement that some form of safety strategy to control the hazards is necessary.

The guidance provided in the literature in safeguarding industrial robot systems concentrated upon anticipation strategies particularly in terms of hardware. Guidance on training and information was surprisingly slender considering the importance placed on it by, for example, the MTTA. Systems of work were considered as an enhancer of physical safeguards. Some detail was given on operating procedures with a considerable proportion on programming practices and maintenance.

There was a tendency throughout the guidance to concentrate on the robot and not to consider the way in which the rest of the equipment in the system should be included in any safeguarding. This was illustrated most clearly in the failure to state explicitly that emergency stops needed to prevent all hazardous motion within a system.

The concentration upon anticipation strategies and the focus on hardware placed the majority of the guidance in the field of safety engineering. In contrast, the management of safety has been all but ignored by most of the guidance.

CHAPTER 4

THE EMPIRICAL STUDY: AIMS, PROPOSITIONS AND METHODS

INTRODUCTION

This chapter describes the empirical study undertaken as a major part of this research. The first section details the aims and objectives of the empirical study and their relevance to the overall aims of the thesis within the context of the literature on robot safety presented in the previous chapter. The second section identifies the propositions which guided data collection and analysis. The substance and methods of the study are then described. Finally, the data analysis techniques used in this study are reviewed briefly.

AIMS AND OBJECTIVE OF THE EMPIRICAL STUDY

The study focusses on industrial robot systems in productive use on the shopfloor. Robots in use in an educational or purely experimental setting were not included since those designed specifically for this purpose tend to be different in design and are used in a different manner from industrial robots in constant production. Working practices and safety implications for robots in educational and experimental settings would therefore bear little relation to conditions in an industrial setting.

Each case study comprised a company using industrial robots in a production process. The overall aim was to describe and analyse the robot systems' operation in terms of safety and production problems and to identify the safety strategies adopted in each case study.

The discussion of the literature on industrial robots in Chapter 3 has shown that previous work on robots is deficient in some respects. Surveys on safety implications have concentrated almost exclusively on small samples of accidents rather than the more frequent hazardous occurrences. There is only anecdotal information on production problems with robots; no comparative study has been undertaken. Guidance on safeguarding robots does not deal with the whole of the requirements of an appropriate safety strategy. Furthermore, no previous study has been undertaken of the application of safety strategies for industrial robot systems. Therefore, this study of safety and productions problems and

and safety strategies with industrial robot systems is primarily of an exploratory nature, to provide information to fill the gaps in the existing literature.

Several specific objectives were identified for this study. The first was the collection of information on safety and production problems with particular robot systems. The whole range of incidents which resulted in production problems, that is loss of production time, and their safety implications were considered. The hazards arising from interruptions to production and the subsequent actions of personnel were identified and analysed. Information on accidents with the robot systems were also considered.

The second objective was the investigation of the strategies developed and adopted to safeguard the robot production systems. Strategic options were identified along with problem areas and adaptations to control measures and system design subsequent to their introduction. The third was the description of the safety implications of the interactions between equipment and personnel by an investigation of working practices of personnel with the robot production systems. The fourth objective was the development of an understanding of the structure of safety and production functional groups within the context of the overall organisations and their proficiency in dealing with problems. Problems produced or exacerbated by organisational structures were thus identified as well as those structures which were more successful.

This empirical study considers events which could lead to an accident or injury with industrial robot systems, not only the accidents or injuries which occurred historically with the robot systems studied. In terms of Heinrich's concept of an accident triangle (see Chapter 2), this study considers those occurrences at the base of the triangle. The hazards arising from production problems and from other interactions between equipment and personnel in industrial robot systems are the source from which accidents with industrial robots arise. These hazards are therefore the safety problems for which safety strategies with robot systems should be designed. The information on safety problems provides a sound basis on which to assess the safety strategies with each robot system.

The information on production problems serves another purpose besides the provision of data on safety problems. The information also facilitates an in-depth study into problems of robot production and their means of solution. This part of the overall study provides data which is a major contribution to the understanding of industrial robot system production behaviour.

PROPOSITIONS OF THE STUDY

Propositions were formulated for the objectives of this study within the context of existing literature, to provide a focus for the data collection and analysis. In a way, the aims and objectives of the research reflect a general theme in the propositions, that the consideration of production problems, organisational structures and working practices implies an assumption of their link with safety at work. This link is also found in the literature reviewed in Chapter 3.

Proposition Set 1. The Current Use of Robots and the Understanding of Hazards.

1.1 The diffusion of robots through industry, particularly the rapid rate of increase in their adoption and spread, creates problems in terms of the general level of understanding of hazards associated with their use. Although the means of ensuring safety with robots is developed to some extent, it is expected that this knowledge is poorly distributed amongst user companies.

1.2 The introduction of robots could result in the potential for greatly improved safety, but poor perceptions of the risks and inadequate means of ensuring safety could prevent this potential being realised.

1.3 Exceptions to the generally poor level of understanding of robot safety are expected where substantial experience of robot use has accumulated within the factory.

Proposition Set 2. The Design of Robots.

Each design of an industrial robot is likely to have different failure and problem characteristics from other robot designs and as a result the impact on safety of robots will not be constant. The problems and failures to which each robot design is susceptible will influence the hazards posed by the different designs.

Proposition Set 3. The Interactions of Equipment in Robot Production Systems.

Different applications of robots involve different processes and hence can be expected to involve different hazards. The robot production systems present different hazard levels due to the interactions of the robots with the process and other equipment in the systems. As a corollary, major safety and production problems arise from the interaction of equipment in the robot production systems and not solely from each machine in isolation.

Proposition Set 4. The Exposure of Personnel to Hazards.

The shift in levels of exposure to hazards is expected to be from relatively lower skilled workers to maintenance and other skilled grades.

Proposition Set 5. Physical Safeguards.

5.1 It is expected that physical safeguarding forms a major part of the safety strategies adopted for each robot production system.

5.2 It is expected that physical safeguards remove hazards mainly from the passive observer and inexperienced or unauthorised employees.

Proposition Set 6. Working Practices

The working practices of personnel in contact with equipment in robot production systems has an important influence on the overall safety, notwithstanding the effects of other safeguarding means. Workers' actions during periods of interaction with robot systems will determine the uncontrolled hazards and could also act to prevent the remaining hazards (such as robot motion) from being realised.

Proposition Set 7. Training

7.1 Training of personnel is expected to focus on the needs of production. Elements concerned with safety are likely to be introduced as personnel learn of the equipments operations. Training will be assisted by considerations of equipment interactions.

7.2 On-site training is more likely to give a good understanding of the problems of the robot production systems than training at the suppliers site.

Proposition Set 8. The Role of Management and the Organising for Safety.

8.1 Management strategies towards the introduction and safeguarding of robot production systems are likely to be critical in deciding the effectiveness of the measures to be adopted.

8.2 It is expected that the importance placed on safety will be reflected in the influence of and resources available to the safety function. The overall climate towards safety in the factory is expected to have an influence on the steps taken with the robot production systems.

8.3 The power, responsibilities and authority of those involved in ensuring safety and the mechanisms for ensuring accountability are expected to influence the implementation of the safety strategies and hence influence the safety of the systems.

8.4 The means of monitoring and evaluating the safety performance of the system design and personnel are also expected to be particularly influential in maintaining and adapting system design or working practices.

DATA COLLECTION METHODS

The Empirical Study focussed on industrial robot systems performing a variety of tasks. At the beginning of the study in 1982 the total number of robots in use in the UK was 1152, rising to 1753 near the end of the study (December 1983) (see Chapter 1 for a review of current robot use). An attempt was made to contact a large number of the users of these 1,000+ robots. Over 100 companies were identified from a literature survey of robot users. An initial letter was sent to over 30 robot users from this large group who appeared in a position to assist in the research (see Appendix A for the form of letter sent). Of this group, roughly 20 responded, some more favourably than others. The initial letter was then followed by a telephone call to arrange a visit to discuss the requirements of the research. Following this, the number of collaborating companies were reduced to 11. Of these, 2 companies used robots for spot welding, 4 for arc-welding, 3 for materials handling and 3 for more unusual tasks (drilling and routing in one case, adhesive bonding in another and stapling/assembly work in the third). Table 4.1 gives the companies (denoted alphabetically) with the tasks and numbers of robots in each.

The number of robots in Table 4.1 is well over 10% of the total number of robots in Britain in 1983, with a range of tasks which is also

Factory	Number of Robots	Tasks
A	12	Arc-welding
B	52	Spot-welding
	2	Adhesive Bonding
C	7 (later 9)	Arc-welding
D	2	Materials Handling
E	12	Arc-welding
F	2	Spot-welding
	5	Arc-welding
G	2	Stapling/Assembly
H	2	Drilling/Routing
I	1	Materials Handling
J	38	Materials Handling
K	4	Arc-welding
	1	Materials Handling
	142	

Table 4.1 Initial Cooperating Robot Users

quite representative. However, in the final stages of obtaining access these 11 companies were further reduced. Factories I, J and K withdrew their support relatively quickly, stating that they could not provide the extensive access required for the research. Nevertheless, they did provide useful background information for the study. Factories E and G cooperated for a short time but information was not forthcoming in the depth required. The numbers of robots and systems to be studied was thus reduced to a total of 6 companies and 84 robots.

The loss of 5 companies (E, G, I, J and K) affected the number of systems to be studied more severely than the number of robots, since 84 robots still constituted more than 7% of the robot population at the beginning of 1983. However, the final stage of reduction of access meant a strong concentration on two of the most common tasks - arc-welding and spot welding. Both of these have a higher percentage of robots in the study than in the total UK population at the beginning of 1982, whilst materials handling has become considerably underrepresented.

Table 4.2 shows the distribution of robots between factories and tasks. In Factory B the three robot systems are denoted by the numbers 5 to 7, according to the factory's own numbering system.

The study covered the six different types of robots described in Figure 4.1. The distribution of these six types of robots between the factories and systems is shown in Table 4.3. There is a good spread of robot types, but a strong concentration on electrically powered designs.

Access was gained to each of the six factories in the middle of 1983, with most of the research data being collected in the rest of that year. Some systems were studied for a short period in 1984, but this was exceptional. For each system, access involved extended periods in the factory observing the production process and discussing matters with personnel. In some cases this meant a presence in the factory for three consecutive days, and in all cases numerous visits to the factory were necessary to ensure satisfactory coverage of the information required. Table 4.4 shows the background details of each factory.

	Tasks					
Company	Arc Welding	Spot Welding	Materials handling	Adhesive bonding	Routing	Total
A	12	-	-	-	-	12
B5	-	8	-	-	-	8
B6	-	22	-	1	-	23
B7	-	22	-	1	-	23
C	7	-	-	-	-	7
D	-	-	2	-	-	2
FI	5	-	-	-	-	5
FII	-	2	-	-	-	2
H(I&II)	-	-	-	-	2	2
TOTAL	24	54	2	2	2	84

Table 4.2 Robots and Their Tasks in the Companies Studied

Robot Type	Description
Type 1	A medium-sized floor mounted, electrically powered, 5 axes robot with a limited articulated configuration to the arm and a payload capacity of 6 kg.
Type 2	A large floor mounted, hydraulically powered, 6 axes robot with an articulated configuration to the arm and a payload capacity of over 100 kg.
Type 3	A large floor mounted, electrically powered, 6 axes robot with a limited articulated configuration to the arm and a payload capacity of 100 kg.
Type 4	A medium-sized gantry mounted, electrically powered, 6 axes robot with a (rectangular) configuration to the arm and a payload capacity of 60 kg.
Type 5	A large floor mounted, hydraulically powered, 5 axes robot with a Turret configuration to the arm and a payload capacity of 70 kg.
Type 6	A medium sized floor mounted, hydraulically powered 5 axes robot with a limited articulated configuration to the arm and a payload of 10 kg.

(Robot arm configurations are expressed in the terms used in Chapter 1. Limited articulated configurations are caused by limited motion in the two horizontal pivots).

Figure 4.1 The Types of Industrial Robot Covered by the Empirical Study

N.B. All six robot types are programmed with a handheld teach pendant.

Factory	Approximate Number of Employees	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Total
A	450	12	-	-	-	-	-	12
B5	Over 10,000	-	-	8	-	-	-	8
B6		1	-	4	18	-	-	23
B7		1	-	4	18	-	-	23
C	200	4(+2 later)	-	-	-	-	3	7 (+2 later)
D	400	-	-	-	-	2	-	2
FI	125	-	2	-	-	-	-	2
FII		-	-	-	-	-	5	5
H(I & II)	6000	-	2	-	-	-	-	2
Total		18(+2 later)	4	16	36	2	8	84(+ 2 later)

Table 4.3 Robot Types in Each Factory and System

	FACTORIES					
	A	B	C	D	F	H
Size of company to which factory belongs (employees)	Over 100,000	Over 60,000	Over 13,000	~2,000	~1,500	Over 70,000
Main activity of company	Motor vehicle production	Motor vehicle production	Food and drink	Moulded plastic products	Automotive components	Aircraft
Factory size (employees)	Approximately 450	Over 20,000	Approximately 500	400	100	7,000 (in 2 factories)
Size of production engineering function (and title)	15 (Plant and Production Engineering)	Over 50 (Mechanical and and Plant Engineering)	1 Production Manager 1 Services Manager	60 Engineers on the shop floor (Works Engineering)	About 10 (Production Engineering)	Over 300 (Works Services, Production Engineering and Manufacturing)
Size of Safety Function	1 Safety Officer (for 3 factories) 1 Secretary	18 - 1 Chief Safety Engineer 3 Supervisors 6 Specialist Machine Examiners 7 Safety Engineers 1 Assistant	1 Safety Officer (who also acts as Works Study Engineer) 1/5 Secretarial support	1 Safety Engineer 1 Secretary	Works Manager responsible for factory safety	6 - Chief Safety Officer 3 Safety Officers 1 Technician 1 Secretary

Table 4.4 Summary of Company Information

Data Required

Required data fell into 12 categories:-

(i) interruptions to production,
(ii) accident statistics,
(iii) the context of company and factory organisation,
(iv) the role of safety and production engineering functions,
(v) the Safety Policy and role of safety committees and worker representatives,
(vi) the physical working environment,
(vii) the robot system design,
(viii) safeguards and safety measures,
(ix) the organisation of work on the robot system,
(x) monitoring functions,
(xi) working practices, and
(xii) training provisions for personnel.

Each of these headings is elaborated below giving details of the sort of information required.

Data on interruptions to production

Each incident of interruption of production was recorded, with the following information sought:-

(1) The date and time of each incident;
(2) The robot type, task and number (if the system contained more than one);
(3) The amount of downtime caused;
(4) The total weekly hours of robot use in production;
(5) The actions taken in each incident;
(6) The reasons for the action;
(7) The means of interruption to the system's production;
(8) A classification of the severity of the incident (into accidents, damage to equipment, near misses, hazards anticipated or incidents where no damage occurred or was likely to occur);
(9) The involvement of personnel in identifying and sorting out problems;
(10) The underlying reason or cause for the incident (identifying component failures and problems and distinguishing between robot related reasons and others).

The final 6 headings were the most important from a safety viewpoint, giving the severity of the incident and the types of contact between people and equipment in the subsequent actions. The underlying reason is arguably the most important from a safety viewpoint but at the same time is also of a subjective nature. Isolating the underlying reason from the coincidental effects is largely a matter of judgement. The underlying reason recorded here is the direct underlying cause for the downtime, rather than some more deep-rooted reason which by a series of causative steps has led to the problem.

The main measure from the production viewpoint was the downtime figures along with the hours of robot production. This gave the proportional loss of production time. When combined with the underlying reasons, the proportional loss of production time for different causes was given.

Accident statistics

Accident data is commonly of the form of injuries and treatments by first-aid centres in the factories. Although the data on interruptions to production provided some data on accidents - in the form of the heading of severity of outcomes of incidents - the overall picture of accidents in each factory was gained from the collation of general statistics.

Organisational context of company and factory

Robots use and associated work organisation needed to be understood in terms of the overall context of the organisation and product history with particular relevance to the organisation of safety and production functions within the company, the overall industrial relations environment and the presence of any policy or strategy towards new technology. At the company, or corporate, level, the size and market setting were described. At the factory level, the overall production organisation, variations and permanency of the workforce and presence of other new technology or technology similar to robots were also considered.

Role of safety and production engineering functions in the companies

These two functions are particularly important in a study of safety and production problems with industrial robot systems since their involvement and expertise in the area of advanced manufacturing technology were expected to influence the problems experienced. A description of roles and responsibilities of those involved in both functions at management level were required, as well as an assessment of the importance of both functions within the factory.

Safety policy and the role of safety committees and worker representatives

The Factory or Company Safety Policy Document was considered. Duties and responsibilities placed on people in this document were noted as well as any detailed specifications of actions to fulfill the duties and responsibilities. The expressed policy and its implemented state were also compared.

Details of the form (if any) of workforce representation and the operation and structure of safety committees, including their membership, frequency of meetings and levels of attendance were investigated. The issues normally raised and their sources were identified. Any grievance or disciplinary procedures arising from meetings were noted along with influences of the safety committees. Information on the involvement of safety committees and representatives in robot introduction was collected, particularly details on any consultation. Information on the level of understanding among safety representatives of problems of robot systems and any specific safety training on robots was also gathered.

Physical working environment

An assessment of the hazards of the workplace as a whole was required. For this the working conditions and characteristics of the factory buildings (lighting, ventilation, heating, levels of dust and noise and so on) were described with particular emphasis on the environment in the vicinity of the robot system. For example, details on cramped surroundings or the build-up of work in progress were noted.

Robot system design

The design of the robot system, including the robot, auxiliary equipment and interlocking was specified in close detail, giving a description of the workflow, equipment design and layout. Details on the size and performance of equipment were also collected. Any alterations to the design during the period of study were noted. The role of outside agents, such as suppliers or commissioning companies, and the involvement of in-house engineers were considered.

Safeguards and safety features

Descriptions of safeguarding features were required as well as their mode of operation. Their connections with the rest of the system were specified, particularly their interlocking with the operation of other equipment. Any means by which these safety features could be circumvented by the workforce and any experience of this in the factories studied were also considered.

The organisation of work on the robot system

Details on the groups of workers involved in working on the robot system were required. Their tasks were given, as well as their line of supervision, discretion, accountability and the knowledge of their supervisor in comparison to the expertise of the workers. The permanency of allocation of workers to the system and the numbers in each group were also gathered.

Monitoring functions

Monitoring of the robot system was expected to take a number of forms. Of interest were the monitoring of the following parameters:-

a) accidents and dangerous incidents
b) maintenance work
c) working practices
d) production, especially lost production time.

(Quality of production was one major area not of direct concern here).

Details on what was monitored, by whom, by what means and for what purpose was needed for each of the above parameters. Details on the content of the information gained was required, as well as any re-evaluation of activities that resulted.

Working practices

A description of both formal and informal practices was needed for each type of worker involved with the robot systems. Any particular safety problems with either formal or informal practices were noted. The hours worked each week were also of interest.

Training provisions

The length, content and siting of any training given to the work-groups involved with the robot systems was noted. Of particular importance to this study was the content of safety in the training programmes, that is, on safe working practices and possible dangerous incidents or failures.

Data Collection Means

It should be clear from the description of the data required that a large amount of information was required on each robot system. It is difficult to envisage how one means of data collection could be successful. In this study, four means were used in conjunction. A diary form and company records provided the production data and open-ended discussions with observation were used to gain the majority of the rest of the information. Company records were also used as sources of information for such things as minutes of Safety Committee meetings, the Safety Policy Document and accident statistics. Each of these means are considered below in more detail, along with any problems in information gathering.

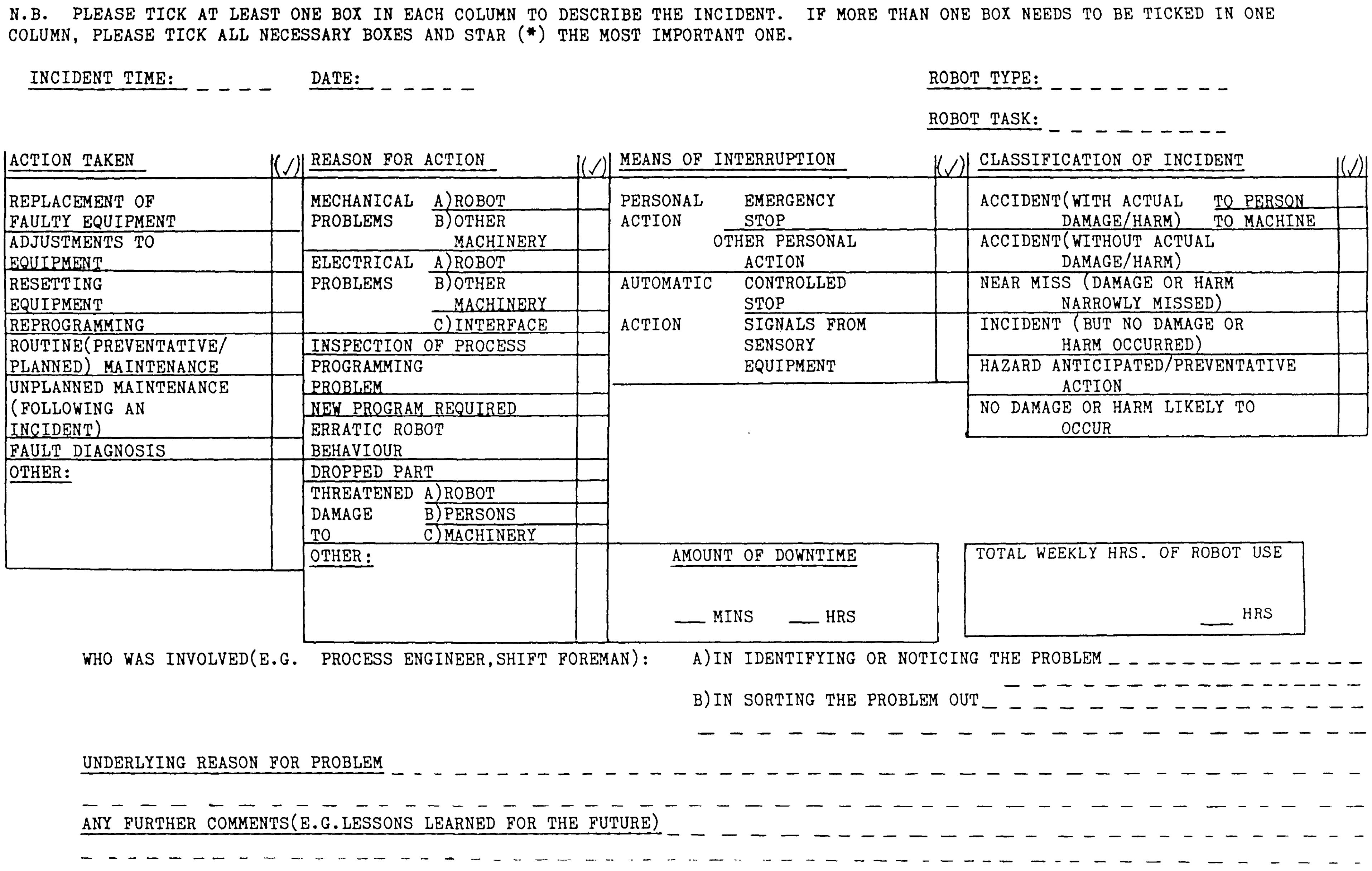
The diary form and company production records

The data required on each incident of interrupted production shaped the form of the means of data collection. A diary form was created for use in each robot system, which had separate sections for the information required for each incident under each heading (see above). A copy of this diary form is presented here (Figure 4.2). It is important to note that the use of the diary was triggered by production interruptions and was not directly for workers' activities. For each interruption of production, respondents were asked to complete the form in terms of sets of options for the Actions Taken, Reasons for Action, Means of Interruption and Classification of the Incident. The specific options given on the form for each heading were chosen after initial investigation of the characteristics of interruptions to production. With Actions Taken and Reasons for Action, the final option is blank so that any other action or reason not already included can be added.

This diary form was introduced on each system and explained to the relevant personnel. Several pages of explanation were included, giving three test cases and instructions on how to fill out the forms. These are shown in Appendix B. They show the purpose behind the data collection and explain the content required.

In a few companies, workers on the robot systems were already recording incidents of lost production time. Although the format varied considerably from the diary form, the information gathered from the companies own records were comparable in some cases. In Factory A and Factory B, it was decided that the records kept by maintenance workers permanently allocated to the systems could be used since it was a simple task to convert from their records to the format of the diary. In F, the records kept by the chargehands were used alongside the diary forms. Some information was not stated explicitly on the company records each time, namely the means of interruption and the classification of the incident and the people involved, but these could be filled in from the information provided with an understanding of the system operation and working practices.

In two factories, C and D, it did not prove possible to collect production data comparable to the other systems. The factories' own record-keeping did not provide sufficient detail and attempts to encourage the introduction of the diary forms proved unsuccessful. In both factories the foreman responsible for the robot systems and their record-keeping



N.B. PLEASE TICK AT LEAST ONE BOX IN EACH COLUMN TO DESCRIBE THE INCIDENT. IF MORE THAN ONE BOX NEEDS TO BE TICKED IN ONE COLUMN, PLEASE TICK ALL NECESSARY BOXES AND STAR (*) THE MOST IMPORTANT ONE.

INCIDENT TIME: _ _ _ _ DATE: _ _ _ _ _

ROBOT TYPE: _ _ _ _ _ _ _ _ _ _

ROBOT TASK: _ _ _ _ _ _ _ _ _ _

ACTION TAKEN	(✓)
REPLACEMENT OF FAULTY EQUIPMENT	
ADJUSTMENTS TO EQUIPMENT	
RESETTING EQUIPMENT	
REPROGRAMMING	
ROUTINE(PREVENTATIVE/ PLANNED) MAINTENANCE	
UNPLANNED MAINTENANCE (FOLLOWING AN INCIDENT)	
FAULT DIAGNOSIS	
OTHER:	

REASON FOR ACTION		(✓)
MECHANICAL PROBLEMS	A)ROBOT	
	B)OTHER MACHINERY	
ELECTRICAL PROBLEMS	A)ROBOT	
	B)OTHER MACHINERY	
	C)INTERFACE	
INSPECTION OF PROCESS		
PROGRAMMING PROBLEM		
NEW PROGRAM REQUIRED		
ERRATIC ROBOT BEHAVIOUR		
DROPPED PART		
THREATENED DAMAGE TO	A)ROBOT	
	B)PERSONS	
	C)MACHINERY	
OTHER:		

MEANS OF INTERRUPTION		(✓)
PERSONAL ACTION	EMERGENCY STOP	
	OTHER PERSONAL ACTION	
AUTOMATIC ACTION	CONTROLLED STOP	
	SIGNALS FROM SENSORY EQUIPMENT	

CLASSIFICATION OF INCIDENT		(✓)
ACCIDENT(WITH ACTUAL DAMAGE/HARM)	TO PERSON	
	TO MACHINE	
ACCIDENT(WITHOUT ACTUAL DAMAGE/HARM)		
NEAR MISS (DAMAGE OR HARM NARROWLY MISSED)		
INCIDENT (BUT NO DAMAGE OR HARM OCCURRED)		
HAZARD ANTICIPATED/PREVENTATIVE ACTION		
NO DAMAGE OR HARM LIKELY TO OCCUR		

AMOUNT OF DOWNTIME

___ MINS ___ HRS

TOTAL WEEKLY HRS. OF ROBOT USE

___ HRS

WHO WAS INVOLVED(E.G. PROCESS ENGINEER,SHIFT FOREMAN): A)IN IDENTIFYING OR NOTICING THE PROBLEM _ _ _ _ _ _ _ _ _ _ _ _ _ _

B)IN SORTING THE PROBLEM OUT _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

UNDERLYING REASON FOR PROBLEM _

ANY FURTHER COMMENTS(E.G.LESSONS LEARNED FOR THE FUTURE) _

Figure 4.2 The Diary Form

(PLEASE RETAIN ALL SHEETS IN THE FOLDER PROVIDED) had very high workloads and time could not be found to do the extra form-filling. Therefore production data from the robot systems C and D had reluctantly to be discarded.

It should not be assumed that all safety issues were identified from the incidents of lost production time, since hazards were also presented by close proximity to the robots and other equipment during automatic operation. If means were available to allow access without preventing automatic operations, such events would not be recorded in the production data. This type of hazard could be discovered by observation, which is discussed below.

Observation and open-ended discussions

These two means of data collection are considered together, since they were intricately enmeshed during the actual data collection. For both of these, a checklist was prepared which listed the areas to be covered. This checklist is shown in Appendix C. Several areas could not be covered by observation or discussions alone, notably the organisational content. The information on this was gained from the companies' documents and publically released reports such as the Annual Report to Shareholders. An important part of the initial period of this data collection was used to check that the information identified as relevant was complete and whether additional information was necessary.

Observation was a particularly useful means of gathering information on working practices and to some extent system design. However it was useful to compare the expressed views with reality. For example, monitoring functions might be stated to be more extensive than they were in practice. Also, technical information provided by management, supervisors, maintenance workers or operators could be checked with observations of the process and the design.

Discussions were carried out with all groups involved in the robot system operation. For some information - such as monitoring, working practices, system design and operation and training - more than one group was asked because of their differing knowledge of the system and experience of its operation. Access to workers and technical or confidential information varied from one company to another, depending on their policy towards releasing information and the cooperation gained from personnel in the factories. Although sufficient information was felt to have been gathered in most areas in each factory, insufficient coverage of some areas was found. In Factory B, it was not possible to discuss issues at length with workers on the systems nor to talk to worker safety representatives. Company rules about access meant that a visitor to the factory had to be accompanied at all times by a member of supervision or production engineering. In Factory D maintenance workers were not observed or talked to and accident data was not provided. Elsewhere, access within the factories was more relaxed, with few restrictions on movement. Few difficult problems arose elsewhere and none were felt to be insurmountable.

DATA ANALYSIS

The production data from the 4 factories was collected and converted to a computer code. An SPSS programme was written to store and analyse the raw data. This and the coding system are shown in Appendix K. The code has separate sections for each parameter. Each incident had its place and case number recorded, with the robot type, number and its task. The downtime was recorded in hours and minutes. Each action taken and reason for action was given a separate space, because these were not mutually exclusive. However, means of interruption, classification of the incident and underlying reasons could only have one value each, since only one means of interruption, one outcome of the incident and one underlying reason could occur. There could be a number of persons involved at both stages of identifying and sorting out a problem. An initial study showed that room for three separate groups of workers was sufficient.

The categories of underlying reasons used in the analysis were chosen to encompass reasons given on the diary forms. In all, 28 different categories were used, of which 15 were robot related. These are given below in Figure 4.3 with a brief definition of each. These categories have the merits of being applicable in each system and allowing comparisons between systems and robot tasks. Robot related reasons were described by

1.Robot Related Problems.

Category	Definition
Component failure in Robot Arm.	A discrete, known failure in the robot arm.
Fuses Blown.	The fuses in the robot's controls fail for various reasons-including faults elsewhere.
Fault in cabinet.	A recognised fault in the components of the control cabinet-e.g. a faulty circuit board.
Fault in teach pendant.	Component failure in teach pendant-e.g. a faulty button.
Power supply fault.	The power supply to the robot fails (particularly with hydraulically powered robots-possibly due to a faulty filter or dirty fluid causing a blockage.
Cable/Transmission problem.	Broken cables or other similar transmission difficulty in robot unit.
Overheating hydraulics.	Overheating of hydraulic power pack causes a failure of power and freezes the robot's motion.
Robot collision.	Robot collides with other equipment or another robot.
Robot won't move.	Robot fails to move, though no apparent reason is found - possibly a software problem.
Robot out of synchronisation.	Robot arm position does not match the robot's memory of where it should be-commonly referred to as "out of position" or "lost itself" or "lost wait position"
Robot in Emergency Stop.	The controls bring the arm to a halt-referred to as "stop-in-sequence","trip-out" or "lost control on robot"
Erratic Robot.	The robot moves off the specified path by an appreciable amount.
Stiffness in robot.	Mechanical problems cause the arm to resist motion- results in the controls stopping the motion.
Problems in tools.	A fault is found in the tools carried on the end of the robot arm such as weld guns and their cables.
Robot problems-no detail.	Any robot related problem not covered above.

2.Problems not directly attributable to robot units.

Category	Definition
Other component failure.	Component failure on equipment other than the robot.
Other equipment problem.	Production equipment other than the robots have caused a problem (but not a failure of a component).
Sequence fault.	The normal sequence of events is disrupted by something unspecified-possibly transmission.
System failure.	The whole system fails to work with no single identifiable component at fault.
System checks.	Checks are carried out on the system as a means of preventing problems becoming worse.
Check on parts.	Checks are made on components as they progress through the robot system.
Part problem or variation	The components are at fault,e.g. because of excessive variation from design parameters.
Quality problem.	The quality of the process has been identified as sub-standard.
Services Problem.	Problem with services,e.g. electricity, water, compressed air, other gas supplies.
Safety function problem.	Problem identified with safety equipment e.g. interlocked gates, fencing, light guards.
Human error.	Incorrect human action resulting directly in a loss of production.
*Weld failure.	The robot failed to carry out it's welding task. This could be due to a number of things.
Process problem.	The process has been shown to be faulty in some other way than above.

* In Company A, the robot systems and data collection were such that it was often impossible to specify the underlying reason for a fault in any greater detail than "weld failure". It will be seen that such cases accounted for more than 50% of incidents from this company. The robots' tasks were arc-welding and the first indication of a fault was an alarm signalling the failure of the robot to carry out it's task. In each case, a number of factors could have been important in this failure. For example, part variation or some problem with the weld equipment or some unspecified erratic robot motion. In many cases it was considered that in fact the problem was robot related and should therefore have been ideally categorised in Section 1. of Figure 2.

Figure 4.3 Description of the Underlying Reason Categories more categories and consequently in more detail. In particular, 6 categories of robot related failures were given:- component failure in robot arm, fuses blown, fault in cabinet, fault in teach pendant, power supply fault and cable problem. For the majority of the analysis, comparisons of frequencies for combinations of variables were made, utilising the SPSS command:-

```
FREQUENCIES        GENERAL = ......
```

For some of the subsequent analysis some other SPSS commands were used, for example for the significance of differences in means of downtimes (see Appendix G).

SUMMARY

This chapter has presented the aims and objectives of the empirical study and the propositions which guided data collection and analysis. The analysis in the subsequent chapters considers the eight sets of propositions and presents conclusions on each topic.

The data collection methods showed the companies originally contacted and gave details on the six who co-operated in the empirical study. The categories of required data were presented and the means by which the data was obtained were also given. A short description of the computer analysis of the data was the final section of this chapter.

CHAPTER 5

THE ROBOT SYSTEMS: WORK ORGANISATION AND PRODUCTION PROBLEMS

INTRODUCTION

This chapter discusses the robot systems in six factories and the data gathered about the interruptions to production in four of these factories.

The first part of this chapter provides a description of each system in terms of:

a) the physical environment in the factories
b) the system layout
c) the safety features incorporated into the system design
d) the hazards of the systems
e) the working practices
e) the training provisions
f) accident statistics on the systems.

The second part of this chapter analyses interruptions to production with robot systems in four factories. This provides information on the performance of robot systems of a kind not available elsewhere in the literature. The safety implications of interruptions to production are considered in the final section of this chapter.

SYSTEM DESCRIPTIONS

The Physical Environment

Table 5.1 summarises the environment in each factory and in which each robot system operates. This table concentrates on the general conditions, for example the amount of free space within work areas and the levels of noise and dirt. Such details on the conditions within the robot system and the surrounding area is expanded upon in subsequent sections.

A	B	C	D	F	H
Factory Building poorly ventilated. Passageways between work areas not kept clear of work-in-progress. High levels of dust and smoke. Few safety signs.	Factory Building well lit, spacious and well ventilated. Products of welding contained. Well marked passageways, kept clear.	Factory Factory floor cluttered with work-in progress. High levels of dust and fumes in the air. Poor ventilation. Lighting adequate overall.	Factory Factory noisy and dirty. Copious amounts of oil on floor. Adequate ventilation and lighting.	Factory Poor ventilation. Lighting adequate overall. Factory noisy. Factory floor slippery with a mixture of metallic dust and oil.	Factory Factories spacious and well ventilated. Good lighting. Well marked passageways. No build-up of work-in-progress.
Robot System Area Dust not cleared away. Lighting and working conditions better than average in factory.	Robot System Area Area kept clear with wide passageways. Conditions equal to the rest of the factory.	Robot System Area Some robot systems particularly cramped by work-in-progress. Poor lighting in some parts. By-products of welding allowed to build up.	Robot System Area High levels of noise and oily deposits. Area well lit, adequately ventilated and uncramped.	Robot System Area Area unrestricted by work-in-progress. Most by-products of arc- and spot-welding allowed to build up.	Robot System Area Adequate space, well lit and ventilated conditions.

Table 5.1 Physical Environment in Each Factory

Robot Systems Layout

Factory A

The robot system in Factory A consists of 12 Type I robots (see Figure 4.1 in Chapter 4 for a description of the robot types studied). The dimensions of the system are approximately 4 metres wide and 25-30 metres long. It is divided into a number of sections, 5 in all, 3 of which contain 4 robots. The whole system is enclosed in a continuous 2 metre high sheet metal fence. A number of interlocked access doors are in the fencing, adjacent to the robot sections.

Parts are assembled manually on a jig outside the first section of the system. The moveable platform to which the jig is fastened (known as the 'jig truck') has a motor and a rack and pinion drive mechanism which moves the platform in and out of the first section where the robots 'tack' together the various parts.

Part transportation from the first section is performed by hoists which run on tracks above the robots and the jig. There are four hoists in all, each dedicated to a section of the system. The first hoist moves the parts from the first section to an area between the first and second sets of robots. A second hoist picks up the parts and transports them to the second welding station. A third hoist then transports the parts to a turnover section after which it carries them to the third and final welding section. The robots here weld the underside of the product. The fourth hoist transports the completed parts to the unload station, where they are lowered onto a manually controlled indexing conveyor. There is an observation gantry at the same level as the runways for the hoists, which can be reached by a number of stairways on the sides of the system. Each section of the system has its own control panel for showing the step-by-step progress of parts through the process. One can see the position of each part on this panel along with the point reached in the programme by each piece of machinery. Positional sensors on the hoists,the clamps on the jigs and on each robot's stand are monitored by the overall controller to enable correct sequencing.

The whole robot system was assembled, installed and comissioned by ProdEng Ltd., a company which has gained a great deal of experience in robot system commissioning and in working with Company A. Engineers from ProdEng Ltd., Factory A and production technology specialists elsewhere in the company worked together on a long term basis to overcome problems and bring the system to full production.

Factory B

The unit of this case study is a section of the factory which is divided into three areas, Stations 5, 6 and 7. Stations 6 and 7 are very similar, being the welding lines for the left and right-handed panels for one type of car. Station 5 precedes these two in the direction of the manufacturing process. Two part versions pass through this area and are welded by virtually the same equipment.

Parts are delivered to Station 5 and are loaded manually onto 'turnbucks' - automatic rotating structures which hold parts in their correct positions during welding. There are four of these turnbucks, two for each panel side. Panels are transported from the turnbucks to the next station by means of an overhead transfer mechanism, known as the translift. The translifts consist of a number of electrically powered units which move along a track. Since there are turnbucks dedicated to the right and left-hand parts there are also two separate translift track units feeding the two subsequent systems.

Stations 6 and 7 have the same number of sections. Some of these sections are for welding, some allow the alternative method of manufacturing of manual welding, others are for the loading of the wheel-base unit and some are merely for waiting between active sections. In one further section, adhesive material is applied by a robot to the body side-panel. Parts are transferred between these sections by a set of shuttle transfer machines. Each of these "shuttles" is capable of moving parts forward one section at a time. The transfer of parts down the length of these two systems is performed by 3 shuttles in series. The operation of the whole system is controlled by a main controller, which ensures the correct sequence of operation and identifies any problems. Completely welded body-side panels are unloaded at the end of each Station.

The panels are lifted off the system automatically and loaded by two manual workers onto a moving transfer line.

Station 5

Station 5 can be thought of as 4 identical robot systems, insofar as they differ only in orientation of the panels.

Each system consists of a turnbuck, two Type 3 robots (see Figure 4.1, Chapter 4), interlocked photo-electric sensing devices, operation control buttons and fencing. There are a number of clamps on each jig on the turnbucks to hold the parts whilst rotation or welding takes place. The photo-electric sensing device acts as a guard across the working area and is inactive when the turnbuck is incapable of rotation, that is, when the manual loader can load a new set of parts.

Stations 6 and 7

The panel is covered by the translift into the first section of the system. Manual loading of parts can also be performed and to facilitate this, there are access doors and photo-electric sensing safety devices on each side of the loading area.

The shuttle moves the panel to the next section and the automatic lifter in this section lifts the panel clear of the shuttle bars. The shuttle then moves back to its original position. Clamps on the lifter close when the lifer is in its upper position. This enables the robots in this section (one type 3 and two type 4 robots) to move in to start welding.

Welding equipment is provided for each robot in this system, that is, a spot weld gun and weld timing unit. All three robots have a large spatial coverage and move within each others' working areas for most of their welding operations. They are prevented from colliding by sequencing instructions from the overall controller. It is usual for one robot to wait for another to complete a task and move away from an area before it moves in to weld. The overall controller also informs the robot of which part version is to be welded. The robots then select the correct weld programmes for this model.

The next section has no type 3 robot in it, but is otherwise identical to the previous section, having two type 4 robots. Following this is a manual weld station. The subsequent section has a type 1 robot in it, which applies adhesive sealant.

There are three remaining sections with 3 robots (1 type 3 and 2 type 4) and four sections with 2 robots (both type 4) all of which perform welding. This gives a total of 4 type 3, 18 type 4 and 1 type 1 on both Stations 6 and 7.

Each section has a control panel which summarises information on the section operation and also includes a portion with fault signalling, interruption and re-setting functions, such as fault reset buttons, sequence stop, reset sequence stop buttons and an Emergency Power Off push button. The equipment used on these systems has been standardised throughout. The lifter mechanisms used in each of the 23 sections are an identical design with harmonic drive electric motors. The three shuttles and their drive mechanisms on each station are also identical.

Stations 6 and 7 each have a main control area, from where the operation of the systems can be monitored. There are controls and indicators which summarise all the parameters of the system. There is a lighted panel for each of the stations, prominently placed to aid workers on Stations 6 and 7 in identifying problems with the systems. This shows which section is still operating. Should there be a fault in one section, the light for that section flashes. There are also some general indications, such as Emergency Stop conditions, normal conditions, whether the system is unloading correctly and the position of each of the shuttle mechanisms.

To minimise damage from any collision or other unexpected occurrence, the shuttle support bars are held in place by brittle nylon screws. These break easily if any resistance is encountered, thus minimising the damage which may be caused to the shuttle or the panels.

Sensors are also used in profusion to aid the performance of the systems. There are two on each lifter table to identify which of the two models is present. Each clamp on the lifter tables has a sensor to check that it has completed its movement. Similarly, on Station 5, each clamp has a limit switch to signal its position.

The whole this factory area was desiged and commissioned with a great deal of involvement from outside companies. The stations considered here were commissioned by one company who had had substantial experience of similar tasks. Factory B's own Manufacturing and Plant engineers were heavily involved in the design, since all the equipment used had to conform to company standards for performance. Technical specifications were provided by Factory B, with the commissioning company undertaking the detailed design of the systems. The two sets of engineers worked alongside each other throughout the system introduction.

Factory C

Seven robot systems are considered in Factory C. The most common system layout has two jig tables, one each side of the robot with a heavy green curtain surrounding it. The parts are fastened onto the jig tables by manually operated clamps whilst the robot is working on the other jig table. The robot comes to rest at the mid-point between each table, awaiting a signal from the operator to proceed to the other jig table. The operator is separated from the welding process by a safety curtain which the operator pulls across the side of the jig table. Each system also has a welding wire drive and control unit and the robot control cabinet. The weld wire and weld control unit is placed behind the robot, with the robot control cabinet about 1 metre further back.

One system differs from the usual arrangement in this factory and has a robot working with a turntable. Other equipment in this system consists of the robots controls, welding equipment and an interface to sequence the turntable motion. The system is surrounded by a wire mesh fence 3 metres high, with a sliding door for loading and unloading parts. The sliding door has a limit switch which records when the door is open and shut. The operator instigates the programme start by closing the access door and another switch.

There are two different robot types here, Types 1 and 6 (see figure 4.1, Chapter 4). They have a lot of similar characteristics, but differ in terms of accuracy and dynamics and also in the internal design of power transmission. The pattern of introduction is given below with approximate dates:-

No. 1	July	1977	Type 1
No. 2	April	1978	Type 1
No. 3	July	1979	Type 1
No. 4	March	1981	Type 6a
No. 5	October	1981	Type 6a
No. 6	July	1982	Type 6b*
No. 7	July	1983	Type 1a*
Nos. 8 & 9	February	1984	Type 1a

(The 8th and 9th were introduced after the study)

Robot Introduction in Factory C

*A slight redesign was introduced to the Type 6 robot between the purchase of the 5th and 6th robots and for Type 1 robots by the purchase of the 7th robot.

The dimensions of each system with the jig tables allows the robots to reach almost to the furthest edge. These jig tables are approximately 1.3 metres wide and 3 metres long and the two in each station are set in a V-shaped configuration with the robot in between the two tables. The six stations with this design, Numbers 1, 2, 3, 4, 5 and 7 vary slightly from each other. Different parts are produced by each station varying in size, the number and length of welds and cycle time. Different clamping methods are also employed, partly because of the difference in tasks. However, in all seven systems, the clamps are engaged manually.

The jig tables in each station differ from each other in a number of ways. Several jigs are capable of rotation. Two tables, in stations 1 and 2, are capable of automatic rotation and another two (4 and 5) can be rotated manually. On the manually operated ones, the robot comes to a halt awaiting the movement of the jig table to its second position. Once the lock-pin on the table has re-engaged the robot continues to weld. This movement is controlled by limit switch interlocks on the table. The automatic rotating jig tables are pneumatically powered and controlled by signals from the robot controls.

The robots and ancillary equipment were supplied as a package for each system, but the final layout was Factory C's own concern. The jig tables were developed internally. No external companies were involved in implementing the system or bringing them to operation. A slight exception to this occurred with No. 6, where the presence of a turntable meant that the suppliers were involved in ensuring correct sequencing of their equipment.

Factory D

There are two robot systems in Factory D, identical except for a few minor details. Each system consists of a Type 5 robot (see Figure 4.1, Chapter 4) for materials handling with an injection moulding machine. Several other pieces of equipment are present, such as pressure-sensitive mats covering the floor and a conveyor system which takes the parts unloaded from the injection moulding machine by the robot. The robot and one side of the injection moulding machine is enclosed in a mesh cage. Each injection moulding machine can produce any of 5 different products using different mould tools (platens) on the moulding machine. A set of handling tools for the robot were designed and made by the factory to pick up these parts from within the injection moulding machine. Each product needs a different tool on the end of the robot arm. A specialist platen maker is used for new platens. The systems have numerous interlocks to co-ordinate the operation of the process. The main purpose for the 13 interlocks on each system is to prevent damage to the expensive equipment and to comply with an industry Code of Practice on Horizontal Injection Moulding Machines (British Plastics Federation, 1984). These interlocks include the safety interlocks designed into the injection moulding machines and those added in the design of the surrounding equipment.

The platen movement is interlocked to a signal from the robot to start the platen motion (No. 1 interlock). The robot also signals to the door on the conveyor belt to open when it brings a part to the conveyor (No. 2 interlock) and waits until the part has left. The door shuts once it receives a signal from the light beam which indicates that the part has left the system (No. 3 interlock). The shutting of the door sends a signal to the robot (No. 4 interlock) which then returns to its home position. The conveyor system then transports the part to a nearby stacking area. The robot also sends a signal to the injection moulding machine (No. 5), which opens the platens once more and the process is repeated.

The wire mesh cages have a sliding door for access in each system. These are fitted with an interlocked key system. A person cannot enter the enclose whilst the equipment is powered on. The act of opening the door causes the hydraulic power to the injection moulding machine (No. 6 interlock) to be discharged and removes the power to the injection moulding machine (No. 7 interlock). The floor inside is covered with pressure sensitive matting. Activation of the matting also removes power from the injection moulding machine (No. 8) but allows the robot to move under 'teach restrict' (No. 9).

The other interlocks on the system are on or in the injection moulding machines. There is the interlock on the door on the front of the machine (No. 10). Pressure sensitive matting is also present inside the machine between the platens. This is interlocked to prevent the platens closing with someone within this area (No. 11) and to remove power from the robot manipulator (No. 12). There is also a spring loaded access platform within the front door to prevent the platens moving when this platform is depressed (No. 13).

The fourteenth interlock is an additional feature which was added immediately prior to the study, which prevents the platens from closing on the robot arm and the part. This is a photo-electric guarding system across the access area on the robot side of the injection moulding machine which records the motion of the robot on one sensor and the part on another.

The systems were designed and assembled by factory personnel from the equipment supplied by different companies. No similar experience of automated systems had been accumulated within the company and little consideration was given to the problems of connecting and interlocking the equipment. The supplying companies were similarly handicapped. In fact, a large proportion of early faults were considered to be caused by malfunction or misunderstanding of the operation of the sequencing interlocks.

Factory F

There are four robot systems in this factory. This study concentrates on two of these, the spot-welding system and the largest arc welding system.

Spot-welding system - robot system I

This system consists of a number of working stations on a circular moving track. There are 10 jigs on the track onto which the parts are loaded at two points, one just before the robots in the direction of motion and one just after. There are two Type 2 robots in this system (see Figure 4.1, Chapter 4), both of which perform spot-welding tasks. There are also three dedicated spot-welding machines which complete the welding process. Parts are unloaded in a finished state adjacent to the first loading area. Loading is performed manually, but unloading is automated. The loading areas have perspex barriers which must be in the down position for the track to move forward. Once the track has been locked in position, the barriers are pushed up by an air cylinder.

The parts are held in place by manual clamps throughout the process. Location pins are also used to ensure that the parts are positioned properly on the jigs and that the jigs are locked in position during welding operations. The track is driven by an electric motor via a gear and train mechanism. This moves the track at roughly 1 m/s. The exact positioning of the jigs at the end of each movement is ensured by the lock pins adjacent to each welding machine.

The robots have location switches on the stands which must be depressed for the track to move. The two perspex barriers on the loading areas have two limit switches each which sense when the barriers are up or down. The dedicated spot-welding machines and the circular track also have numerous sensors. All these sensors and limit switches are interlocked with the overall controller, which sequences the signals to the robots and controls the movements elsewhere in the system.

A commissioning company - ProdEng Ltd. - designed the whole system, and used some of their own designs for the most idiosyncratic items, such as the pneumatic unloader and the automatic spot-welders.

Arc-welding system - robot system II

System II has five Type 6 robots (see Figure 4.1, Chapter 4), each performing arc-welding tasks. Parts are loaded, moved around the system on a rotary jig table with five stations and then unloaded. The five robots are arranged so that they weld at three of the five stations, the other two being the loading and unloading stations. The first weld station has two robots which weld at the two extreme ends of the parts. The second station has one robot which welds in the centre of the part. For the final weld station, the part is turned upside down and the two robots weld on the underside. The part is moved between these stations once the signal is given by the loader/unloader that the finished part has been removed and a new part has been loaded. The loader/unloader has two forms of controls at his disposal. There is a roller bar on both the unload and load stations which prevents table motion when pushed inwards. There is also a push button control which starts the next part of the cycle.

The table is about 4 metres in diameter, with the jigs just large enough to take the parts (which are 2 metres long). The system fencing covers an area of about 7 - 8 metres in diameter. Within this area are the robots and their controls, the welding equipment and the rotary table.

When the parts are loaded, manual clamps position the parts correctly. Once the automatic process begins, pneumatic clamps engage. These clamps release once the tube has rotated back to its original position in the unloading station. Pneumatic power is also used for the rotation of the jigs and the table.

There are about 125 switches on the rotary table to ensure correct interlocking, which sense the position of the table and the activation of the clamps. The table is also locked in place by pins during loading/unloading/welding operations, and these pins also have limit switches on them.

A commissioning company was brought in to do the installating as in System I, although a different company was used. ArcWelding Engineers produced the design and supplied all the additional equipment to the robots, such as the pneumatically powered rotary table and the fencing.

Factory H

Two similar robot systems were studied, one in each of two factories in the same division of Company H. The two factories are close geographically and can be seen as one unit in terms of production technology and work organisation. One system (System I) is used for routing panels - refining their edges - in Factory H(I) and the other (System II) is used for drilling and routing a different set of panels in Factory H(2). Both systems consist of Type 2 robots (see Figure 4.1, Chapter 4) and a table to hold the panels whilst the robot carries out its task. Parts are loaded manually and the table moved to the correct position and orientation for the robot. The robot then performs the required tasks. In Factory H(2) drilling takes place first with a plate over the panel to aid the drilling action. Several points are drilled and then the plate is removed. The tool on the robot arm is then changed for the routing tool. When the task is completed, the panel is removed from the table and a new panel is loaded.

Robot System I (in Factory H(1)) is in a corner of the factory with a solid wall on two sides and within a restricted area. This segregation from the rest of the factory is emphasised by fencing. The main walkways are some distance from the system. Fencing was installed during the period of the study on the one side of the system not protected by the fencing for the restricted area. Extraction equipment to remove the swarf produced by the routing action was also installed during the period of study. Robot System II has fencing on four sides because of its more exposed position in the factory. Extraction equipment was planned but was not installed during the study. Other differences between Systems I and II are mainly minor differences in spacial arrangements.

The systems were developed within the division with expertise from suppliers for the key interlock mechanisms. The design of the system was based partly on observation made of other installations in the area with the same type of robot and on articles in the technical press.

Overview of robot systems

The robot systems in three factories (A, D and H) were a new and untried method of undertaking the process. As a result, a certain amount of experimentation took place. The spot and arc-welding applications in the other three factories were more established as suitable for robot use and so experimentation was not so necessary.

Safeguarding and Safety Features

The safeguarding and safety features in each system are summarised in Table 5.2.

Factory A

There are four types of safeguards in Factory A:-

(1) Photoelectric guards around the loading area and also between the first section and the rest of the system. These signal the presence of an object in the path of the photoelectric beam. The activation of these in the loading area incapacitates the jig truck whilst the other results in a halt to the whole system.

(2) Four roller bars on the loading area, which act as physical barriers on the jig truck motion when pushed in and are also interlocked electrically with the overall controller. They were designed and installed by ProdEng Ltd., the commissioning company.

(3) An interlocking key system operating on the access doors to the system. There are 8 doors in all and 3 sets of keys - one for each robot welding section. Each section has a master key which frees other keys to open the access doors. The overall controller brings the system to a halt when the master key is inserted into the master panel which leaves the robots in automatic mode, but prevents all motion except teach motion. The factory engineers stated that the interlock is through the robots embedded software. The power to all other equipment in a section is removed when the master key is inserted.

(4) Three weld parameters - the flow of cooling water for the weld torch, the flow of gas to shield the arc and the flow of electric current - are monitored continuously whilst each robot is welding. Should any one of these parameters suffer an interruption, a failure is signalled for the particular robot by the overall controller. This sets off an alarm and the relevant robot stops. The other robots, including those in the same section, continue to the end of their programme, unless a weld parameter is interrupted for these as well. To restart the system, the problem has to be dealt with and the robot reset.

FACTORIES					
A	B	C	D	F	H
2m high short steel fencing with access gates. Photo-electric guards on loading area and between first section and rest of system. Roller bars on loading area. Interlocking key mechanism on access doors. Monitoring of weld parameters by overall controller. Limit switch on robot stand.	2m high mesh wire fencing with perspex screens in hazardous areas and access gates. Photo-electric guards on loading and unloading areas and on manual sections. 2 Limit switches on each access gate (operating in opposite modes). "Dead man's" control on robot motion and on lifters. Safety locking pins and lock-off hasps and padlocks. Anti-collision device on Type 3 robot arms.	Safety curtain on jigs tables. System No. 6:- wire mesh fencing (3m high). Cloudy green plastic barrier in centre of turntable. Interlock on sliding gate. Anti-collision device in robot arms of all but first 3 robots.	All surrounding wire mesh fence. Interlocks in system design. Robot software restrictions - "safe start position" and "teach restrict".	System I 3m high wire mesh fence with access gate. Perspex screens on loading areas (with 2 limit switches to each one). Perspex safety visors for loaders. Limit switch on robot stand. System II 3m high wire mesh fencing with locked access gate. Roller bars on loading and unloading sections. Cloudy PVC curtain within system fencing. Anti-collision device on robot arms.	Fencing 1m of wire mesh and 1.5m of perspex. Double sets of interlocked access gates. Emergency exits. 'Break-glass' bolts on emergency exits and on interlocked access gates.

Table 5.2 Safeguarding and Safety Features

Factory B

Attempts to co-ordinate common means of safeguarding and standardisation of safety measures and equipment are particularly noticeable in Factory B. All the limit switches on access doors to robot systems are the same, with two switches on each access gate. All photo-electric guards are from the same manufacturer and are installed in a consistent manner. All the position sensors used on the translift and on the lifter devices are of an identical design.

In Station 5, each turnbuck is isolated by 2 m high, 2 inch mesh fencing surrounding the turnbuck and the two robots. On certain parts of this fencing, perspex screens are placed to contain any sparks from the spot-welding. There are gates to each section to allow access to the robots. There is also a key switch on these doors to prevent inadvertent entry.

The operation of the turnbuck systems is controlled by pneumatically activated valves.

Signals from the various sensors and photo-electric guards are used to control the sequence of the operation of the robots and turnbucks. Each pneumatic clamp has a sensor on it to identify when it is in the closed position. If any of the clamps close incorrectly then the process is prevented from continuing. The sequencing of the turnbuck is also controlled by the manual loader. The correct pressing of buttons to put on the clamps and start the rotation have to be performed from outside the loading area because of a one metre long photo-electric guard across the turnbuck area. A locking pin mechanism constrains the movement of the turnbuck in all its stationary positions.

Fencing encloses the whole of the overhead translift systems. This protects workers below from the possibility of a dropped panel.

Stations 6 and 7 were designed with many access points. Each station has an overall controller which ensures correct sequencing and safe operation. Each station can be halted by three different forms of stops to the operation.

(1) Emergency Power Off

This disconnects the power to the system at the main circuit breakers. To reset, the glass from the push button which was pressed (if any) must be replaced and the circuit breakers closed manually.

(2) Sequence stop

This stops the whole system by hardware and software means, removes the voltage from the control output to the motors of the robots, opens the welding contactors and stops the pneumatically controlled movements (such as clamps) at the end of their instructed movement. The "Central Start" control is also removed. Access to the system is possible under this condition. To reset the cause of the stoppage must be overcome and the system reset from a control panel.

(3) No "control start"

This is an automatic hold on the system operation, instigated by a number of manual and automatic actions. The effect is a stoppage of the section concerned, via the system software. To reset the "Central Start" button is pressed. A description of each type of safety feature follows:-

Fencing

The whole of the system is enclosed by two inch mesh iron fencing which stands two metres high with perspex shields at various points. The perspex contains the sparks produced by the weld guns of the robots to the area within the fencing.

Access gates

These are present in all sections of the system. Each door has two limit switches at the hinge side, which operate in opposite directions (as BS 5304 requires for high risk areas). The opening of the gates results in a Sequence Stop. The robots and lifter in the section affected can move under teach mode control following the selection of a special switch and the use of a 'Dead man's Button'.

Safety Locking Pins

There are manually operated pneumatic pistons in each section which lock the lifters and also lock the relevant shuttle transfer mechanisms. There are also similar devices to lock the rotating frame on the unload station and the loading mechanisms on the wheel-house loading area. For each of these there is the facility to use personel lock-off hasps and padlocks.

Photo-electric barriers

Photo-electric sensing devices act as safety barriers on a number of sections where manual work is or may be necessary. The interruption of the beam from an operational photo-electric barrier causes all dangerous movements in the relevant work area to be stopped via the systems hardware. This is an Emergency Power Off stop.

Type 3 robot collision protection system

Each type 3 robot on Stations 5, 6 and 7 has an electro-mechanical device on the end of the manipulator. This device has the function of protecting the robot, the weld tool and the workpiece in the event of a collision by immediately shutting down the robot by an emergency stop.

Factory C

Few safeguards are used in this factory. The main safeguard on all but one system is the curtain material around the whole station and the curtains across the jig tables. Other devices with some safety function are more concerned with sequencing motion, such as the interlocks on jig tables and the start buttons. Dark glasses are also provided for robot operators.

Robot system No. 6 has some extra safety features, for example the wire mesh fence. However, the sliding door could be open during robot operation and is wide enough to allow access around the side of the turntable. Moreover, one part of the fencing moves on its hinges, creating a 4 metre wide gap. A barrier of cloudy green plastic across the middle of the turntable is use, thus restricting the exposure of the operator to the bright light whilst loading the parts.

The interlock on the sliding door is another safety feature. The robot checks that the gate is open just before it stops at the end of its programme. It then waits for the signal from the closed gate and the magnetic contact before continuing on the programme once more. However, the motion of the robot is not affected directly by the action of this interlock.

A safety feature is incorporated into the weld torch design of the robots purchased after the first three. The weld torch is attached to the robot by a set of springs with a microswitch embedded in each. A small separation of one of these springs would result in a control halt of the robot.

Factory D

The most noticeable safeguard in Factory D is the all-surrounding wire mesh fencing with its access gate. The fencing forms a cage completely enclosing the robot and one side of the injection moulding machine. Other safety features linked to system design concern the interlocking of equipment to remove power from the system, particularly the access door and pressure sensitive matting. These interlocks ensure safety of personnel during any work within the robot system. Other interlocks are present to co-ordinate the movement of the equipment, particularly the robot and to prevent damage to equipment.

Two additional safety modifications were made to the robots. Each robot has a software restriction which requires the robots to be at a "safe start position" before the commencement of an automatic cycle. This eliminates the possibility of the reset button sending the robot to the cycle start position, perhaps through a collision with another piece of equipment, such as the expensive mould tools. The robot is driven to the "safe start position" under teach control before the cycle reset can be pressed.

The robots also have a "teach restrict" function - with the robot able to move at a creep speed only - on programming and programme repeat. This allows the programme to be run through at low speed without a serious danger of a collision.

Factory F

The safeguards on each system are mostly those provided in the original design by the commissioning companies. Little alteration to the designs has been carried out by engineers in the factory.

System I

The main safeguard on this system is the provision of a three metre high fence all round the system, made of one inch iron wire mesh. One access door is placed in this fencing, which is not interlocked to the operation of the system or even locked in any other way.

The loading areas have perspex screens which act as barriers in their down position. To load parts, they are pushed up, which leaves an area of about 1 square metre above waist height through which to load parts. Two limit switches sense both positions of the screen. A signal from either switch which signifies that a screen is in a raised position prevents the movement of the circular track via the overall controller's software. Since the screen is down only when the track is moving, it offers no protection to the sparks produced by the weld guns, as these are produced when the track is stationary. The loaders are provided with perspex safety visors to protect their eyes from the production of appreciable amounts of sparks.

The stands on which each robot rests whilst the track is moving have an interlocked limit switch which sense the presence of the robot. A signal that the switch is depressed allows the controller to commence movement of the track, again via a software interlock.

System II

The main safeguard for this system is the three metre high one inch mesh fencing. In this case, there is a locked access door but panels at the back of the system, that is away from the loading/ unloading stations can be removed with ease. The lock on the access door is connected to a light above the door such that the light comes on when the door is opened

The roller bars on the loading and unloading stations are interlocked with the motion of the rotary table. The robots are not prevented directly from continuing their tasks, but once a cycle is completed, the robots await the signal indicating that the table has completed its rotation before the next programme cycle can start.

There is a curtain of cloudy PVC within the fencing which is very effective in limiting the spread of the arc-flash. It also makes observation of the robots' performance difficult from outside the fencing. The spatter produced during arc-welding is also confined mainly to the area within the PVC curtain.

Each robot weld torch has a micro-switch in its connection with the robot arm which acts as an anti-collision device. If the torch gets stuck or hits an object, this switch immediately causes an alarm in the robot controls and stops robot motion via its embedded software. The robot has to be reset before the process can continue.

Factory H

The fencing in both systems in the company is made of wire grid for the first metre and then perspex for the rest up to a height of 2.5 metres. There is one access door in the outer fence with an interlock key mechanism. The robot controls and operator waiting area are within this door and are separated from the rest of the robot system by a one metre high fence made of sheet metal, with a second access door (also interlocked). Access to the system is controlled by this system of double interlocked doors. The outer must be locked before the robot can be turned on for warming up or for programming, whereas the inner door must be locked shut to enable automatic operation.

There is one emergency exit or access door in the fencing in System I and two in System II. 'Break glass' bolts are fitted to these emergency doors and to the normal means of access as a further emergency exit. Opening any of these doors by breaking the glass in the bolt causes an emergency stop.

Not all the safeguards were in position and operating on either system during most of the period of study. System I was the worst in this respect with no fencing until quite late in the study. However, three signs had been placed in the robot area saying "Do not assume the robot has finished its task just because it is stationary, ask the operator", "Do not enter while the robot is on" and "Never walk under the robot arm". It was clear that the actions which the signs were meant to deter could take place. No physical restraints on access existed at this time. These signs were placed in a less prominent position once the fencing was in place.

An area was marked out in black and yellow stripes showing the extent of reach of the robot arm in each system, but did not include the extension to the arm caused by the addition of the routing tool.

An "abort button" was installed initially on System I which when activated, sent the robot at high speed away from the panel and table to a set point in space. When this was tested, it was realised that it constituted a major hazard itself should it be activated when a person was within the fencing. It was replaced by a programme interrupt button.

The Hazards of the Robot Systems

A full quantification of the level of risk in each robot system is outside the aims and objectives of this thesis. Such a quantification would require a very detailed analysis of equipment failures, hazardous motions and processes and the consequences of close human contact with machinery which was capable of movement. A complete analysis warrants separate research, for which some of the findings of this thesis could prove useful. Nevertheless, an understanding of the hazards in each robot system included in this empirical study can be made. This understanding will assist the appreciation of the need for safety strategies and the implications of the failure to control certain hazards.

An indication of the levels of hazards in each system can be derived from the recognised hazards of robot systems (see Chapter 3). From this the main hazards to be controlled can be identified and a comparison made between systems.

It should be noted that this discussion does not look at the action of any safeguards or safety features in controlling hazards. The extent to which the safeguards act to control hazards and whether they are used as intended depends on the way in which the safety strategies in each factory are developed, implemented and then maintained. The effect of safety measures is therefore discussed as part of the safety strategies in Chapter 6. Table 5.3 gives the main hazards for each system. The hazards are described simply in this table, with general headings (for example the motion of equipment). Naturally, the precise hazards posed by each category in Table 5.3 is dependent on a number of factors concerned with system design and operation. For example the hazards posed by moving equipment depends on the dynamics of motion and the interaction between pieces of equipment and personnel at such times.

Any consideration of the hazards of a particular system has to include the operating conditions and procedures. Thus the hazards of the process are more severe where close proximity exists between the operating robot and workers than where a large separation can be expected. Thus the process presents greater hazards in Factory C and also to some extent in H. However in all other respects, the robot systems in these two factories pose less of a hazard. This is because these robots operate in relative simple and non-interactive systems. The level of risk rises when a system has more high energy equipment, with greater hazards from individual pieces of equipment and from the interactions between separate pieces.

The systems in Factories A and B have a separation between workers and the near automatic process but have a large amount of moving equipment which is capable of interacting in a number of unexpected or unforeseen

FACTORIES					
A	B	C	D	F	H
Motion of robots Jig truck or hoists. The by-products of arc-welding (e.g. fumes, 'arc flash', high voltages, spatter). Loading and unloading hazards.	Motion of robots Turnbucks or other transfer equipment. The by-products of spot-welding (sparks). Loading and unloading hazards. Manual welding.	Motion of robots, jig tables (in some systems) or turntable. The by-products of arc-welding (e.g. fumes etc.) Loading and unloading hazards.	Motion of robots or conveyors. The operation of injection moulding machine.	Motion of robots transfer equipment or rotary table (in System II) Loading and unloading hazards. System I The operation of the automatic equipment. The by-products of spot-welding (sparks). System II The by-products of arc-welding (fumes etc.)	Motion of robots or support table. The use of high energy tools (noise and the production of swarf).

Table 5.3 Main Hazards of Robot Safety Systems

ways. The systems in Factories D and F lie between in terms of hazards, with fewer interactions than A and B but more equipment than C or H. The systems in D are more linear and simpler, that is, the way in which the system operates is clearer and involves fewer occasions when equipment can come close to people or other equipment and result in an accident or damage. The systems in F are quite complex and involve a large amount of high energy equipment. No clear separation between personnel and equipment can be guaranteed because of the proximity of personnel to the system and the ease of access.

The hazards of loading and unloading are more conventional than those concerned with the operation of automatic equipment, but may be significant where these operations take place near equipment which can move unexpectedly. Interlocks which control the sequencing of operations with a system play an important part but it should be remembered that these are capable of failure. An unrevealed failure could prove more hazardous than no interlock at all. A full discussion of the hazards of loading and unloading would involve complex analysis, but the hazards can at least be identified for normal operation. Thus, loaders and unloaders in C and F are faced with the greatest risks because the automatic process continues close by. In the other systems loading is either automatic or separated from the automatic actions of machinery.

Where manual action can substitute within the system for the automatic equipment, the workers who do such actions are faced with greater hazards than those solely from their own actions. Certain automatic equipment in their vicinity can be expected to be still operating. Thus, the ability to substitute for robot welding in Systems 6 and 7 in Factory B present high levels of hazards for the manual welders.

In summary the robot systems in A and B have high levels of potential hazards associated with them, but these are controlled by the separation achieved by system design. Hazard levels rise in B when manual workers substitute for the robots. The systems in C offer little separation from the hazards although these hazards are less severe. In D, the hazards are well limited by system design. In F, the level of potential hazards is quite high and less control is provided by system design since loading takes place near the automatic equipment and access can be gained with ease. In H, close proximity between equipment and personnel is possible, but system design is very straightforward and thus hazards are not very severe. Thus it would appear that the hazards posed in Factories C and F are higher than elsewhere, because of the possible proximity of people to operating equipment. However, the higher risk levels in A and B would become relevant if close proximity occurred in these systems for prolonged periods.

Working Practices

Table 5.4 gives the personnel in each factory who work with the robot systems. The number of personnel in the table is the maximum present at any time.

Factory A

Operators

Loading involves placing 22 separate parts in their correct positions on the jig truck. Parts are clamped manually in the first instance with pneumatic clamps engaging once the operators have withdrawn. Once the loading procedure is completed the jig truck is ready to enter the first section. The loaders then wait until the first section's welding is complete and the jig truck returns to the loading area. The process of loading is then repeated.

The parts have to be carried across a large section of the factory floor. Some parts are heavy and a 30 centimetre step at the edge of the loading area compounds these problems.

The unloading process requires two workers to index the parts off the end of the system with the use of a control button. Once the part is far enough out of the system, it is fastened to a crane and lifted clear.

Maintenance

The maintenance team have to enter the robot system frequently to repair, make alterations or simply to reset equipment. Formal practices state that the relevant section of the system has to be disabled before

FACTORIES					
A	B	C	D	F	H
2 Loaders 2 Unloaders 4 Maintenance workers (2 electricians, 2 fitters) 1 Maintenance foreman	8 Loaders 2 Unloaders 12 Maintenance workers (electricians and fitters) 1 Maintenance foreman (for whole welding and assembly area)	7 Operators 2 Welding foremen 2 Maintenance electricians	No operators Maintenance workers (number unspecified)	2 Loaders (System I) 1 Loader/Unloader (System II) 1 Leadinghand 2 Chargehands Maintenance teams 1 Production Engineer	2 Production Engineers 2 Operators 1 Robot Instructor

Table 5.4 Personnel on the Robot Systems (maximum number of each grade at any one time)

this work is done. Entrance into the system is through the interlocked access doors. Once a problem is solved, the access door is relocked and the key returned to the master panel so that the system can be restarted. The Safety Engineer issued a notice to the maintenance team near the beginning of the study to reinforce this formal practice.

Certain routine tasks are made difficult or impossible to perform by this procedure. The robots are the only equipment enabled when the access doors are open and so diagnosis of certain faults and the adjustment of operation cannot be performed wholly effectively.

Formal practices were altered to make it possible for work to be done according to a set of agreed procedures. This change was instigated by the Safety Engineer. Each maintenance worker had to sign a Permit to Work form at the beginning of each shift. This allowed him to "enter the perimeter guarding of the Robot Line, to observe and make minor adjustments under controlled conditions". This was to be signed by the Safety Engineer each day. Protective clothing was to be worn, in the form of a "close fitting single piece overall" with no loose or flapping pieces, a bump cap and appropriate eye protection. The procedure for work was laid down explicitly, stating that in both automatic and manual modes, the authorised person enters using the interlock mechanism and "at no time must the key system be circumvented or abused". A second authorised person locks him in if necessary and then watches from a suitable position, to hit an Emergency Stop button if necessary. The person inside the system then performs any tasks considered necessary.

These working practices were considered to be within the terms of reference of the Unfenced Machinery Regulations (HMSO, 1938 (SI No. 641)) as amended in 1976 (SI No. 955). This statutory instrument allows maintenance workers to work within a dangerous operational system under controlled conditions (see Chapter 2). However, in this system access under these circumstances was not always essential and it seemed that ease of use was the predominating motive for the working practices rather than immediate necessity.

The maintenance team worked with the robot system in a confident manner borne of their extensive experience. It was clear that maintenance workers carried out reprogramming with good attention to detail and at a slow pace.

Factory B

Operators

Most of the loading of parts takes place in Station 5 and consequently this is where the majority of operators work. There is one operator for each Turnbuck. The loader clamps the parts in place with small manual clamps, retires from the area protected by the photo-electric (p-e) guard and presses a button, which initiates the rotation of the turnbuck.

In the wheelhouse loading area the loader clamps the parts onto the jig and retires from the area across which the photo-electric sensing device operates. The process is then automatic. The unloading at the end of Station 6 and 7 is performed by two people on each station. They lift the finished panels off the automatic unloader and place them on a travelling hoist transfer system.

Maintenance

A safe system of work was devised for these workers. This is presented in flowchart form and displayed prominently throughout the area. Manufacturing and Plant Engineering personnel devised this system and fulfill their requirements of informing the workers of its application. The plant safety committee and the Factory Inspectorate were both involved in the later stages of the system of work's development. Both bodies found it acceptable.

This system of work requires the maintenance workers to use the various safety features (e.g. locking pins on the shuttle transfer devices and the lifter tables) before they enter any section of the stations to perform any repairs or adjustment. Lock-off hasps and padlocks were to be used to prevent the removal of the lock-pins. The only possible motions under this system would be from the robots under teach control or the lifter table on reduced speed.

Factory C

No formal statement of working practices is given, although a training notice contains some such information for operators.

Operators

The number of these workers varied during the study, according to the number of robots in use and the level of orders. There was a general trend for an increase as more robots were introduced. Twelve operators, all full-time employees, worked a two shift week on 6 robots at the beginning of the study. Later, short-term workers were employed on 3-monthly contracts. Most of the full-time workers were then moved onto manual welding.

The major part of the work of the operators involves the loading of components onto the jig table and clamping them down, signalling to the robot to weld them by pressing the start button, then unloading the welded part once the robot has finished. Two jigs are used on all but one system, so that the operator can unload the finished part and load components whilst the robot is working. The turntable arrangement in No. 6 achieves the same function.

The operators' tasks are highly machine-paced. The actions performed by operators in loading and unloading parts have a regular pattern with a short cycle time. These actions are likely to lead to a 'pre-programmed' mode of behaviour, as described by Kay (see Chapter 2).

The operators are also required to carry out some minor tasks to deal with production problems besides their loading and unloading tasks. These other tasks include the changing of the weld wire, the freeing of the wire when it becomes stuck in the wire feed or welded to the part and the cleaning of the plastic cover to the weld torch. Other tasks for the operator mainly involve problems with the weld wire. Sometimes these can be put right by the operator, but can also involve the foremen coming to reset the robot. The operators' repair tasks are mostly of short duration, lasting typically a few minutes.

Foremen and electricians

The most frequent tasks required of these workers are the resetting of the robot after some control halt or emergency stop condition, or reprogramming the robots. These two tasks contrast in the amount of time required. The resetting takes a short time, with some subsequent observation of the process to check that the same conditions do not recur. Programming can take several hours or days if a major change is required. In both cases the welding action is observed after completion from a position of close proximity to the robot. No eye protection is worn on these occasions.

Factory D

The only workers meant to have any close contact with the robots are the maintenance workers, who carry out all necessary maintenance to the production equipment in the factory. Precise details of their tasks are not available, nor were these workers observed at work on the robots. Their tasks are mostly reactive with the occasional replacement of parts which appear susceptible to problems or failure.

The maintenance workers were allowed to perform their tasks independently. Reprogramming is also poorly controlled and documented, being performed by a number of people, often in different ways.

Factory F

Loaders/unloaders

On System I the loaders have clearly defined tasks and work areas. They load parts onto the jigs adjacent to the two loading areas. When the workers have finished loading parts, they bring down the perspex screens. This allows the track to move parts forward by one station. One operator also has sequence stop and start buttons for periods when production is halted. The pressing of the start button will only start the process again if all the interlock switches are giving the correct signal.

On System II the loader/unloader has to unload finished parts and load unfinished parts onto the rotary table. The normal sequence is to wait for the rotary table to turn and move parts forward one station, then to push in the roller bar on the load station. The unfinished part is placed on the jig and clamped down manually. The roller bar on the unload station is then pushed in and the finished part is released by removing the manual clamps. The roller bars are pulled back out and the pneumatic clamps go on the new part. Once the welding has finished within the system, the loader/unloader presses the start button and the table indexes once more.

Chargehands and leadinghands

These are the first-line supervision and are required to carry out the majority of repairs and adjustments. The chargehands supervise with the leading hands, who act as a form of 'deputy' for first-line supervision. On System I the chargehand is very closely involved in the running of the system. A number of events occur frequently, which are minor but require attention from the chargehand to keep production going.

On System II, there is a senior chargehand over the whole production line as well as a chargehand who is involved with the final welding system. The latter chargehand is more likely to be called to sort out a problem. A number of frequent but relatively minor events occur with this system.

Formal company policy, as agreed at safety committees, has been to allow entry within the installation only if properly supervised with services and maintenance involved when necessary. The required mode for the robots or other equipment during such periods is not specified. Formal practices do not specify how hazards can be minimised, only that someone should observe the actions from near an emergency stop button. It is clear that a great deal of reliance is placed on informal instruction and reasonable behaviour on the part of individuals.

Maintenance and production engineers

These are not called upon frequently. There are no formal practices for these workers specific to these systems. Maintenance are expected to repair major faults and as such are expected to have the system powered off.

Production engineers are mostly involved for programming problems. The system is also taken out of production for this test.

Factory H

Production engineers

The Production Engineers' tasks do not require close contact with the robots. Their work requires liaising with the robot operators and checking on the performance of the systems. During periods of testing of tools the engineers assess the changes required to achieve more accurate parts.

The operators

The operators' tasks are laid down in the Safety Booklet for robot use produced by the Division. Working practices for the operators are divided into three sections, for powering up the system, for teaching the robot and for automatic robot production. Each set of actions is given in detail, along with instructions to minimise risks. For example, operators are warned not to go beneath the robot arm whilst it is in teach mode and always to keep the teach pendant with its emergency stop at hand whilst in the system.

Another important feature of the formal practices is the removal of all power from the robot during any maintenance work. The robot systems have been designed so that these formal practices can be introduced easily.

Training

Table 5.5 summarises the provisions given for training personnel in robot use in each factory. Training provisions are discussed in more detail in Chapter 6.

FACTORIES					
A	B	C	D	F	H
16 Engineering, maintenance and supervisory personnel sent on a two-week course at the robot suppliers site.	Extensive training for personnel at company's own training centre.	Foremen trained in programming. Maintenance electrician trained in programming and rudimentary servicing. Intensive maintenance course for 1 electrician. (Courses at suppliers site). Operators receive on the job training.	Numerous maintenance and works engineering personnel on four day course, three days of which were on site. Trade Union Representatives also trained.	Patchy training for chargehands. Some given training on wrong robot type. Maintenance personnel trained on basic equipment maintenance. Training at suppliers site.	Formal one week robot training given by supplier at supplier's site. Robot instructor established to provide continuous means of training.

Table 5.5 Training Provisions

Accident Statistics

Accident statistics from the robot systems studied were rare. None of the factories collected accident information specific to the robot systems and in the majority it was claimed that accidents with the robots had not occurred. However data on accidents specifically with robot systems was gathered from two, Factories C and F.

Factory C

Accidents with the robots were mainly minor complaints, such as arc-eye. Indeed arc-eye was the most common cause of lost time for manual arc-welders and robot operators. Reported cases of arc-eye came to 15, out of the 27 recorded incidents resulting in lost time from industrial causes in 1983. There were about 40 manual welders and between 12 and 19 robot operators. One would expect a large number of incidents to involve the manual welders. In fact 16 out of the 26 recorded incindents involved manual welders, but only 7 of the 15 cases of arc-eye. This suggests that robot operators are more exposed to this hazard of arc-welding.

Other accidents with the robot systems involved injuries to feet and back problems. These were associated with lifting actions and in one case with sparks from the welding process.

Factory F

Accident records at this factory showed a large number of problems with the use of robots. The surgery treatment book showed over 45 cases involving cuts, particles in the eyes or cases of weld flash in the year of the study (1983). A number of more serious cases are recorded in the book for cases requiring hospital treatment. The majority of these were on System I:-

Three cases of sparks in the eye
One case of grindings in the eye
Two cases of hand trapped, once by a clamp, the other by a set of weld guns (not necessarily on a robot).
One case of being struck on the head by the gate on the loading area - a connecting bolt came loose

On the rear cross member line (including System II) two cases occurred:-

One case of a broken toe caused by dropping a part whilst loading

One case of a slight injury to a persons head within the installation as the person stood up.

In all, 24 accidents occurred in this factory, so these nine accidents constitute 37.5% of all accidents in this period (1/1/82 to 6/10/83). Less serious incidents on the robot systems were mostly cut fingers, burns, cases of weld flash or arc-eye and grit or sparks in the eye.

One accident was reported which did not result in injury but nevertheless is a significant incident. It concerned a worker who was in an arc-welding robot system when the turntable rotated. The equipment collided with the worker and knocked him off his feet. It appeared that another person had started the system without realising that the other worker was within it.

PRODUCTION PROBLEMS

The data on interruptions to production, their means of collection and the types of systems studied have been described in Chapter 4, which show that the performance data collected from each factory were not uniform. Comparable data were produced in 4 of the 6 factories, covering periods of production on 7 robot systems. These 7 systems represented 70 robots, as shown in Table 5.6 below:

Factory	No. of Robots Covered	Task
A	12	Arc-welding
B (Station 5)	8	Spot-welding
(Station 6)	23	Spot-welding (22) Adhesive bonding (1)
(Station 7)	23	Spot-welding (22) Adhesive bonding (1)
F (System I)	2	Spot-welding
H (System I)	1	Routing
(System II)	1	Routing and drilling

Table 5.6 Systems with Comparable Robot Performance Data

Data were collected about incidents which resulted in interruptions to production. The data categories are given in Chapter 4. The results of this data collection are discussed and analysed in the following sections. First, the frequencies of occurrence of each variable in the basic data collection format are discussed. Secondly, the data is re-presented in terms of a classification of the severity of incidents, with an analysis of the frequencies of the resultant downtime and the underlying reasons for each classification category. Thirdly, more detail is provided on the underlying reasons for problems in each system. Downtime caused by each underlying reason is considered. Fourthly, more detail is given for robot related problems. Variation in frequencies of robot related problems between robot systems and between robot types are considered. Fifthly, robot failures are given further consideration, with the Mean Time Between Failures for systems and robot types being calculated. Sixthly, the distribution of downtime periods is considered in terms of three groups - short, medium and long duration and also in a fuller consideration of the distribution of downtimes.

Safety problems are linked to both the performance data and the case study information. Thus the discussion of safety problems arising from the performance data also deals with points raised in the case studies. The relevance of the results of the performance data to safety problems forms the final section of this chapter.

A number of differences between robot systems or types are highlighted in the subsequent analysis. The significance of these differences are tested in a statistically rigorous manner in Appendix J, to which the text refers where appropriate. Spurious differences or apparent similarities are identified by these statistical tests.

Missing periods of production were most noticeable in Factories B and F, largely because of variable reporting between workers on adjacent shifts. In particular, night shift operation was poorly documented. This correlates with a lower presence of senior supervisory personnel at such times.

System	Calendar Period Covered	Number of Periods of Production Covered*	Total Production Hours
A	5/7/83-15/12/83	92	629
B5	15/8/83-25/11/83	94	745.5
B6	15/8/83-25/11/83	128	1077
B7	16/8/83-25/11/83	122	974.5
F(I)	14/7/83-16/1/84	139	1166.5
H(I)	23/5/83-23/12/83	89	675
H(II)	12/12/83- 6/4/84	74	577
		Total	5844.5

Table 5.7 Periods of Production Covered in the Empirical Study

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*Production Periods are the lengths of time over which continuous production took place. These varied between factories. They were generally in the range of 7½ to 10 hours, but in fact are not a particularly important measure of the collected data. The hours of production for the study represent a more significant measure.

The Periods of Production

In each system, the periods of production covered by the data span several months. However, it did not prove possible to obtain a set of records for any system with no missing production periods, because of difficulties in persuading individuals to keep records and the problems of record retrieval. Table 5.7 presents the periods of production covered.

The study spanned a period of roughly 10 months, in the second half of 1983 and in the first quarter of 1984. The vast majority of data was collected in 1983, with data for only one system collected mainly in 1984 (H(II)). From Table 5.7 one can see that a total of 5,844.5 hours of system production hours have been covered by the performance data. This can be expressed in terms of robot production hours for each system, as in Table 5.8 below:-

System	Production Hours	Number of Robots	Robot Production Hours
A	629	12	7548
B5	745.5	8	5964
B6	1077	23	24771
B7	974.5	23	22413.5
F (System I)	1166.5	2	2333
H (System I)	675	1	675
H (System II)	577	1	577
Total	5844.5	70	64281.5

Table 5.8 Production Hours Covered in Each System

Note: Total robot production hours is not the product of the total number of robots and the total production hours, but the sum of the products of these two parameters for each system.

The previous three tables show that spot-welding applications predominate, both in the number of robots covered and in the robot production hours. In all, 54 robots were used for spot-welding applications, giving a total of 53,430 robot production hours. Thus, 10,851.5 robot production hours (or 16.9% of the total) deal with other applications. Of this 16.9%, a majority is from the arc-welding application in Factory A (over two-thirds).

One can differentiate the robot production hours between robot types. Table 5.9 gives the production hours for each type of robot in each system. (For the distribution of types of robots in each factory see Chapter 4). Once more, the robots in Factory B dominate the robot production hour figures, but their influence is spread across three different robot types. Type 4 robots have the most hours of production, due to the large number in systems B6 and B7. Although the number of robot production hours in Factory H is quite small, the data from Factory F is for the same type of robot. Thus, each type of robot has a fairly large sample of production hours as a sample base for the analysis.

The Analysis of the Production Problems

1) The overall frequencies of problems

The complete frequency tables for each robot system are given in Appendix D. These give the resultant downtime, and the frequencies for each entry on the records. In each system the figures for incidents involving the various robots are also presented separately. Thus, the results form a matrix of percentages of the incidents in each factory. The total number of incidents is given in the top left hand corner of each table.

The tables are divided into sections that correspond to the types of information gathered. The first section gives the number of cases, those without downtime figures and the recorded downtime. Below this are sections for percentage of incidents involving the various actions, the reasons for actions, the means of interruption, the classification of incidents, the personnel involved in first identifying and secondly sorting out the problems and finally the underlying reason for each incident. The percentage figures given in these tables are of the number of incidents in each vertical column.

Robot Systems	Robot Type				Total
	1	2	3	4	
A	7548	-	-	-	7548
B5	-	-	5964	-	5964
B6	1077	-	4308	19386	24771
B7	974.5	-	3898	17541	22413.5
FI	-	2333	-	-	2333
HI	-	675	-	-	675
HII	-	577	-	-	577
Total of Production Hours	9599.5	3585	14170	36927	64281.5

(For an explanation of the robot types, see Chapter 4)

Table 5.9 Robot Production Hours Covered by the Study for Each Robot Type by System

Downtime

Table 5.10 gives a summary of the overall downtime figures, showing that there is a large number of incidents in each case study. A high proportion of the system production hours is lost in each case, giving an overall figure of 20.8% of all system production hours. However there is some variation, from 31.4% in Factory A to 12.6% in Factory B (System B5). These figures give a production availability of between 68% and 88% for the robot systems.

The design of the robot systems in B5 made it particularly difficult to estimate availability for production since downtime could not be attributed easily to independent production items. Some problems would put all eight robots in B5 out of action, whereas some would affect only a half of them or even just two robots operating together. Problems with one robot could affect that robot alone or affect others. Downtime records did not provide sufficient information to draw a distinction between these different ways of affecting system performance. The figure given in Table 5.10 for downtime as a percentage of production time is therefore an overestimate since they assume that the system is always affected as one unit.

One can see that the downtime is an underestimation in each system, since some incidents have no recorded downtime. This is rarely because no downtime was involved but because no figure was clearly stated. This problem is particularly marked in Factory A and System B5, where barely 50% of all incidents have downtime recorded. The type of incidents involved in these lost cases are generally routine tasks. The failure to report downtime was found to be linked strongly to short interruptions and so it is likely that only a small percentage of the total downtime has been lost as a result. Overall then, the author feels that the downtime records are a good representation of the downtime in these systems.

The variations in system availability are related to the system design and the task. Factory A is the only example of an arc-welding system and has low availability whereas the spot-welding systems (B and F) have a closer band of downtime statistics. This suggests that arc-welding is a more difficult task for a robot to perform, although all the robot systems show signs of inability to cope with continuous

Company	Number Robots Studied	System Production Hours	Number Incidents Recorded	No. of Incidents with Downtime Recorded	Downtime as % of Production Time	System Downtime (Mins)
A	12	629	743	386	31.1%	11745
B5	8	745.5	662	370	12.6%	5654
B6	23	1077	1553	1350	18.5%	11930
B7	23	974.5	1820	1519	18.7%	10951
F	2	1166.5	811	805	27.8%	19486
H	2	1252	13	11	17.4%	13080
Total	70	5844.5	5602	4441	20.8%	72846

Table 5.10 Overall Downtime Figures

production. System design in A also shows some problems not directly connected with the task, for example the difficulties of access within the system.

Factory H has a completely different downtime picture, with high downtime for the systems from very few cases. The table for H in Appendix D shows the availability figures are 26.5% for System I (10740 minutes in 675 hours) and 6.8% for System II (2340 minutes in 577 hours). The percentage of downtime is high even for System II, particularly if one considers that it is produced by only 5 incidents. The vast majority of downtime in both systems arises from 3 exceptionally long downtime periods, one of 172 hours (22 days) in System I and two of over 1 shift period (11 and 16 hours) in System II. Thus the task and system design in H produced problems which were nearly all severe.

Variations in availability need to be tested statistically before variations can be shown to be significant. Since the availability is the product of the number of incidents per production period and the mean downtime of those incidents, the statistical significance of variations in these two parameters decides the significance of variations in availability figures. Both of these parameters are considered below, with the statistical significance of each showing that the variations in availability are also significant.

A feature of the summary table of overall downtime figures is the apparent similarity between two systems which are identical in design, namely B6 and B7. Both have about 18.5% of production time lost as downtime. However, B7 has more incidents per system production hour (nearly 2), whilst B6 has roughly 1.5 per hour. Both these systems have more incidents per hour than any of the others, with only Factory A's figures also producing more than 1 incident for every production hour. The overall mean value comes out as just below unity, at 0.96 incidents per robot system production hour.

Appendix J gives a statistical test for the number of incidents per system production period, giving a X^2 value of 2397.85. This is well in excess of the critical values of 15.09 for a significance level of 0.01 and thus the test shows a statistically significant difference between the systems. The X^2 value for the 5 systems excluding H is also very high at 711.60, well above the maximum acceptable value of 13.28. Even for B6 and B7 alone, the value for χ^2 was 56.37, compared with 6.64 as the maximum acceptable. Thus each system differs significantly from the others in terms of incidents recorded per production period, even though some limited similarity can be observed between B6 and B7.

That systems B6 and B7 should have high frequencies of incidents yet still have a high availability suggest a rapidity in solving problems involved in the incidents. This can also be seen in the low means of downtime. The case study shows that the robot systems were designed for ease of safe access to the system and that well trained experienced maintenance workers were continuously on the systems. Thus the system design, work organisation and personnel training in B6 and B7 assist to produce rapid solutions to problems.

In each system with a large number of robots (A, B5, B6 and B7), the number of incidents and the downtime recorded for incidents associated with each robots vary in a largely unpredictable fashion. A quick glance through Appendix D will show that some robots have considerably more incidents associated with them than others, and thus have more downtime linked to associated problems. However, the variations in the number of robot related incidents per robot were not significant in 3 systems - A, B5 and F (see Appendix J). In A, the χ^2 value was 5.5, less than the critical value of 9.2 at a significance level of 0.01. In B5 the calculated value of 17.3 was just below critical value of 18.2, and in F the calculated value was 3.8 compared with the critical value of 6.6. In B6 and B7 the calculated values are well in excess of the critical value, being 235 and 373.3 respectively, compared with a critical value of 40.3.

In this consideration, B6 and B7 show a greater variation than the other systems. In only these two systems are there significant differences in the frequency of incidents associated with each robot. One can conclude that the system design in B6 and B7 produces an uneven geographical occurrence of incidents. Elsewhere, incidents are as likely to be associated with one robot as any other. The robots in B6 and B7 also show some significant variation in the t-tests on the downtime associated with robots (Appendix J), but for only 8 in B6 and 7 in B7. This provides further support for the conclusion that the system design in B6 and B7 causes an uneven spread of incidents.

The overall mean downtimes varied from one robot system to another. The two systems of identical design, B6 and B7 were very close in the overall mean downtime, but B5 had a value which was nearly twice as great. Each of the other three factories had mean downtimes well in excess of those in Factory B. It is not surprising to find that the robots in Factory H have the highest means, considering the discussion on the pattern of downtime above. A t-test of the downtime in each system showed that there was a significant difference between each system except A and B5 (see Appendix J).

The similarity between A and B5 is somewhat unexpected, since the means do not appear to be very similar (30.7 minutes for A and 15.3 minutes for B5). However since logarithms values of downtime are taken for the significance tests (because of the log-normal distribution of the downtime, see below),these two systems are shown to have a similarity. There is no clear explanation for this phenomenon, since the systems have little which makes them comparable.

In summary, the downtime records for the systems show that a large number of incidents and high unavailability occur. System availability is correlated to some extent with system design and task, with significant variations between the systems. The two most similar systems, B6 and B7 show some limited similarity in downtime records and differ from the other systems by having a significant variation in spread of incidents throughout the systems.

Even though B6 and B7 had the highest number of incidents per system production hour, they still managed relatively high system availability figures. This can only be explained by the rapidity of problem identification and solution in Factory B. This in turn signifies effective system design, work organisation and personnel training, all of which would appear to be the case in Factory B.

Finally, the systems differ significantly in terms of mean downtimes. This emphasises once more that system design, task and work organisation are major factors in deciding the duration of individual interruptions to production.

The Actions Taken

The second section of each table in Appendix D presents percentages of incidents involving eight types of actions. Table 5.11 below gives a summary of the tables. The figures for all incidents in each system and also overall are presented in vertical columns.

It will be seen that the totals in Table 5.11 do not add up to 100%. This is because an incident could result in several different actions being performed in one downtime period. For example, a problem with an arc-welding torch may involve unplanned maintenance, resetting of equipment and even in some cases replacement of faulty equipment within the torch or the weld unit. If the maintenance or equipment replacement has altered the spatial co-ordinates of the end of the torch then some reprogramming work may follow. The discussion below is concerned solely with a discussion and analysis of the differences between systems and not with tests of significance to any differences. This is because each category is not completely independent of other categories of actions and as such is not suitable for statistical significance testing.

The types of actions in each system are strongly linked to system design and the process performed. For example, the design of the system in Factory A made observation difficult and increased the need to carry out unplanned maintenance, whereas elsewhere minor adjustments were more frequent. The problems of arc-welding also increased the likelihood of equipment resetting following a weld failure. In B5 the preponderance of actions other than those specified was due to the need to key model variations into the controls. Such actions resulted in very short periods of downtime - one or two minutes - but occurred every time a change to the parts being spot-welded was required. In Factory H the robots needed regular reprogramming because of the requirements of high accuracy and the number of different parts. (These additional periods of programming work are not shown as interruptions to production because they were set aside from production).

An overall pattern is visible, even with the many differences between the systems. Certain actions are frequent in nearly all systems. Resetting actions occur most often in all but one system. Adjustments and cleaning and unplanned maintenance (considered together) are also

	A n = 743	B5 n = 662	B6 n = 1553	B7 n = 1820	F n = 811	H n = 13	Overall n = 5602
Replacement of faulty equipment	3.6	7.9	17.0	13.7	22.8	23.1	13.9
Adjustment/Cleaning	7.1	29.3	19.3	25.7	50.3	30.8	25.5
Resetting	72.5	42.0	56.7	58.6	41.2	7.7	53.3
Reprogramming	7.8	4.2	6.0	4.9	7.6	38.5	6.0
Routine maintenance	2.0	2.7	4.8	2.5	22.3	-	6.0
Unplanned maintenance	67.4	19.2	29.2	21.4	11.1	38.5	28.0
Fault diagnosis	5.9	2.9	1.4	2.0	1.0	23.1	2.4
Other	6.6	20.8	1.5	1.5	6.3	7.7	5.2

Figures show % of incidents in which specified actions are taken.

Table 5.11 Actions Taken in Each Factory frequent in each system. Replacement of faulty equipment was the fourth most frequent action overall, especially in the systems on the right of Table 5.11 (B6, B7, F and H). Once more the demands of production systems incorporating robot technology for corrective action to ensure production are evident.

One can see a great deal of variation in Appendix D, between the percentages of actions associated with incidents involving robots and where no robot was involved. Those incidents not associated with any robot have a lower percentage than overall for incidents requiring resetting, reprogramming and also unplanned maintenance in some systems. Resetting and reprogramming can be seen to be linked to the needs of robots rather than the system as a whole. Robots also are more prone to unforeseen need for maintenance. However there are some differences between the systems.

Factory A shows a high frequency of adjustments and cleaning for actions not associated with robots and also for 'other actions'. Other actions were also frequent for robots in the first section of the system. These other actions were often concerned with inspection. Certain robots are also associated with a relatively high occurrence of reprogramming tasks (3, 4, 7, and 8) and fault diagnosis (7 and 9). Thus inspection and problems with the quality of the product are more associated with the systems performance, while the requirements for accuracy caused difficulties for certain robots.

In B5, those incidents not associated with any robot are roughly identical to the overall figures, except for reprogramming and other actions.

In B6, those incidents with no robots involved have a slightly lower percentage for the replacement of faulty equipment than the overall figures, but double the percentage for routine maintenance. Therefore system B6 has a more frequent replacement of faulty parts in robots than in other equipment in the system and less need for planned maintenance of the robots. One can conclude that the number of robots influenced the former characteristic and that a practice of responding only to actual faults with robots decided the latter. Resetting is as frequent for incidents associated with robots as for those which are not. The whole system needed to be restarted after an interruption to the sequence, as well as the robots.

Incidents in B7 have a similar pattern to those in B6, but differences do exist, in that resetting is more common for incidents with no robot involved than overall. Thus the whole system is more likely to be out of sequence or synchronisation than the robots. Fault diagnosis is particularly common with two robots in B7 - in B6 three robots required frequent fault diagnosis actions. Thus certain robots had problems which were not easily recognisable.

In F there are more incidents of routine maintenance, replacement of faulty equipment and the inspection of the quality of the process where robots are not involved than overall. For those incidents associated with robots, there are far fewer cases of actions of adjustments or cleaning. Thus other equipment has more failures and need for maintenance or adjustments than robots. Other equipment therefore appears to be more problematic than the robots.

In H all incidents involved one of the two robots, since the systems were quite simple and were built around each robot. However there was some variation between the actions taken with the two robots, albeit from a small number of incidents. Three actions were more frequent with robot No. 1 - the replacement of faulty equipment, reprogramming, fault diagnosis with other actions occurring only with robot No. 1. The remaining three actions occurred either solely or more frequently with robot No. 2. From this it would appear that robot No. 1 was more prone to involved problems.

This information on actions taken therefore shows that the robot systems needed frequent attention for simple tasks and that robots were more prone to unforeseen problems. Variations in system design and system requirements are responsible for some of the variations between the systems in the actions taken.

Reasons for actions

The third section in the tables in Appendix D gives the percentages of reasons for the actions with each incident. As in the previous section, the figures given are percentages of the number of incidents with each category and add up to more than 100%. In other words, there may be more than one reason for any incident. For example, a problem with spot-welding may be one of quality of the parts or mechanical or electrical problems with the robot. It may also be necessary to undertake some inspection of the process before sorting out a weld failure (as in Factory A), which in itself is largely a mechanical problem with the robot and its associated equipment. The reasons given here are those for the actions, either explicitly stated in the production records or in discussions with the researcher. They should not be confused with the underlying reason for incidents, which are mutually exclusive and are a judgement of the cause of an incident. Table 5.12 gives the overall percentages for each reason in each robot system.

Variations between robot systems are too large for the overall column to correspond to an overall trend. Thus there are major differences caused by process conditions and system design.

One of the most striking differences is the high frequency of inspection as a reason for action in Factory A but a far lower frequency elsewhere. The frequency of weld failures in this system are also found to be very high. With a system design that prevents outside observation, the first purpose of any action to correct a weld failure is to inspect the problem. This differs from the other systems, where rather than an inspection being required where full details are not known, fault diagnosis is undertaken.

Another large variation from the overall figures occurs with quality problems in Factory F. The high frequency here is due to the stringent requirements for dimensional accuracy and problems with the production process, both within the robot system and elsewhere in the process.

In B5 the other reason category constitutes nearly 20% of cases. This matches closely with the 20.8% given for the Other category in the Actions Taken and were due to the need to key in model variations.

Nevertheless, the overall figures show a concentration on 5 reasons for actions; mechanical or electrical problems with robots or other

	A n=743	B5 n=662	B6 n=1553	B7 n=1820	F n=811	H n=13	Overall n=5602
Mechanical problems with robot	55.2	16.8	44.4	42.6	13.9	15.4	37.5
Mechanical problems with other machinery	26.2	51.2	43.3	42.5	43.5	30.8	41.7
Electrical problems with robot	3.2	10.4	29.6	27.4	16.2	23.1	21.2
Electrical problems with other machinery	8.3	36.3	31.3	30.9	18.0	-	26.7
Electrical problems with interface	4.7	4.5	2.5	5.2	3.1	-	4.0
Inspection	59.0	1.5	1.0	0.5	3.2	-	8.9
Programme problem	3.2	1.4	0.5	2.2	1.8	15.4	1.7
Quality problems	7.5	12.5	10.3	16.3	42.9	-	16.9
Erratic robot	0.5	-	3.0	0.7	1.6	7.7	1.4
Dropped part	0.5	0.2	0.1	-	0.2	-	0.1
Threat of damage to:-							
robot	1.2	0.2	0.4	0.5	5.4	7.7	1.2
persons	-	-	-	-	0.2	-	0.04
machinery	1.6	0.8	0.9	1.0	3.0	15.4	1.3
Any other reason	1.3	19.9	0.7	0.9	3.2	7.7	3.5

(Figures show percentage of incidents in which reasons were given)

Table 5.12 Reasons Given for Incidents in Each System machinery and quality problems. This concentration is fairly uniform across the systems. These 5 reasons are the only ones to be given in more than 10% of incidents overall. Inspection comes close to the 10% mark, but that is solely the result of the disproportionately high in frequency in A. Thus the immediate reasons were concerned in the main with poor behaviour of robots or other equipment.

There is a great deal of variation in the reasons given in each table in Appendix D, with many reasons appearing only with some robots or only with incidents not associated with any robot. For example, few problems with other machinery occur in incidents associated with robots. This is very much as one would expect, since incidents involving robots would tend to have mechanical or electrical problems with the robots themselves and not necessarily also with other machinery. Cases of electrical problems with the interface between the robots and other machinery are rare, involving only a few robots in most systems (A, B5, B6 and B7). The systems in H do not have a controlling interface between the robots and other machinery and thus problems of this category could not arise. Among the other reasons, the most ubiquitous is quality problems, with all but 11 of the 70 robots being affected to some extent. Variations in the percentages are considerable, even within the same system. This does not necessarily mean that those robots with higher percentages for quality problems are more problematic in their operation, since the processes involved place different requirements on the robots. Some robots have more difficult tasks to perform which are more critical to the quality of the finished product.

To summarise, the reasons given are concerned predominately with equipment performance. Variations between the systems are caused by the differences in system design and task. Variations between robots in the same system can be seen as the result of the different requirements of each robot.

The means of interruption

The fourth section of the tables in Appendix D deals with the means of interrupting the process. Table 5.13 gives a summary for each system.

The overall figures show that personal actions form a minority of means of interruption, with emergency stops being used very rarely. However, where emergency stops are used, there is an indication of hazard - not necessarily that an accident or damage has actually occurred, but that these are a distinct possibility.

In A, the three cases of emergency stops occurred within a period of two days and are all connected to a sequencing problem. On one occasion there was also a possibility of damage to machinery.

Four incidents of the use of emergency stops occur in Factory B. The incident in B6 results from an erratic robot which is stopped and reset. The three in B7 are all for more spurious reasons. Two are simply human error, in pressing an emergency stop button. The third is due to the presence of a maintenance worker within the fencing.

In F, as many cases of the use of the emergency stop occur as in all the other 5 systems combined. Six are fairly minor incidents involving broken tools, over-run of the jig trucks or incorrect welding. The other two incidents are more serious. One involved a sequence fault causing a robot to lift the circular track on which parts are transported. The track began moving whilst the robot was still welding. Some minor damage resulted from this incident. The other incident involved a person being within the system when it began operating. To be able to let the person get out, the emergency stop was pressed. The latter incident illustrates the possible consequences of working within the system with no external halt applied at the same time. The system description for F shows that access within the system did not cause the system to become inoperative. The occurrence of such a hazardous event illustrates the dangers inherent in this system design.

One incident of the use of an emergency stop button is recorded in Factory H. This incident also results in damage to the robot's tool and the work station from an incorrectly positioned work station.

It is clear that the more serious occurrences of the use of emergency stops are associated with problems in the sequencing of

Means of Interruption	n=743 % A	n=662 % B5	n=1553 % B6	n=1820 % B7	n=811 % F	n=13 % H	n=5620 % Overall
Emergency stop pressed	0.4	-	0.1	0.2	1.0	7.7	0.3
Other human action	21.7	15.3	14.7	10.7	30.0	53.8	16.7
Automatic stop	10.9	9.7	32.5	28.3	25.4	38.5	24.5
Sensor stop	66.0	74.5	52.5	60.8	41.6	-	58.0
Missing cases	0.1	0.6	0.2	-	2.1	-	0.4

Table 5.13 The Means of Interruption for Incidents in Each System

(Figures show % of incidents in which means of interruption is used)

N.B. As with Tables 5.11 and 5.12, the figures are percentages of incidents in each column, but unlike the previous two tables these categories are mutually exclusive. The percentages in each column add up to 100% (when missing cases and rounding errors are taken into account).

Classification	n=743 % A	n=662 % B5	n=1553 % B6	n=1820 % B7	n=811 % F	n=13 % H	n=5620 % Overall
Accident to person	-	-	-	-	0.1	-	0.02
Accident/damage to machine	1.3	1.1	6.1	4.8	2.1	23.1	3.9
Accident/damage to both	-	-	-	-	-	-	-
Accident no damage	0.7	0.5	1.5	0.7	0.4	15.4	0.9
Near miss	0.1	-	0.2	-	0.2	-	0.1
Incident - no damage	74.6	63.0	72.1	81.5	17.1	15.4	66.3
Hazard anticipated	-	0.6	0.3	1.0	1.6	23.1	0.8
No damage likely	23.3	34.4	19.6	11.9	75.1	23.1	27.4
(Missing)	(-)	(0.5)	(0.2)	(0.1)	(3.3)	(-)	(0.6)

Table 5.14 Classification of Incident for All Incidents in Each System

(Figures show % of incidents with each classification) production. Not only are the majority of incidents instigated by some sequencing problem or an automatic sensing of a problem, but that when human intervention is made to prevent an accident or control a hazard, the problems of automatic sequencing play an important part. This shows the difficulties involved in performing automatic robot production. One can see a link in this to Perrow's identification of the problems of tight coupling in systems (see Chapter 2). The tight coupling results in more serious problems when the sequencing is faulty.

The category of other human actions relates to matters such as making the system inoperative by the breaking of interlocks. These are quite frequent in each system. The normal means of human intervention is through the design features which allow such action.

Few incidents where an emergency stop is pressed involve robots. Thus anticipated hazards concern the operation of the wider system.

In some systems, those incidents involving no robots vary considerably from the overall figures (A, B6 and B7). The main variation in A is an increase in human action and a decrease in the frequency of 'sensor stops', whereas in B6 and B7 a massive decrease in 'automatic stop' and a corresponding increase for 'sensor stops' is found. The overall figure for 'automatic stop' in B6 and B7 is high overall, but occurs mainly in connection with the robot controls. In F, the overall controller plays a greater part in interrupting the process. The variations can be seen to be closely related to the interfacing of the robots with the overall system.

The means of interruption can be seen to be largely unconnected with safety problems. Some hazards are anticipated and these emphasise the problems associated with sequencing production. Differences in the means of interruption are linked strongly to the manner in which robots are incorporated into system operation.

The classification of the incidents

The severity of the outcome of the incidents has been recorded in the production data in terms of the occurrence of accidents, damage, near misses and other safety related outcomes. These are given in the

the fifth section of the tables in Appendix D. Table 5.14 gives the frequencies for each classification. As with Table 5.13, the percentages in each column add up to 100%, since the classification is mutually exclusive.

One accident to a person occurs in F. This involves a loader being hit on the head by the perspex screen used as an interlock and as a form of safety device. A clamp attaching it to a counterweight failed and this allowed the screen to come down on the person. The injury was not severe and did not require anything more than basic first-aid.

Incidents causing damage to machinery are far more frequent, with an overall frequency which made it the third most common outcome. The number of incidents of machinery damage is highest in B6 and B7 (though the percentage in H is higher, it denotes only 3 cases). A large number of these incidents in B6 and B7 result from sequencing problems, causing the shuttle transfer bars to be broken off. Thus B6 and B7 have some of the most severe sequencing problems. Once more, this reflects the problems of system sequencing and points to tight coupling within the design of robot systems.

It should be noted that the damage resulting from an outcome is not the same as a failure as the underlying reason for an incident. The former is an effect of the incident and is a measure of the severity of the outcome and a reflection on problems in system design. The latter is the immediate cause of the incident and a source of machine unreliability.

Accidents with no damage are rare. This classification category can be visualised more clearly as incidents which do not have sufficient energy to cause an accident, even though the reports showed the possibility. Typically, such incidents are collisions between a robot and an object, requiring the robot to be reset but causing no obvious damage to the robot or the struck object.

Incidents classed as near misses are also rare. A typical case of this would be the prevention of an accident by the use of the emergency stop or the motion of a robot to within a short distance of a person or other machinery. The infrequency of these two categories suggests that it is rare for the potential for damage to be present without its realisation to be achieved.

By far the most common classifications are incidents with 'no damage occurring' and incidents with 'no damage likely'. Thus the vast majority of interruptions to production do not result from hazard realisation or even its potential.

However, the pattern of separation between accidents and potential accidents and other incidents is not uniform. Appendix J shows that the pattern of frequency of these two groupings of the categories of classification differs significantly from one system to another. When the 5 most similar systems (A, B5, B6, B7 and F) are considered together, the X^2 value is 55.1, compared with a critical value of 13.3. For B6 and B7, there is some similarity, shown by the X^2 value of 3.1 compared with the critical value of 6.6. Thus the frequencies of the two groups of categories are considered separately, there is a significant difference (at the chosen level of significance of 0.01). The calculated value for X^2 is 58, with the critical value of 15.1.

In some systems, the incidents involving robots are concentrated on the two most common and least severe classifications. This occurs in A, B5, and to a lesser extent in F. In B6 and B7 certain robots are involved in a number of incidents resulting in accidents to machinery. In B6, robots numbered 251, 262 and 312 are frequently involved, whereas in B7, 173 and 302 are involved but to a lesser extent than the same in B6. A number of robots are involved in incidents with damage to machinery or accidents without damage in both these systems. In B6, only five robots and in B7 only ten do not have incidents that result in one of these two classifications. Thus the occurrence of accidents is more frequent in B6 and B7 and the severity of incidents is worse. This is borne out by the significance test in Appendix J. F also has a few cases of damage involving one robot.

One can identify system design as important in the frequency of hazardous incidents. In B6 and B7, the complexity and interactions of the equipment in the systems lead to tighter coupling. The system design in F also allows equipment to interact with the robots. The involvement of robots in these hazardous incidents shows that the motions of the robots are capable of bringing some of them into close proximity with other equipment, which may also be in motion, and cause collisions.

The involvement of personnel

The people involved in the maintenance and operation of the robot systems varied considerably. Table 5.15 presents the frequency of involvement of various categories of personnel on the systems, first in identifying problems (A) and secondly in sorting them out (B). Naturally, more than one person can be involved in identifying and sorting out a problem, so the categories are certainly not mutually exclusive. Thus the columns add up to far more than 100%.

The system descriptions show that the types of workers depended on the work organisation for the robot systems and overall in the factory. One can see that maintenance workers in Factories A and B were heavily involved in both identifying and sorting out problems. The maintenance foreman was also involved in A, but hardly at all in B. In F, the production chargehand, the leading hand and to a lesser extent also the operators were involved. The operator was more involved at the identification stage. The actions required to sort out problems were mostly left to the chargehand and the leading hand. In H the operator mostly identified problems with electrical maintenance workers involved on some incidents. These points are in agreement with the information gathered from the incidents of interruptions to production.

One can see a shift towards maintenance workers for sorting out problems, by comparing the overall columns in Tables 5.15A and B. In Factory B, two types of maintenance tradesmen worked on the systems continuously, calling on a further two types if necessary. This is reflected in the high percentages for 'other personnel'. The higher figure for B6 suggests that more problems occurred which required the attention of other tradesmen than in the other two systems in this factory. In F 'other personnel' were mainly inspection or quality control personnel and so were more involved in identifying problems than sorting them out. The other categories of workers, such as production engineers and service engineers were rarely present at either stage of involvement. In H, the operator plays the major role in identifying problems, but is less important in sorting out the problems. One can therefore see a shift onto well trained and experienced personnel in some systems for sorting out problems.

PERSONNEL INVOLVED A. In identifying problems	% Overall	% (n=743) A	% (n=662) B5	% (n=1553) B6	% (n=1820) B7	% (n=811) F	% (n=13) H
Fitter	13.9	97.7	2.6	1.3	0.8	0.2	-
Electrician	80.2	97.8	89.4	92.2	95.2	0.7	15.4
Production Engineer	0.5	0.1	2.6	0.3	0.2	-	-
Operator	1.5	0.4	0.2	-	-	8.5	92.3
Foreman	10.7	75.3	1.2	1.7	0.2	-	-
Chargehand	7.7	-	-	-	-	53.1	-
Leading Hand	2.1	-	-	-	-	14.5	-
Service Engineer	0.02	0.1	-	-	-	-	-
Other	3.3	0.8	3.9	4.3	1.8	6.7	-

(Figures show % of incidents in which specified personnel were involved)

Table 5.15a The Involvement of People in Recorded Incidents

PERSONNEL INVOLVED B. In sorting out problems	% Overall	% (n=743) A	% (n=662) B5	% (n=1553) B6	% (n=1820) B7	% (n=811) F	% (n=13) H
Fitter	48.1	99.1	40.6	51.3	45.0	8.9	23.1
Electrician	84.5	99.1	93.5	95.8	98.1	12.1	30.8
Production Engineer	0.1	0.1	0.3	0.3	-	0.1	-
Operator	0.2	0.1	-	-	-	0.2	46.2
Foreman	10.1	76.1	-	-	-	-	-
Chargehand	10.9	-	-	-	-	75.1	-
Leading Hand	6.5	-	-	-	-	45.0	-
Service Engineer	0.2	0.7	-	0.1	-	0.1	15.4
Other	4.9	1.3	2.3	11.9	2.3	2.5	-

(Figures show % of incidents in which specified personnel were involved)

Table 5.15b The Involvement of People in Recorded Incidents

The underlying reasons

The eighth and final section in Appendix D is the Underlying Reason for an incident. Table 5.16 gives the frequency of each underlying reason category for each system, and for all incidents. As in Table 5.13 and 5.14, the categories are mutually exclusive. Table 5.16 shows that robot related incidents were 29.2% of all incidents*.

Two of the 15 categories of robot related underlying reasons are the most frequent; a robot in a control 'emergency stop' and 'problems in the tools' carried by the robot. 'Parts variation', 'quality problems', 'weld failures' and most importantly 'other equipment problems' are the most frequent underlying reasons for non-robot related incidents. These four together with the two most frequent robot related reasons account for 72.7% of all incidents. Thus six underlying reasons account for nearly three-quarters of all incidents.

The pattern in the overall figures is not followed very closely in any of the systems. In some, robot related problems are more frequent than other equipment problems and component failures combined (B6, B7 and H). In each of these systems, robots form a major part of the contents of each system. In B6 and B7 there are 23 robots, all of which are required for the operation of the system. In H, both robot systems are of a simple design with the robot as the only complex piece of automated machinery. It is therefore not surprising that in these three systems robot related incidents play a major part.

F has a system which contains a lot of dedicated spot-welding equipment. Consequently, robot related problems are a small proportion. 'Other equipment problems' and 'component failures' have well over double the number of incidents of robot related reasons.

Appendix J shows that the variation between systems in terms of the frequency of underlying reasons is highly significant. For all six systems, χ^2 is 488, compared with a critical value of 15.1. For B6 and B7 alone, there is no significant difference between the systems

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*Robot related incidents are to be distinguished from incidents associated with robots. The latter involves a robot in the problem leading to the incident whereas the former has a robot problem as the underlying cause for an incident.

Underlying Reason	n=743 % A	n=662 % B5	n=1553 % B6	n=1820 % B7	n=811 % F	n=13 % H	n=5620 % Overall
(Robot related)							
Robot - no detail	0.7	2.0	1.5	1.9	0.7	-	1.5
Robot out of synchronisation	0.4	0.2	4.4	5.2	0.2	-	3.0
Stiffness in robot arm	0.3	-	0.5	0.2	-	-	0.2
Cable problem	-	0.9	0.8	1.2	1.0	7.7	0.9
Component failure in robot arm	0.1	0.5	1.2	0.5	0.4	7.7	0.6
Blown fuses	-	-	0.7	0.3	-	-	0.3
Robot in emergency stop	1.1	5.3	14.5	11.9	0.9	7.7	8.8
Fault in cabinet	0.1	0.2	0.8	0.5	0.4	7.7	0.5
Erratic robot	0.9	0.9	2.3	1.5	5.3	23.1	2.2
Fault in teach pendant	0.3	-	0.1	-	-	-	0.1
Power supply fault	-	-	-	-	6.3	-	0.9
Problem in tools	2.2	4.1	10.6	13.5	2.2	15.4	8.4
Robot won't move	0.3	0.3	0.6	0.5	0.2	-	0.4
Robot collision	-	-	2.7	1.0	-	-	1.1
Overheating hydraulics	-	-	-	-	1.4	-	0.2
(Total Robot Related)	(6.3)	(14.2)	(40.8)	(38.3)	(19.0)	(69.2)	(29.2)
(Other Reasons)							
Other component failures	0.8	2.1	2.6	2.0	16.8	7.7	4.2
System failure	2.3	1.5	1.2	4.5	-	-	2.3
System checks	2.3	-	-	-	0.1	-	0.3
Check on parts	3.2	-	-	-	-	-	0.4
Part variation	3.2	6.2	9.0	10.2	3.6	-	7.5
Quantity problem	5.5	6.5	6.2	4.4	23.1	-	8.0
Process problem	1.6	20.7	1.4	1.3	1.4	-	3.7
Services problem	1.6	0.6	1.0	1.1	2.3	-	1.3
Other equipment problem	12.9	39.4	30.5	29.1	31.1	-	28.8
Safety function problem	1.5	-	0.2	0.1	0.4	-	0.3
Human error	1.3	0.8	0.6	0.5	0.9	23.1	0.8
Weld failure	51.3	4.4	4.8	8.0	-	-	11.2
Sequence fault	6.1	3.0	1.1	0.1	1.1	-	1.6
(Missing)	(-)	(0.6)	(0.6)	(0.4)	(0.4)	(-)	(0.4)

Figure 5.16 Underlying Reason for Incidents with Each System
(% of all incidents)

when the incidents are grouped as robot related and other reasons, but there is when the individual categories of reasons are considered. χ^2 is then 108.2, compared with a critical value of 40.3.

Thus, system inventory shapes the underlying reasons. The presence of many other pieces of equipment make robot related problems of less overall importance.

This conclusion makes some intuitive sense and could be said to be wholly as expected. However, it is worth emphasising that it is the system design and the equipment within the system which governs the underlying reasons for interruptions to production, rather than merely being the result of the presence or absence of robotic equipment.

Certain reasons are considerably more frequent in some systems than elsewhere. This is true of 'weld failures' in A, 'process problems' in B5, 'robot in E-stop' in B6 and B7, 'quality problems' and 'component failures' in F and 'erratic robot' and 'human error' in H. Further discussion of these differences between systems is warranted as they cast light on how system design and task determines the relative importance of underlying reasons.

In A, the robot system design includes a number of sensors of the weld parameters which could cause the robot to stop welding. Likely causes for interruptions to the weld parameters include problems with the weld equipment or some shift in the robot's programme. Thus a number of other underlying reason categories could be relevant to the incidents of weld failure, of which some could also be robot related.

In B5 'process problems' are the underlying reasons of over a fifth of all incidents. This category acts as a 'catch-all' for underlying reasons which are unclear. Incidents with this category are signified by low downtime, and the recording of other action and other reason in the relevant section of the production records. Therefore the system requirements in B5 produce a large number of short duration and low hazard incidents.

'Robot in E-stop' appears as a major underlying reason in both B6 and B7. Generally, such an incident causes the robot to stop in mid-sequence. The figures show that this reason was also frequent amongst robot related reasons in B5 (5.3% out of 14.2% for robot related incidents). In some cases it was suspected that one cause for the control emergency stops was a stiffness in the arm joint or motor transmission. This was surmised from discussion and observations on the shop floor. The types of robots used here and the process make the robots more susceptible to this problem. The discussion of this underlying reason is continued later in this chapter when details of the robot related incidents are considered in more detail.

In F 'other component failures' amount to 16.6% of incidents and quality problems to 23.1%. The former figure signifies a high rate of failure for components on equipment developed and supplied by the commissioning company. The latter figure shows once more that quality was both a problem and a high requirement of this systems' production.

In H, two reasons have nearly half the number of incidents between them, covering 3 incidents each. Human error is the cause of three incidents in System I. System design left a lot to the discretion of the operator and so a high proportion of incidents due to errors by workers could be expected. Erratic robot motion is also a major cause of interruption, since high accuracy was required from the robot. However, a concentration of 3 cases out of 13 is not highly significant.

The discussion above on the underlying reasons for incidents shows how features of system design, task and work organisation can influence system performance. These features can turn some underlying reasons into major causes of interruption to production whereas elsewhere they account for only a small percentage.

2) Further analysis of the classification of incidents

This section expands on the presentation of the classification of the severity of outcomes of incidents given above (see Table 5.14). Here the data are collated according to the classification categories and the downtime and underlying reasons for each category are considered. Other information, for example on the actions taken, reasons for action, means of interruption and persons involved are covered adequately in the preceding discussion and so are not presented here.

Appendix E gives the full tables for each category of classification. Table 5.17 below summarises the overall figures. Each column of underlying reasons can be compared directly with the final column of Table 5.16, which

	(1) Accident to Person	(2) Accident Damage to Machine	(4) No Damage	(5) Near Misses	(6) Incident no Damage	(7) Hazard Anticipated	(8) No Damage Likely	(9) Missing Records
Number of cases	1	220	48	6	3716	43	26448	34
Downtime total (mins)	15	5659	11844	129	26258	1934		559
Cases with downtime	1	193	45	5	2993	36	1136	32
Mean downtime (mins)	15	29.3	263.2	25.8	8.8	53.7	23.3	17.5
Underlying Reasons (% of cases)								
Robot - no detail	-	2.7	-	-	1.3	4.7	1.6	5.9
Robot out of synch.	-	1.4	2.1	-	4.3	-	0.2	2.9
Stiffness in robot arm	-	1.4	-	-	0.2	-	0.1	-
Cable problem	-	1.4	-	16.7	0.9	-	0.9	-
Component failure in arm	-	1.4	4.2	-	0.6	4.7	0.3	-
Blown fuses	-	-	-	-	0.5	-	-	-
Robot in E-stop	-	0.9	-	-	13.0	-	0.5	-
Fault in cabinet	-	0.5	2.1	-	0.6	-	0.3	-
Erratic robot	-	9.1	2.1	33.3	0.8	18.6	4.0	5.9
Fault in teach pendant	-	-	-	-	0.1	-	0.1	-
Power supply fault	-	-	-	-	1.0	4.7	0.7	2.9
Problem in tools	-	11.8	4.2	-	7.9	23.3	9.2	2.9
Robot won't move	-	-	-	-	0.5	-	0.4	2.9
Robot collision	-	5.9	56.3	-	0.6	-	-	-
Overheating hydraulics	-	-	-	-	-	-	0.7	-
(All robot related reasons)	(0)	(36.4)	(70.8)	(50.0)	(32.1)	(55.8)	(19.0)	(23.5)
Other component failure	-	16.4	2.1	-	2.0	7.0	7.6	8.8
System failure	-	0.5	-	-	3.2	-	0.6	-
System checks	-	-	-	-	-	-	1.2	-
Check on parts	-	-	-	-	0.03	-	1.5	-
Part variation	-	15.5	8.3	-	8.2	-	5.1	-
Quality problem	-	2.3	-	-	0.5	-	27.6	2.9
Process problem	-	3.2	-	-	0.5	4.7	11.6	-
Services problem	-	-	-	16.7	1.0	-	2.0	-
Other equipment problem	-	22.7	14.6	16.7	32.9	27.9	19.8	44.1
Safety function problem	100	-	-	-	0.2	2.3	0.5	-
Human error	-	2.7	-	-	0.5	2.3	1.0	2.9
Weld failure	-	-	-	-	16.6	-	0.9	-
Sequence fault	-	0.5	4.2	16.7	2.1	-	0.6	-
(Missing)	-	-	-	-	(0.1)	-	(0.9)	(17.6)

Table 5.17 Classification of Incidents with Downtime and Underlying Reasons Overall

gives the overall percentages for each underlying reason category. From such a comparison, one can see the degree of variation between each category of the classification.

There is considerable variation from the overall figures in Table 5.16. Perhaps the clearest example is the variation of the total of robot related reasons from zero in category 1 (accident to person) to 19.1% in category 8 (No Damage likely) to 70.8% in category 4 (Accident - no damage). The comparable figure in Table 5.16 is 29.2%.

Mean downtimes also show a great deal of variation, from 8.8 minutes in category 6 (Incident - no damage) to 263.2 minutes in category 4. The overall mean downtime figure is 16.4 minutes (obtained from Table 5.10 by dividing total system downtime by the number of incidents with downtime recorded).

These variations in mean downtime do not follow a pattern which suggests itself from the categories involved. One could imagine that incidents involving damage to machinery would result in the largest periods of downtime, with accidents involving no damage below this. Cases of near misses, incidents with no damage caused or those where damage is not likely would have lower mean downtime values. Hazards anticipated could be expected to have higher than average periods of downtime.

Although the pattern of mean downtimes overall do not follow the expected pattern, the behaviour in each system is much more as expected. This is particularly true in A and F and to a large extent also in B5, B6 and B7. The incidents in B6 and B7 exert a distorting effect on the overall figures since these systems have low downtimes and there are more incidents resulting in accidents from B6 and B7. The effect of B6 and B7 is particularly noticeable in incidents with accidents resulting in damage (category 2).

Thus in almost all the systems, accidents with damage are the most prolonged. Anticipated hazards are slightly longer in duration in three systems (B5, B7 and H). In these systems some hazards were anticipated which had very severe consequences for downtime.

A t-test on differences in the downtime of the classification categories showed more similarity than in Table 5.17 (see Appendix J). The values for accidents with damage to equipment, near misses and hazards anticipated had no significant differences. Near misses were found to have only a significant difference with incidents involving no damage. Accidents with no damage also had no significant difference from incidents involving no damage and from those where no damage or harm was likely. However, in these last two comparisons some difference was found, in that the variances of the samples were significantly different.

Though there was a clear variation in the mean downtimes, the concentration of over 90% of incidents in two categories made the differences in values between some of the other categories less significant. Hence it is difficult to draw firm conclusions from the results of the significance test.

There are considerable variations in the frequency of underlying reasons in the different classification categories. These variations are shown to be significant in Appendix J. The two groups of categories - robot related and other reasons - have a χ^2 value of 149.9 all classifications, compared with the critical value of 15.1 at a confidence level of 0.01.

'Problems in tools', 'erratic robot', 'robot collisions', 'other component failure', 'part variation' and 'other equipment problems' are predominant where damage occurs. Robot collisions are particularly important in incidents where accidents occurred but no damage ensued. 'Weld failures' are all classed as resulting in no damage or no damage likely. Some robot related reasons are major reasons for other classification categories. 'Cable problems' 'erratic robot' and 'sequence problems' are a frequent cause of near misses. 'Erratic robot' and 'problems in tools' dominate amongst incidents where hazards are anticipated.

Taking a more detailed look at the tables in Appendix E, one can see that the vast majority of incidents involving accidents to machinery (category 2) are in B6 and B7. However the mean downtime in these two systems is considerably less than elsewhere. The underlying reasons are also quite different, with a large number of robot related reasons. In only two other systems were there robot related reasons for incidents resulting in accidents with damage to machinery, and only with one category in each - 'erratic robot' in B5 and 'problems in tools' in F. Thus robot actions result in damage more frequently in B6 and B7 than elsewhere.

The large number of robots and the close proximity of these to each other and other equipment create a tight coupling of the system. A malfunction of a robot is thus more likely to lead to damage. However, system design and personnel training allow rapid and straightforward recovery from an incident.

It should also be noted that robot related reasons are no more frequent in this classification category than overall for B6 and B7. The robots in B6 and B7 are no more likely to cause damage than other equipment. The system as a whole produces the large number of incidents with damage.

The majority of incidents resulting in accidents without damage are once more in B6 and B7 with mean downtime figures lower than in the other systems. Incidents of robot collision are a particularly important cause of such an incident in B6. Although 'robot collisions' in B6 and B7 account for over 50% of all cases of accidents without damage, other reasons are also important. 'Part variation' and 'other equipment problems' predominate, indicating once more the role played by the overall system.

Incidents which constitute near misses (category 5) are present in only 3 systems, and moreover were rare even in these. Mean downtimes vary only slightly. Robot related incidents are found only in B6 ('cable problem' and 'erratic robot'). 'Sequence fault' was the cause of the single incident in A, and 'services problem' and 'other equipment problem' were the causes of the two in F.

The distribution of incidents which result in no damage is more uniform than for other categories. The underlying reasons match quite closely the overall figures for each company in Table 5.16. In Factory A, the main difference is the higher frequency of 'weld failure'. In B5 the main difference is low frequency of 'process problem' (only 0.7% rather than 20.7%). In B6, B7 and F the main difference is the low frequency of 'quality problem'.

Incidents where hazards were anticipated are infrequent but are distributed relatively evenly between 5 systems (excluding A). Thus no particular ability is found in any system to anticipate hazards and for personnel to act on this anticipation regularly.

This distribution of incidents with no damage likely is also quite even, but with the system in F having the largest number. Robot related incidents are more infrequent than in the overall figures. 'Quality problems' in most systems and 'process problems' in B5 are major reasons for this category. 'Other equipment problems' is also less frequent than overall.

This analysis of the classification categories shows that relatively few incidents produce hazards when the incidents occur, even if subsequent actions may prove hazardous. Automatic operation therefore raises few safety issues. However no special ability is found in any system to anticipate the hazards which do arise.

Robot related problems and problems with other equipment are considered to be more hazardous than other causes of incidents. Hazards are rarely involved in the occurrence of incidents when quality problems or process problems are underlying reasons.

3) The downtime for underlying reasons

The downtime resulting from each underlying reason in each system forms a basis for comparison of the severity of underlying reasons in the systems. The table of underlying reasons for each system is presented in Appendix F, giving downtime totals, mean downtime, the number of incidents and the number of incidents with downtime. Table 5.18 below gives a summary of the percentage of total downtime for each underlying reason in each robot system. Table 5.19 gives the mean downtime for the same. Both of these tables denote the underlying reasons with numbers - the key to which is to be found at the bottom of Table 5.19.

The percentages in Table 5.18 should not be confused with those given in Table 5.16 since they are percentages of the total downtime in each system (and overall in the far right column), not of the number of incidents. However the percentages can be compared with those in Table 5.16 to gain an understanding of the difference between frequency of certain accidents and their duration. This comparison shows that overall, the average robot related problem endures for longer than other incidents. This is true for all systems except F, where the percentages for downtime and number of incidents are roughly the same. Thus with the exception of the system in F, robot related problems are more serious in terms of lost production than in their relative frequency of occurrence. The reason for the exceptional pattern in F can be traced to the many problems of a serious nature with the other equipment.

Underlying reason	A(N=743) %	B5(N=662) %	B6(N=1553) %	B7(N=1820) %	F(N=811) %	H(N=13) %	Overall N=5602
RRP							
10	0.2	7.5	1.7	4.6	3.6	--	2.5
11	0.1	0.2	2.9	3.1	0.5	--	1.1
12	-	-	1.0	0.09	-	--	0.2
13	-	4.0	1.7	4.3	2.2	2.8	2.3
14	1.5	3.3	3.1	1.9	3.3	7.3	3.5
15	-	-	1.5	0.6	-	-	0.3
16	0.07	2.4	5.9	6.5	0.3	0.9	2.4
17	3.6	0.5	3.0	1.6	1.8	78.9	16.0
18	1.3	4.4	9.8	5.1	2.9	2.1	4.1
19	0.09	-	-	-	-	-	0.01
110	-	-	-	-	2.4	-	0.6
120	0.7	12.3	14.0	17.3	1.5	1.9	6.7
130	0.4	0.1	0.9	0.5	0.05	-	0.3
140	-	-	3.6	2.1	-	-	0.9
150	-	-	-	-	0.7	-	0.2
Total RRP	(8.1)	(34.6)	(49.2)	(47.7)	(19.1)	(93.9)	(41.1)
Other Reasons							
22	0.1	9.2	8.4	8.8	32.1	5.0	12.9
33	5.6	1.2	1.2	2.0	-	-	1.5
34	2.1	-	-	-	0.08	-	0.4
41	3.2	-	-	-	-	-	0.5
42	2.1	0.9	8.9	10.7	2.4	-	4.1
43	15.7	4.2	5.2	5.0	12.7	-	7.9
44	5.0	2.2	1.7	2.0	0.9	-	1.8
55	1.5	0.5	1.8	2.2	2.3	-	1.5
66	31.5	34.7	20.2	18.9	28.6	-	21.6
77	0.2	-	0.5	-	0.2	-	0.2
88	1.4	1.1	0.2	0.2	0.8	1.1	0.8
200	9.0	0.5	1.8	1.9	-	-	2.1
210	14.5	9.2	0.8	-	0.5	-	3.3
999	-	1.5	0.1	0.4	0.3	-	0.3

Table 5.18 Analysis of Downtime and Underlying Reasons for Incidents

Underlying reason	A(N=743) %	B_5(N=662) %	B6(N=1553) %	B_7(N=1820) %	F(N=811) %	H(N=13) %	Overall N=5602
RRP							
10	5.75	38.4	9.9	20.0	115.7	-	27.8
11	13.0	10.0	5.3	4.0	47.5	-	5.3
12	-	-	15.4	2.5		-	11.1
13	-	56.3	15.8	22.2	52.5	360.0	35.7
14	180.0	61.7	23.3	52.5	216.7	960.0	91.4
15	-	-	16.7	11.5	-	-	14.9
16	2.7	6.1	3.2	3.4	8.6	120.0	3.8
17	420.0	28.0	32.9	19.9	116.7	10320.0	448.4
18	77.5	50.0	38.9	24.3	13.1	135.0	28.2
19	10.0	-	-	-	-	-	10.0
110	-	-	-	-	9.0	-	9.0
120	17.6	36.7	12.6	9.3	15.8	125.0	12.8
130	26.0	3.5	12.0	6.9	10.0	-	10.5
140	-	-	10.2	13.6	-	-	11.2
150	-	-	-	-	12.7	-	12.7
Total RRP	(47.5)	(28.8)	(10.2)	(8.5)	(24.4)	(1535.0)	(20.9)
Other Reasons							
22	4.0	52.0	31.2	33.3	46.1	660.0	44.6
33	47.1	13.8	7.5	2.8	-	-	9.2
34	22.2	-	-	-	15.0	-	21.6
41	20.8	-	-	-	-	-	20.8
42	17.8	6.5	8.3	6.9	16.4	-	8.6
43	97.1	10.7	14.0	22.0	13.4	-	19.4
44	84.0	1.5	20.7	14.7	15.9	-	10.3
55	34.8	9.3	16.5	12.9	23.9	-	18.9
66	63.8	14.3	5.4	4.3	22.4	-	11.4
77	4.3	-	18.3	-	10.0	-	7.9
88	21.1	32.5	3.1	2.7	22.9	70.0	15.5
200	6.1	3.4	4.7	3.0	-	-	5.1
210	54.9	28.9	5.6	-	10.0	-	31.7
999	-	21.8	2.1	7.0	16.7	-	9.7
Overall	30.7	15.3	8.8	7.2	24.2	1189.1	16.4

Key to Figures Robot Related Reasons (RRP)

10 Robot fault - no detail
11 Robot out of synchronisation
12 Stiffness in robot arm
13 Cable problem
14 Component failure in robot arm
15 Blown fuses
16 Robot in control emergency stop
17 Fault in control cabinet
18 Erratic robot
19 Fault in teach pendant
110 Power supply fault
120 Problem with tools
130 Robot will not move- reason unspecified
140 Robot collision
150 Overheating hydraulics

Other Reasons

22 Other component failures
33 System failure
34 System checks
41 Check on parts
42 Part variation
43 Quality problem
44 Process problem
55 Services problem
66 Other equipment problem
77 Safety function problem
88 Human error
200 Weld failure
210 Sequence fault
999 Reason not given

Table 5.19 Mean Downtime (Mins) In Each Company by Underlying Reason

Among the 15 robot related underlying reasons, the pattern in each system is less uniform. Certain failures of the robots, that is incidents of 'cable problems' (13), 'component failure in robot arm' (14) 'blown fuses' (15) (to some extent) and 'fault in cabinet' (17) have considerably higher percentages for downtime than for frequency of incidents, both overall and in nearly every system. The last of these 'fault in cabinet' is the clearest example, with 16% of all downtime but only 0.5% of incidents. These robot failures are characterised by a high proportion of incidents with large downtime. They involve lengthy downtime because of the time required to carry out extensive repair or equipment replacement. The other two categories of robot failure - 'fault in the teach pendant' (19) and 'power supply fault' (110) - are characterised by shorter downtime periods. Clearly, less time is required for such problems.

The other robot related problems tend to have correspondingly smaller percentages of downtime than of incidents, with the exception of 'erratic robot' (18) in each system and 'problems with tools' (120) in Factory B. Erratic robot problems are more serious in terms of the disruption they cause than in terms of their frequency. The robot needs to be put back onto its correct programme path, which could involve extensive reprogramming or checking of programme steps. Tool problems in the three systems in Factory B were quite a major problem area when measured by the number of incidents, but are even more so in terms of downtime. Thus problems with the tools caused serious problems in their rectification. For example the resultant change in the alignment of the tools could result in the need to reprogramme the fine points in the robot's path.

Amongst the other reasons, 'other component failure' is conspicuous with far greater percentages of downtime than of incidents in all systems except A. The only other reasons for which the same occurs is 'sequence fault' (210), particularly in A and B5, where the frequency of occurrence was also quite high. The one reason which is of much less importance in terms of downtime than in number of incidents is 'weld failure'. This is true in each system but particularly true in A, where the greatest concentration of incidents in this category occurs. Component failures and faults in sequencing have severe consequences. Both can require major maintenance work. The low downtime for weld failures re-emphasises the short duration and relative unimportance of each incident of this kind.

A direct comparison between downtime percentages and frequency percentages can mean that a reason with a high number of incidents for which no downtime is given can be judged to be of lesser importance than is actually the case. To overcome this drawback, a consideration of the mean downtime for incidents will assist. This is shown in Table 5.19. This table shows that those cases identified to be more important in terms of downtime than in terms of frequency occurrence also have the highest mean downtimes. Four reasons of robot failure, the problems of erratic robot behaviour, other component failures and sequence faults all have high mean downtimes relative to the other reasons. Most have means of the order of 130 minutes, although the mean for blown fuses is around 15 minutes. The reservations expressed above over the importance of the downtime for incidents of blown fuses is supported by the low mean downtime figure.

The figures for mean downtimes can be compared with the means for all incidents in the tables in Appendix D, and with the overall mean of 16.4 minutes. The variations in mean downtimes for each system is considerable. However there is nearly an order of magnitude difference in the variations between the two systems with the least variation (B6 and B7 with about 20-fold difference) and the two with the most (A and H with about a 150-fold difference). The narrower band of downtimes in B6 and B7, coupled with the lower means, suggests that the maintenance teams in Factory B were more proficient in dealing with a wide range of problems than their counterparts elsewhere.

The analysis in this section shows that robot related problems have a more serious effect on lost production than suggested by the frequency of such incidents. This is particularly true of certain failure categories. The same applies to component failures elsewhere in the systems and to sequencing problems. Robot systems B6 and B7 appear in a favourable light, once more suggesting the benefits of system design, the use of experienced personnel and extensive training.

4) Robot related incidents

To obtain greater detail on the incidents whose underlying reasons concern facets of robot performance (that is 'robot related problems'), robot related incidents are considered in isolation. First the downtime caused by robot related incidents are considered and then robot related underlying reasons are analysed by robot systems and robot types.

Appendix G has 6 tables for robot related problems - one for each system - giving the downtime, number of cases, number of valid cases (i.e. with downtime figures) and the mean downtime figures. Table 5.20 below summarises these figures and puts them into the context of the rest of the incidents, of the production hours and the robot production hours covered.

Table 5.20 shows that robot related problems constitute a substantial proportion of production time. Thus, between 2.5% and 16.3% of production time was lost in the systems studied. The last column shows robot related downtime as a percentage of robot production hours. Only 0.2% of robot production time was lost through robot related problems in A, rising to 16.3% in H. Figures for H are once more strongly affected by the one extremely long incident. Without this incident, robot unavailability in H would be 2.6% of robot production hours and total robot related downtime as a percentage of robot production hours would be 0.5%. This is almost exactly the same as the figures derived for B5, B6 and B7. The narrow band of values for systems in B suggests a high degree of similarity between the robots in B. This is to be expected, since they are performing similar tasks and are of similar design.

The downtime as a percentage of production time is the product of two parameters:- the mean downtime for incidents and the number of incidents per production period. The number of incidents per robot production period is shown to be significantly different in all the systems (see Appendix J). For all the systems, $\chi^2 = 327.3$ compared with a critical value of 15.1. Even for B6 and B7, which are considered to be the most alike, the calculated value is nearly twice the critical value, at 12.7 (compared with the critical value of 6.6). Thus the appearance of similarity above is not borne out by the statistical analysis. Though these systems are similar, the differences are still large enough to be statistically significant.

A t-test on the downtime shows a significant difference between the systems in all but 5 comparisons (see Appendix J). The figures for Factories

Factories	Number of RRP Cases	No. of RRP Cases with Downtime Record	RRP Cases as % of all Cases	Downtime for RRP (Mins)	RRP as % of all Downtime	RRP as % of Production Time	RRP as % of Robot Production Time
A	47	20	6.3	949	8.1	2.5	0.2
B5	94	68	14.2	1959	34.6	4.4	0.5
B6	634	575	40.8	5866	49.2	9.1	0.4
B7	697	611	38.3	5219	47.7	8.9	0.4
F	154	153	19.0	3727	19.1	5.3	2.7
H	9	8	69.2	12280	93.9	16.3	16.3
Overall	1635	1435	29.2	30000	41.4	8.6	0.8

(Robot production hours = 64281.5)

Table 5.20 Robot Related Downtime (RRP = Robot Related Problems)

A, B5 and F were found to have no significant difference between them and B6 and B7 were also similar to each other. F was found to have significantly different variances from A and B5, suggesting that the incidents in F came from a different population from A and B5, even though the means were similar.

Looking at Appendix G in more detail, one can see that some robots are more severely affected than others. In A the mean downtimes vary from 156.7 minutes to 2.8, being non-existent for 5 robots. These 5 have only four robot-related incidents between them, none of which provide downtime figures. However variations in downtime for each robot's related incidents within each system are not very pronounced. Little statistical difference is found overall (see Appendix J). In A, robots number 3 and 9 show some significant difference. In B5 the same is true of only one robot (number 122) whilst in B6 and B7 a minority of robots show the same characteristic. This minority in B6 and B7 can be divided into those with far higher than average means and those with far lower than average. T-tests between one of each group almost always shows a significant difference. In F and H the two robots in each factory are shown not to have significant differences in their downtime.

One can also see that the electrical robots used in A and B are less affected by robot related problems than the hydraulic robots in F and H. The latter two systems have considerably higher percentages for robot related downtime as a proportion of robot production hours. This is due to the high number of robot related incidents per production hour in F and the high mean downtime in H. The frequency of robot related problems in F is linked to the use of hydraulic robots, but clearly the task and system design plays a role. In H, the task causes acute difficulties for the robots, suggesting that the task 'over-stretched' the robots in some way.

The analysis of robot related problems by systems and types

Robot related incidents can be considered separately for each system or each type of robot. Appendix H has complete statistics for robot related incidents by robot system and also by robot types. In these tables, that part of all the incidents which relate to robot behaviour is compared for different systems and robot types. Table 5.21 shows a summary of robot related problems by robot systems, giving the downtime statistics and the frequency of occurrence of underlying reasons. Later Table 5.22 presents the same for each robot type.

a) Robot related problems by systems. It is apparent from Table 5.21 that incidents in systems B6 and B7 dominate the total. Both account for about 40% of incidents, leaving less than 19% for the other 4 systems. Of the remaining incidents, F has over half. This bias towards the two largest systems in the study affects the overall figures considerably, making the overall frequencies highly dependent on systems B6 and B7. Thus it is better to look at the figures in each system rather than compare each to the overall figures.

The figures for mean downtime have been considered earlier, showing that B6 and B7 have the lowest mean downtime and H by far the highest. A has quite a high figure of 47.5 mins. This has been shown above to be linked to task,system design and work organisation. Both B6 and B7 have a design which allows rapid recovery from a problem in a straightforward manner and also have a highly trained and experienced workforce. A has a large number of problems which arise from the type of task, which proved difficult to handle with the particular system design. The robot systems in H suffer from a few severe problems which appear aggravated by the task required of the robot.

When considering the underlying reasons, it is clear that some reasons are only relevant to one or two systems. Other reasons appear with far higher percentages with some systems than others. Four robot related reasons are relevant to only one or two systems. Two of these are relevant to B6 and B7 ('Blown fuses' and 'robot collision') and two to F ('power supply fault' and 'overheating hydraulics'). The 'blown fuses' incidents were the result of too much power demand on a circuit, such as a motor drive circuit. This was to some extent linked to the system design and the motions required of the robots, but also to the maintenance workers' practices of overcoming problems by turning up the robot current controls. 'Robot collision' was partly the result of system design, with a number of robots moving within the working envelopes of other robots. Both the reasons relevant only to F are linked to the use of hydraulic power for robot motion. One reason was power system failure and the other was a cut-out because of some problem in the cooling cycle of the hydraulics flow. Though H also had hydraulic robots, these problems were not given in the

	Overall	A	B5	B6	B7	F	HI	HII
Number of incidents	1635	47	94	634	697	154	4	5
Downtime total (mins)	30000	949	1959	5866	5219	3727	10600	1680
Robot production hours	64281.5	7548	5964	24771	22413.5	2333	675	577
Mean downtime (mins)	20.9	47.5	28.8	10.2	8.5	24.4	2650	420
Underlying Reason (%)								
Robot no detail	5.0	10.6	13.8	3.8	4.9	3.9	-	-
Robot out of synchronisation	10.3	6.4	1.1	10.9	13.5	1.3	-	-
Stiffness in robot arm	0.9	4.3	-	1.3	0.6	-	-	-
Cable problem	3.1	-	6.4	2.1	3.2	5.2	-	20.0
Component failure in robot arm	2.2	2.1	3.2	3.0	1.3	1.9	-	20.0
Blown fuses	1.0	-	-	1.7	0.9	-	-	-
Robot in Emergency stop	30.2	17.0	37.2	35.5	31.1	4.5	-	20.0
Fault in cabinet	1.7	2.1	1.1	1.9	1.4	1.9	25.0	-
Erratic robot	7.5	14.9	6.4	5.5	4.0	27.9	50.0	20.0
Fault in teach pendant	0.2	4.3	-	0.2	-	-	-	-
Power supply fault	3.1	-	-	-	-	33.1	-	-
Problem in tools	28.9	34.0	28.7	26.0	35.2	11.7	25.0	20.0
Robot won't move	1.5	4.3	2.1	1.6	1.3	1.3	-	-
Robot collision	3.7	-	-	6.6	2.7	-	-	-
Overheating hydraulics	0.7	-	-	-	-	7.1	-	-

Table 5.21 Robot Related Problems by Systems

small number of incidents here. Thus the exclusive occurrence of these reasons in these systems reflects system design and working practices in B6 and B7 and the use of hydraulic robots in F.

Nearly all the reasons have some distinguishing difference between the systems. For 'Robot - no detail', the percentages in A and B5 are higher than in the other systems, but great importance should not be attached to this, since this reason is a 'catch-all' for those incidents not covered elsewhere. For 'robot out of synchronisation', the frequency in B5 and F is quite low. 'Stiffness in the robot arm' only appears with 3 systems and is high only in A. (The low number of incidents as a base for the figures creates a distorted view: 4.3% in A is actually only one incident). 'Cable problems' are high in B5 and F as well as present in H. The frequency of 'Robot in Emergency stop' is especially high in each system in Factory B, and very similar. This similarity is quite remarkable after the differences found in the overall figures between these systems. This change in the perception of the frequency of occurrence of robot related problems and the importance of each category is perhaps the clearest benefit of considering robot related incidents alone. This presentation shows that the problem of a control emergency stop is an important robot related cause of disruption to production in all three systems in Factory B.

The frequency of incidents of 'erratic robot' is high in A, and also in F. To some extent the source of the problem in A can be traced to arc-welding. However it is the underlying reason in a sizeable proportion of incidents in each system. In F, the hydraulic power supply for the robots was found to result in a slight shift of robot motion over a period of time. The robots path would move to one side of the path which was programmed. Problems in tools also occur frequently in all the systems, but markedly less frequently in F. The high frequency of occurrence of problems with tools and with the position of the robot during its programmed motions suggests that the process in each system proved somewhat difficult. The accuracy required of the robots sometimes exceeded their capability. Problems with the tools are also the product of the demands of the process since the tools are not capable of performing satisfactorily at all times.

The variations in robot related underlying reasons noted in this section are tested for significance in Appendix J. For all the systems, the χ^2 is 203.9 with a critical value of 30.6, thus a significant difference exists between the systems. A test for the three systems in Factory B gives a X^2 value of 27.7 (with a critical value of 16.8). For B6 and B7 the value is 14.2 (critical value 11.3). Each of these tests show that differences between the systems noted in this section are statistically significant, although the differences between B5, B6 and B7 are less marked.

The other parameters shown in Appendix H are more dependent on the system design and operating practices of the system. That is, the Actions Taken, the Reasons for Actions, the Means of Interruption, the Classification of Accidents and Personnel Involved are linked to features of each system which are not directly robot-related. Therefore a full discussion here of these parameters would not be appropriate. However, some features are worth noting. The actions taken and reasons for actions are more biased towards those which are strongly related to robots, for example reprogramming for actions and mechanical and electrical problems with the robots as reasons for actions. Replacement of faulty equipment is also a more frequent action. This is despite the fact that more component failures occurred with other equipment than with the robots overall. The need for the replacement of parts of the tools carried by the robots is the cause of this. 'Automatic stop' and 'human action' are more frequent and 'sensors stops' correspondingly less frequent than overall. The classification of the incidents follow a similar pattern to the overall figures, with a slight increase in the frequency of accidents, both those involving damage and those not doing so. The part played by incidents from B6 and B7 is significant in this increase, as explained above.

This section has identified certain robot related reasons which can be associated with certain systems and has proposed explanations for these. The role of task, system design and work organisation in determining the importance of certain reasons has been emphasised. The analysis also provides further evidence of the types of major difficulties experienced by robot systems in general, although any such conclusion must be tempered by the fact that significant differences exist between the systems.

b) Robot related problems by type. The analysis of robot related problems can be undertaken also for the different robot types. As Table 5.9 showed earlier, the robot production hours can be separated into robot types. Table 5.22 presents a summary of the results for each type of robot, giving downtime, mean downtime, the robot production hours, the

	Overall	Type 1	Type 2	Type 3	Type 4	Unknown
No. of Incidents	1635	86	163	463	911	12
Downtime total (mins)	30000	1263	16007	4963	7602	165
Robot production hours covered	64281.5	9599.5	3585	14170	36927	
Mean downtime (mins)	20.9	28.8	99.4	12.5	9.4	15.0
% Downtime (of Robot production hours)	0.8%	0.2%	7.4%	0.6%	0.3%	
UNDERLYING REASONS (%)						
Robot - no detail	5.0	23.3	3.7	6.9	2.6	-
Robot out of synchronisation	10.3	4.7	1.2	2.2	16.8	-
Stiffness in robot arm	0.9	2.3	-	-	1.3	-
Cable problem	3.1	-	5.5	2.6	3.2	-
Component failure in robot arm	2.2	1.2	2.5	1.7	2.5	-
Blown fuses	1.0	-	-	1.3	1.2	-
Robot in Emergency stop	30.2	14.0	4.9	45.8	28.4	16.7
Fault in cabinet	1.7	3.5	2.5	1.3	1.6	-
Erratic robot	7.5	10.5	28.2	6.3	4.0	16.7
Fault in teach pendant	0.2	2.3	-	-	0.1	-
Power supply fault	3.1	-	31.3	-	-	-
Problem in tools	28.9	26.7	12.3	29.8	31.4	50.0
Robot won't move	1.5	11.6	1.2	0.9	1.0	-
Robot collision	3.7	-	-	1.3	5.8	16.7
Overheating hydraulics	0.7	-	6.7	-	-	-

Table 5.22 Robot Related Problems by Robot Type

percentage of robot production time lost through robot related problems and the underlying reasons for each robot type. Not surprisingly, the robots in B6 and B7 dominate the number of cases and robot production hours, with type 4 robots having over 50% of all incidents and also over 50% of total robot production time. Incidents of unknown robot type occur where there are more than one type of robot in a system, that is, in B6 or B7. Thus the types of robots in these two systems, (types 1, 3 and 4) have a slight under-reporting of problems.

The mean downtimes for robot related incidents for each type vary by over one order of magnitude, from a low of 9.4 minutes to a high of 99.4 minutes. The high figure is for type 2 robots and is influenced by the one exceptionally long incident (of 10320 minutes). However if this one incident is excluded the mean downtime figure is still high, at 35.5 minutes.

A t-test on the downtime for robot related incidents with each robot type showed significant differences in all but two cases (see Appendix J). When robot type 1 is compared with either type 3 or 4, no significant difference is found. However, the variances in both tests show significant differences at a confidence level of 95% and so the similarity is limited. It is more notable that the t-test between types 3 and 4 shows a significant difference like the others. Thus the hydraulic robots suffer longer periods of downtime than the electric robots studied, but each type of robots is significantly different from the other in terms of downtime for robot related problems.

The downtime as a percentage of robot production hours vary by a factor of more than 30. Once again, the one exceptionally long incident influences the degree of variation. If this incident is excluded, the percentage figure for type 2 robots becomes 2.6%, still over one order of magnitude greater than the lowest, (for type 1 robots). These figures show the production reliability for each type of robot irrespective of task or system. It gives the highest reliability to type 1 robots and shows hydraulic robots in an even worse light than in Table 5.20. However an availability figure of 92.6% for type 2 robots is still quite high (c.f. machine tool reliability data provided in Chapter 1), and an average availability of 99.2% for all the robots is enviable. Thus the problems with robot systems is not that robots are used, but that the operation of systems incorporating robots creates interactions and problems which are numerous and difficult to remove.

The variations in availability are due to the amalgamation of two measures, namely the mean downtimes and the number of incidents per robot production period. The mean downtimes are shown above to have a significant variation, and Appendix J also shows that the number of incidents per robot production period for the robot types is significantly different. The calculated X^2 value is 190.4 for all 4 types, compared with a critical value of 11.3. Thus the difference in availability is also statistically significant.

Consideration of the underlying reasons for each robot type here is restricted to only those features which are in addition to the preceding discussion on robot related problems in each system. Each robot type has high percentages for certain categories,that is 'erratic robot' and 'robot won't move' for type 1, 'erratic robot', 'cable problems' and 'power supply fault' for type 2, 'robot in Emergency stop' for Type 3 and 'robots out of synchronisation', 'robot in Emergency stop' and'robot collisions' for type 4. 'Problem in tool' is high for each robot type. Some of these frequencies merely amplify the discussion in the previous section (for example the high percentage for 'erratic robot' with Type 2 robots) but other features are seen more clearly by this presentation. Robot collisions are caused by type 4 robots far more frequently than by type 3. Stiffness in the robot arm is shown to be present with robot types 1 and 4. Blown fuses occur only with robot types 3 and 4.

These variations in underlying reasons are shown to be significant in Appendix J. For all 4 types of robot, X^2 for the robot related reasons is 1024, compared to a critical value of 51. For types 1, 3 and 4 (the three types of electric robots), X^2 is considerably less at 236, but still well above the critical value of 32 for the three types. For types 3 and 4, which have the closest set of frequencies, the X^2 value is 119.4, compared with a critical value of 21.7. Thus each type of robot has a significantly different related set of underlying reasons. These differences are to some extent the result of differences in robot design, but differences in working practices and the effects of system requirements upon robot behaviour cannot be ignored. Thus it would be wrong to conclude from this analysis that the design of the four types of robots is the only relevant factor in deciding the susceptibility of a robot to certain problems, such as stiffness in the robot arm, even though it appears to be a major cause of the differences. Thus it is not possible to isolate the influence of robot design on problems and associated hazards.

The other parameters for robot related problems are an amalgamation of frequencies from a number of systems in each case. Since these parameters are strongly system-dependent, there is little benefit in discussing their variation in this section.

5) Robot failures

Incidents related to actual robot failures are of particular interest as they represent a record of the failure of components within robots during operation. Such incidents can be considered as distinct from other problems. The data provide six categories of robot failures:- 'cable problems', 'component failure in the robot arm', 'blown fuses', 'fault in control cabinet', 'fault in teach pendant' and 'fault in the power supply'.

a) Analysed by systems

Table 5.21 has shown that the frequency of occurrence of robot failures in each system is low but nevertheless significant. Table 5.23 below gives the number of incidents of robot failures in each system, with their downtime, mean downtime between failures (MTBF). MTBF values are calculated by dividing the robot production hours in each system by the numbers of incidents for each failure. Table 5.24 summarises the information in Table 5.23 by giving the robot production hours, overall number of incidents of robot failure and the overall MTBF for each system. The evidence of a low MTBF overall provides general support for Sugimoto and Kawaguchi's finding of poor reliability for industrial robots (see Chapter 1), although it appears that the robots in this study are more susceptible to failures than in the Japanese survey.

	No. of Cases	Downtime (Mins)	Mean Downtime (Mins)	MTBF (Hrs)
System A				
Manipulator fault	1	180	180	7548
Fault in cabinet	1	420	420	7548
Fault in teach pendant	2	10	10	3774
Overall	4	610	203.3	1877
System B5				
Cable problem	6	225	56.3	994
Manipulator fault	3	185	61.7	1988
Fault in cabinet	1	28	28	5964
Overall	10	438	54.8	596.4
System B6				
Cable problem	13	205	15.8	1905.5
Manipulator fault	19	373	23.3	1303.7
Blown fuses	11	184	16.7	2251.9
Fault in cabinet	12	362	32.9	2064.3
Fault in teach pendant	1	-	-	24771.0
Overall	56	112.4	22.0	442.3
System B7				
Cable problem	22	466	22.2	1018.8
Manipulator fault	9	210	52.5	2490.4
Blown fuses	6	69	11.5	3735.5
Fault in cabinet	10	179	19.9	2241.4
Overall	47	924	23.1	476.9
System F				
Cable problem	8	420	52.5	291.6
Manipulator fault	3	650	216.7	777.7
Fault in cabinet	3	350	116.7	777.7
Power supply fault	51	458	9.0	45.7
Overall	85	1378	28.9	35.9
System H				
Cable problem	1	360	360	1252
Manipulator fault	1	960	960	1252
Fault in cabinet	1	10320	10320	1252
Overall	7	11640	3880.0	417.3

Table 5.23 Robot Failures for Each Robot System

System	Robot Production Hours	Number of Incidents of Robot Failure	Mean Time Between Robot Failures (Hours)
A	7548	4	1887.0
B5	5964	10	596.40
B6	24771	56	442.34
B7	22413.4	47	476.88
F	2333	65	35.89
H	1252	3	417.33
Overall	64281.5	185	347.48

Table 5.24 Mean Times Between Failures for Robot Systems

The first three columns of Table 5.23 are taken from Appendix F. From this we can see that the systems in Factory F have high mean downtimes for three categories of robot failure, with lower mean times between failure for these than in the other systems. The lowest mean time between failure was for 'power supply faults', which only occurred in F. The figure of 45.7 hours for the MTBF was much lower than for any other robot system. Although no such incidents were recorded with H (which also had Type 2 robots) it was found that a period had occurred prior to the study when faults in the power supply had been frequent. Thus one can conclude that this is a type of failure to which hydraulic robots are particularly prone.

It is a feature of this failure in F that a large proportion of incidents of power supply faults occurred in a short time period. Over a period of less than a week in the middle of the period of study, 31 of the 51 incidents with this failure occurred on one of the two robots in F. There were similar concentrations of incidents in the following four weeks and 1-2 months later. This type of failure was different from others in that the downtime caused was short (see Table 5.23) and the actions often involved little more than a reset or minor replacement. What is more the concentration of this type of failure over a short period suggests a common cause of failure.

The proportions of various categories of robot failures are not significantly different for the three systems in Factory B. A X^2 value of 10.8 is found, compared to a critical value of 16.8 (see Appendix J). F is significantly different from these systems in this respect. When the number of incidents per unit robot production time are compared, F appears once more as significantly different. The X^2 value for all 6 systems is 532.9, compared with a critical value of 15.1. When F is excluded from the comparison, the X^2 value drops below the critical value (9.7 compared with 13.3). The other 5 systems therefore do not have a significant difference in the proportions of various robot failures.

T-tests on the downtime figures showed that A and H have significant differences from the other systems whereas the other systems show little significant difference between each other. It should be noted that A and H have the fewest robot failures (see Appendix J). Thus the four systems with relatively numerous robot failures show a great deal of similarity in the downtime. F is not significantly different from the systems in Factory B in respect of the downtime caused by failures. However, the previous discussion in this section would suggest that this lack of a difference is not particularly noteworthy.

b) Analysed by robot type

Table 5.25 presents the information for robot failures for each robot type on the number of incidents, downtime and MTBFs. It is equivalent to Table 5.23, for types of robots rather than systems. Table 5.26 summarises the information from Table 5.25. Type 2 is shown once more to be the worst robot type. Robot types 3 and 4 have overall MTBFs of approximately one order of magnitude greater than type 2, whereas type 1 has MTBF overall of more than three times the second largest (Type 4). Even excluding the numerous (though short duration) incidents of power supply faults, type 2 robots have an MTBF of 239 hours, roughly half the nearest (type 3). Type 1 robots are the most reliable, and Type 2 the least in the systems studied.

Types 3 and 4 are quite similar in terms of overall MTBF and mean downtimes. The four categories of robot failure with type 3 are also present in 4, with the addition of 1 incident of a fault in a teach pendant. No significant difference in the robot failures between these two robot types is found (see Appendix J). When types 1, 3 and 4 are considered together, the χ^2 value of 13.2 just falls within the critical value of 13.3. Thus at the confidence level of 0.01, there is no significant difference between these 3 types. For all 4 types however, the χ^2 value was 140.2 (Chi-square crit = 21.7). Thus the differences between the four are significant but not between the three electrical robot types, showing that the types of failures of hydraulic robots are significantly different from those of electric robots.

T-tests on downtimes showed more significant differences between type 1 and the others (see Appendix J). At a significance level of 0.05, type 1 is significantly different from all three other types. At a significance level of 0.01, it is still significantly different from type 4. The other three types do not display any significant differences from each other.However, there are significant differences between the

	No. of Cases	Downtime (Mins)	Mean Downtime	MTBF
Type 1				
Component failure in robot arm	1	180	180	9599.5
Fault in cabinet	3	465	232.5	3199.8
Fault in teach pendant	2	10	10	4799.3
Overall	6	655	163.8	1599.9
Type 2				
Cable problem	9	780	86.7	398.3
Component failure in robot arm	4	1610	402.5	896.2
Fault in cabinet	4	10670	2667.5	896.2
Power supply fault	51	458	9.0	70.3
Overall	68	13518	198.8	52.7
Type 3				
Cable problem	12	392	39.2	1180.8
Component failure in robot arm	8	232	33.1	1771.2
Blown fuses	6	84	14.0	2361.7
Fault in cabinet	6	81	13.5	2361.7
Overall	32	789	27.2	442.4
Type 4				
Cable problem	29	504	18.0	1273.3
Component failure in robot arm	23	536	33.5	1605.5
Blown fuses	11	169	15.4	3357
Fault in cabinet	15	443	31.6	2461.8
Fault in teach pendant	1	-	-	36927.0
Overall	79	1632	23.7	467.4

Table 5.25 Robot Failures by Robot Type

Type	Robot Production Hours	Number of Incidents of Robot Failure	Mean Time Between Robot Failures (Hours)
1	9599.5	6	1599.9
2	3585	68	52.7
3	14170	32	442.8
4	36927	79	467.4
Overall	64281.5	185	347.5

Table 5.26 Mean Times Between Failures for Robot Types

variances of type 2 and 4, and also to some extent between types 2 and 3. This suggests that even though the downtime distributions are not significantly different, these downtime figures do not come from the same overall population. This would be in keeping with the fact that type 2 robots are hydraulically powered whilst types 1, 3 and 4 are electrical.

The analysis in this section shows that the failures of robots in Factory B have considerable similarities. The differences between failures of electrically powered robots are also not significant. The robot failures of the hydraulic robots in F are clearly of a different type even if some similarity in the resultant downtime is found. A major cause of the difference is likely to be the different source of power for the robots. The failure of the robots in H to follow the same pattern as in F can be explained by the task requirements. There was evidence to suggest that historically the behaviour of the robots in H had been similar to those in F even though this was not so during the study period. This would agree with the experience in F of short periods of unusual behaviour by the robots.

6) The distribution of periods of downtime

The majority of incidents have a short duration. This feature of the data is shown to some extent by the mean downtime figures, but these figures do not give a full understanding of the proportion of incidents in the lower end of the downtime scale. The predominance of short duration incidents suggests that on the whole, personnel were able to solve problems. with relative ease.

a) The subdivision of downtime into three categories

Appendix I divides the incidents into short, medium and long duration categories, that is under 10 minutes, between 10 minutes and 1 hour and over 1 hour. This appendix gives the number of cases in each system, the downtime total, the mean values and the underlying reasons for each group.

Table 5.27 below is a summary of Appendix I giving percentages of incidents (with each system) and percentages of downtime. This table shows that a higher percentage of incidents last 10 minutes or less and a small percentage last 1 hour or more. H is exceptional in having high downtime from few incidents. Appendix F shows that each underlying reason in H

Systems	Short Duration Incidents			Medium Duration Incidents			Long Duration Incidents		
	No. of Incidents	% of all Incidents	% of Downtime	No. of Incidents	% of all Incidents	% of Downtime	No. of Incidents	% of all Incidents	% of Downtime
A	264	35.5	10.5	87	11.7	18.8	35	4.7	70.7
B5	281	42.4	20.1	62	9.4	25.9	27	4.1	54.0
B6	1150	74.1	32.8	169	10.9	33.0	31	2.0	34.2
B7	1333	73.2	38.6	161	8.8	34.3	25	1.4	27.1
F	458	54.4	20.1	307	37.9	33.6	60	7.4	46.3
H	1	7.7	0.08	1	7.7	0.12	9	69.2	99.8
Overall	3467	61.9	19.1	787	14.0	25.3	187	3.3	55.6

Short Duration - 10 minutes or less
Medium Duration - between 10 minutes and 1 hour
Long Duration - over 1 hour

Table 5.27 Downtime of Short, Medium and Long Duration has a mean downtime figure of over 1 hour. However it needs to be pointed out that the number of incidents in H is a negligible proportion of the overall total, being roughly 0.2% of all incidents. Indeed the number of incidents exceeding one hour in H is a smaller number than those with any other system, even though these formed a majority of incidents in H.

The proportion of incidents of short, medium and long duration periods in each system is tested for significant variation in Appendix J. Excluding H and its obviously different distribution, the X^2 value for frequencies of occurrence is 437.1, compared with a critical value of 20.1. For B6 and B7, which Table 5.27 shows to have quite similar percentages of incidents in short and long periods of downtime, the X^2 value is 4.3, compared with a critical value of 9.2. Thus, whereas there is a significant difference overall in the percentages in each category of length of downtime, for B6 and B7 there is no significant difference. The similarity of system design, task and work organisation produces highly similar grouping of downtime. However, it should be remembered that a significance test of all incidents in B6 and B7 showed a significant difference(though not for robot related incidents).

The mean downtime figures given in both sets of figures in Appendix I give some indication of the distribution within each group of incidents. The overall figure for short duration incidents gives a mean of below 5 minutes. In other words, there is an even greater concentration of incidents towards the bottom half of this group. For long duration incidents, the mean is over 3 hours. Thus there are a large proportion of these incidents which lasted for much longer than one hour.

b) A Statistical analysis of downtime

The discussion of the distribution of downtime above provides a coarse level of understanding of the spread of downtime values. For a fuller understanding, the individual occurrences of downtime need to be considered. This section presents a statistical analysis of the data and compares the downtime with suitable mathematical distributions. The most suitable distribution is applied to the overall figures and to some of the groups of incidents considered above, to show the applicability of the same distribution throughout. This analysis identifies the accuracy of the representation of the figures by a single distribution and clarifies some areas of similarities between groups.

If one considers only the recorded incidents with downtime, there are 4441 relevant incidents overall. The total downtime is 72846 minutes, with a mean of 16.4 minutes. Computer analysis of the data also provides the median value (4.6 minutes), the standard deviation (161.4 minutes) and the skewness (58.9 minutes). The mean value is thus between 3.5 and 4 times greater than the median value. Thus the figures are highly skewed, for which a Gaussian distribution is not a good approximation.

The conclusion above is supported by the value for the standard deviation. If the distribution of downtime figures were approximated to a Gaussian distribution then 68.26% of all the sample would be expected to fall within 1 standard deviation above and below the mean (Green and Bourne, 1972). This would be nonsensical with the data in this study, since one standard deviation below the mean would give a value of -145.04 minutes, clearly an impossible value. The high value for the skewness (58.9) further emphasises the inapplicability of the use of the Gaussian distribution to describe the data. Initial visual inspection of the recorded incidents with downtime suggests that a log-normal distribution would be a suitable approximation to the distribution of downtime (see Graph 1).

Green and Bourne (1972) give the probability density function of the log-normal distribution as:-

$$f(x) = \frac{1}{x\,\sigma\,\sqrt{(2\pi)}} \exp\left[- (\log_e(x-\mu)^2/2\sigma^2 \right] \qquad (1)$$

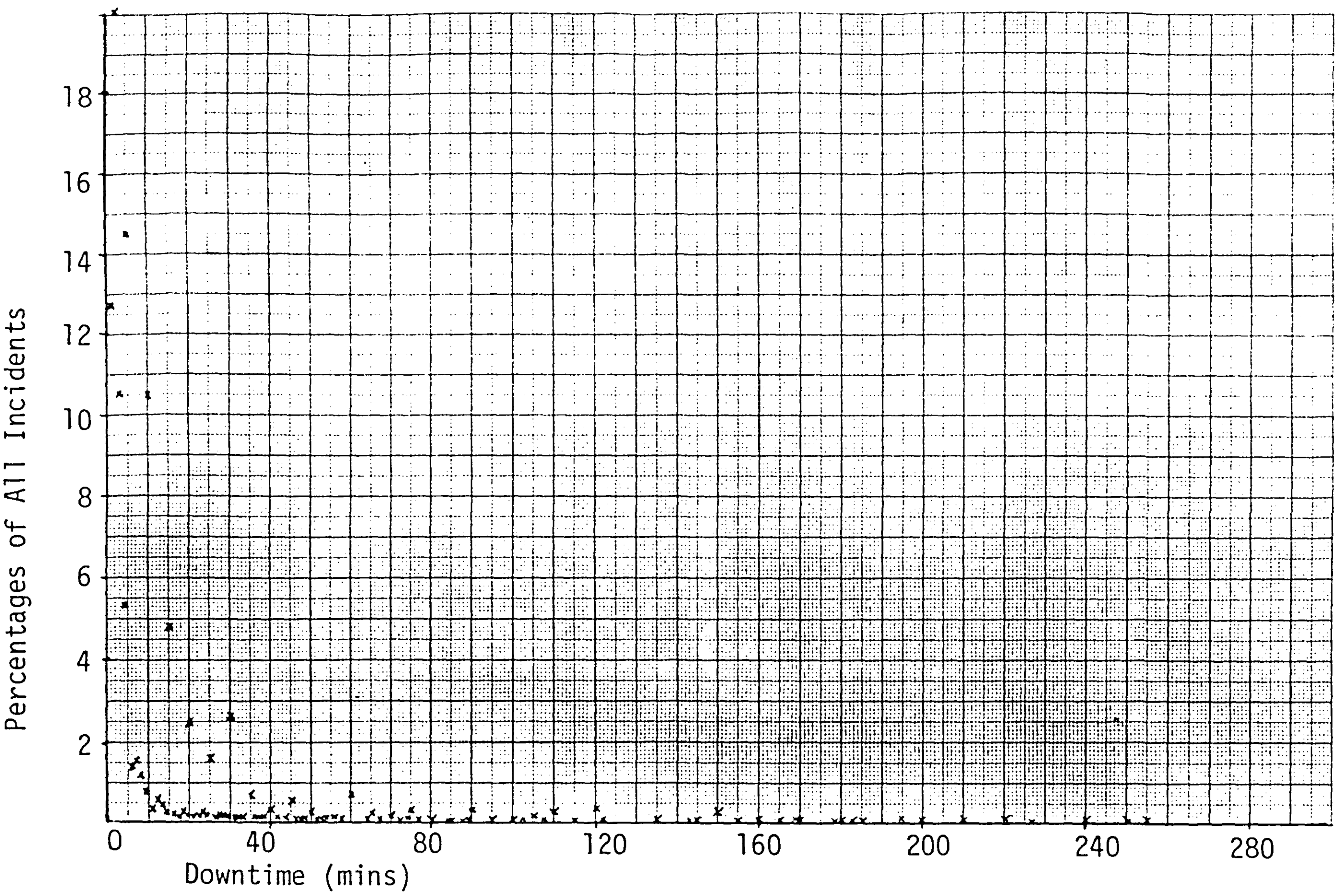
where x has values in the range $0 < x < \infty$.

This compares with the normal or Gaussian distribution of:-

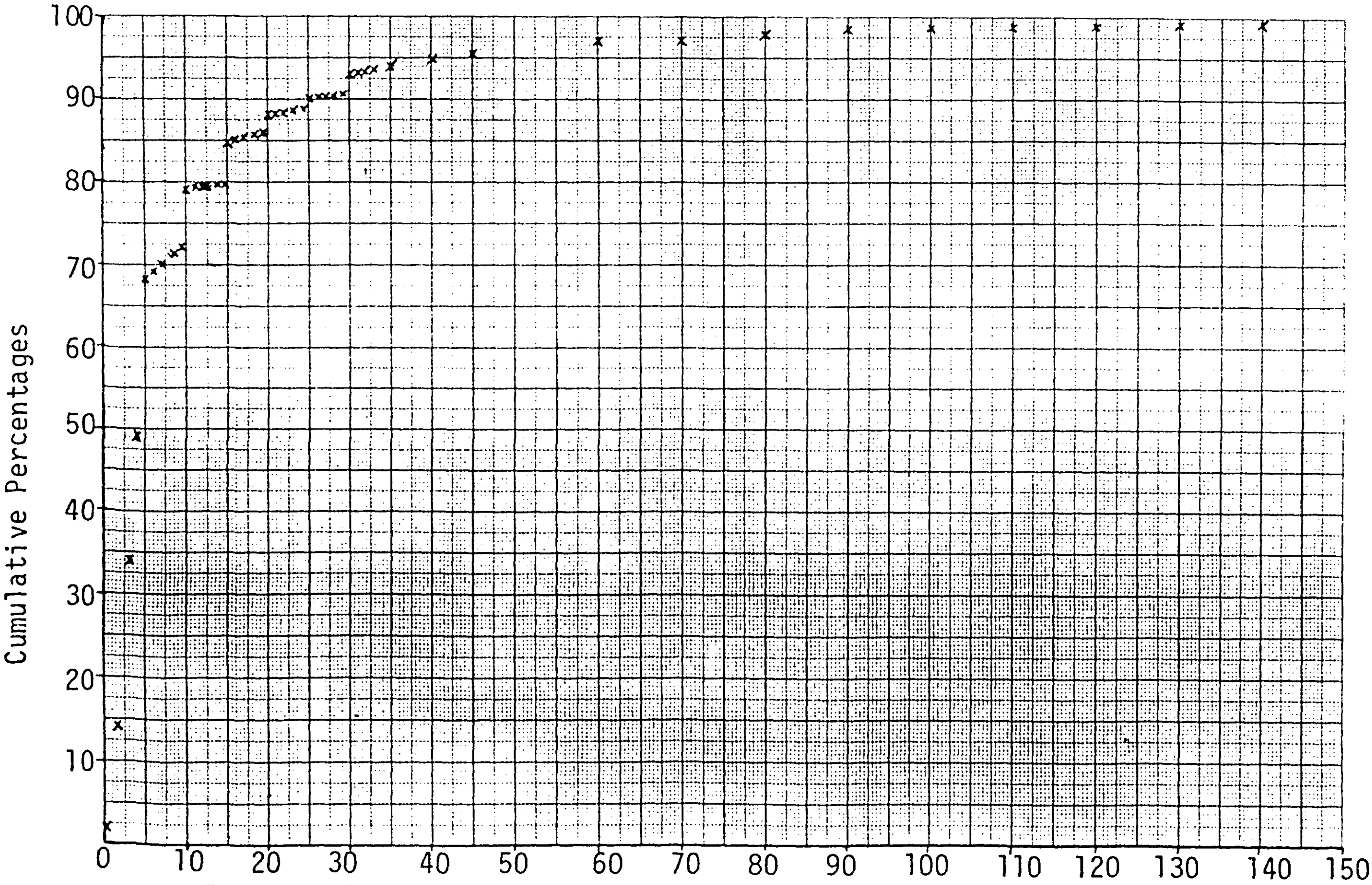
$$f(x) = \frac{1}{\sigma\sqrt{(2\pi)}} \exp\left[- (x-\mu)^2/2\sigma^2 \right] \qquad (2)$$

with x in the range $-\infty < x < \infty$.

Thus for a log-normal distribution the natural logarithm of the variable follows a normal or Gaussian distribution. Graph 1 shows that the highest frequency of incidents occurs at the extreme left, with short duration. In fact, the mean value of 16.4 minutes has 84.7% of incidents below it. The cumulative distribution is shown in Graph 2, with the mean (μ_1) shown. Graph 2 shows that roughly 93% of incidents with downtime recorded lasted less than 30 minutes.



Graph 1 Probability Density Function for All Incidents



Graph 2 Cumulative Distribution for All Incidents

To show that this distribution can be approximated to a log-normal distribution, the cumulative distribution function is plotted on log-probability paper. This type of graph paper is produced specifically to draw log-normal distributions and has a logarithmic scale on the abscissa and a probability scale on the ordinate. A plot of a function on this paper produces a straight line for the cumulative distribution if the function is distributed log-normally (Bompas-Smith, 1973). The values for cumulative percentages of incidents are plotted against the downtime for all the production problem data in order to test the applicability of the log-normal distribution.

Graph 3 is the plot for all incidents with downtime. There are 4441 incidents overall with downtime recorded. However, 78 of these have a downtime of 0 minutes. These must be classed as missing cases, as their natural logarithm value is $-\infty$. Thus there are only 4363 incidents in Graph 3. A reasonably straight line can be drawn from this. A computer analysis of the natural logarithms of the downtime values produces a mean value of 1.660 and a standard deviation of 1.209. Green and Bourne gives the mean value of a log-normal distribution (p. 244-249, 1972).

The mean of the distribution given in Equation (1) is:-

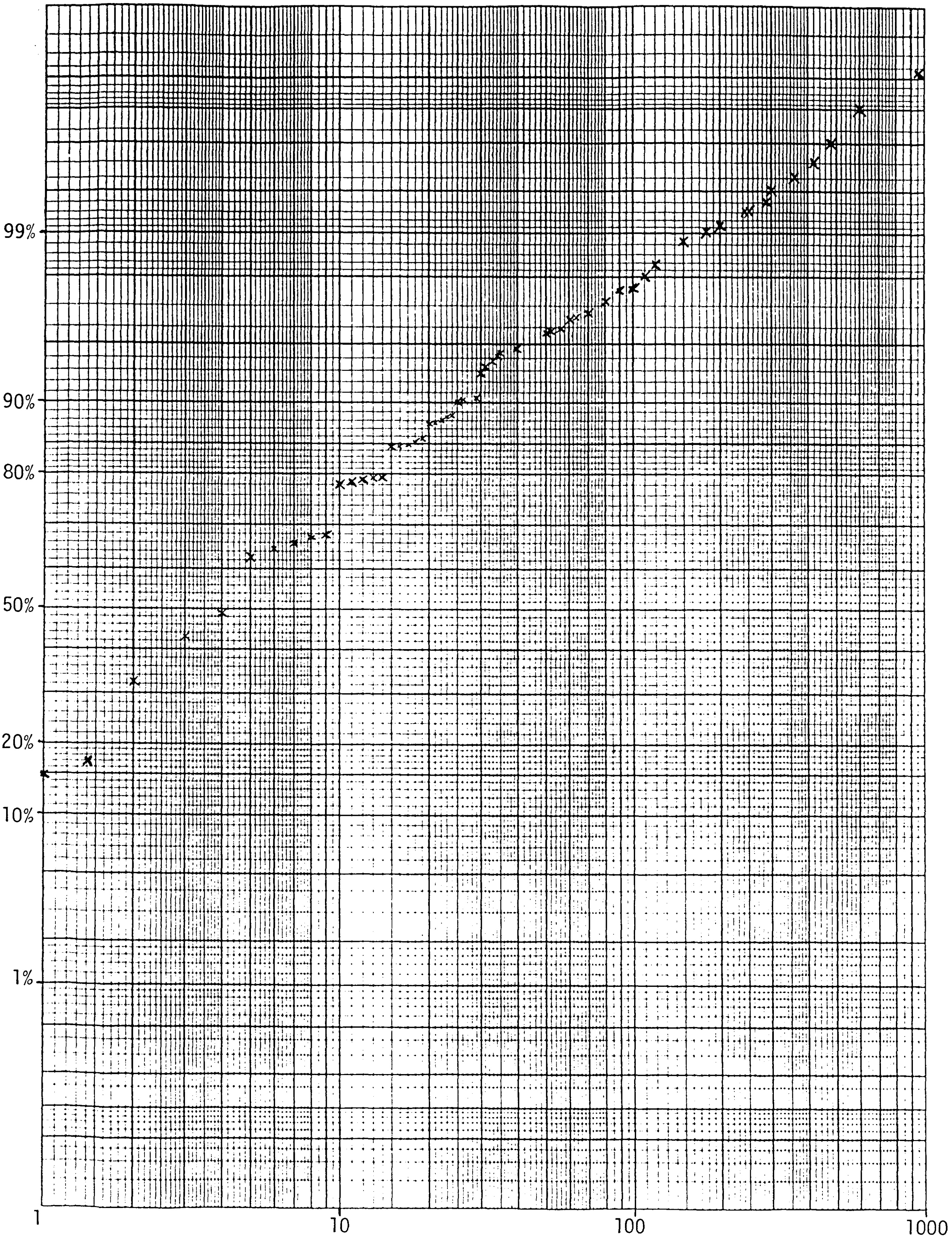
$$\text{mean} = \exp(\mu + \frac{1}{2}\sigma^2) \tag{3}$$

For the distribution in Group 3, the mean downtime is 10.92 minutes. The value for skewness of the distribution is $+0.860$, signifying that the distribution extends further in a positive direction than it would if it fitted the above distribution exactly.

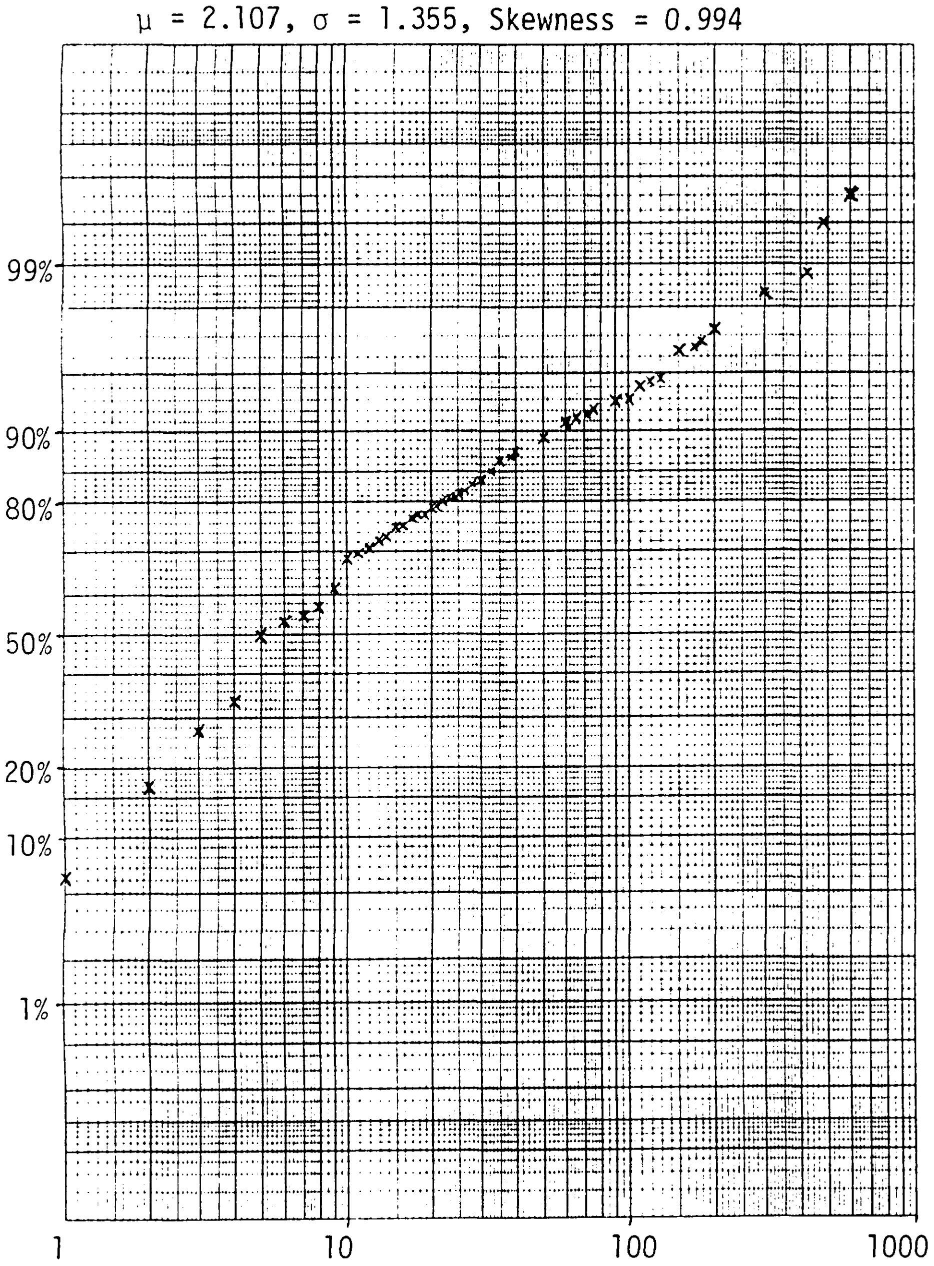
The robot systems. Plots of the downtime in each system on log-probability paper are presented in Graphs 4-9. In each, the values for the mean and standard deviation generated by computer analysis of logarithm values of time are presented.

In A, a straight line does not occur, but rather a central part which is straight and a divergence above and below (below 10 minutes and above 400 minutes). This distribution suggests the possibility of a combination of more than one distribution function each of which could be log-normal. In B5 a straight line is a close approximation to the points. In B6 and B7 similar plots occur, with very good agreement between the values

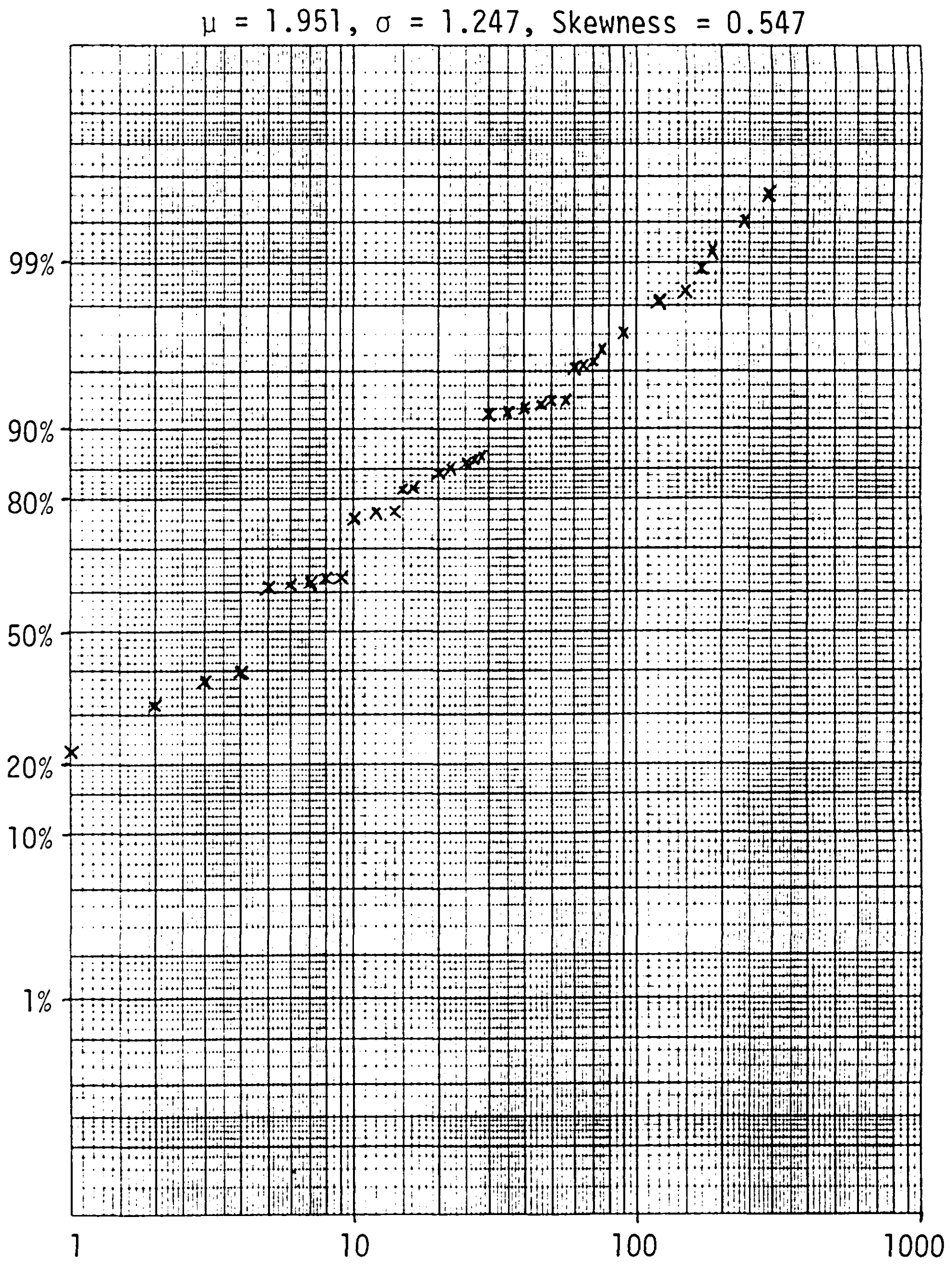
μ = 1.66, σ = 1.209, Skewness = 0.860



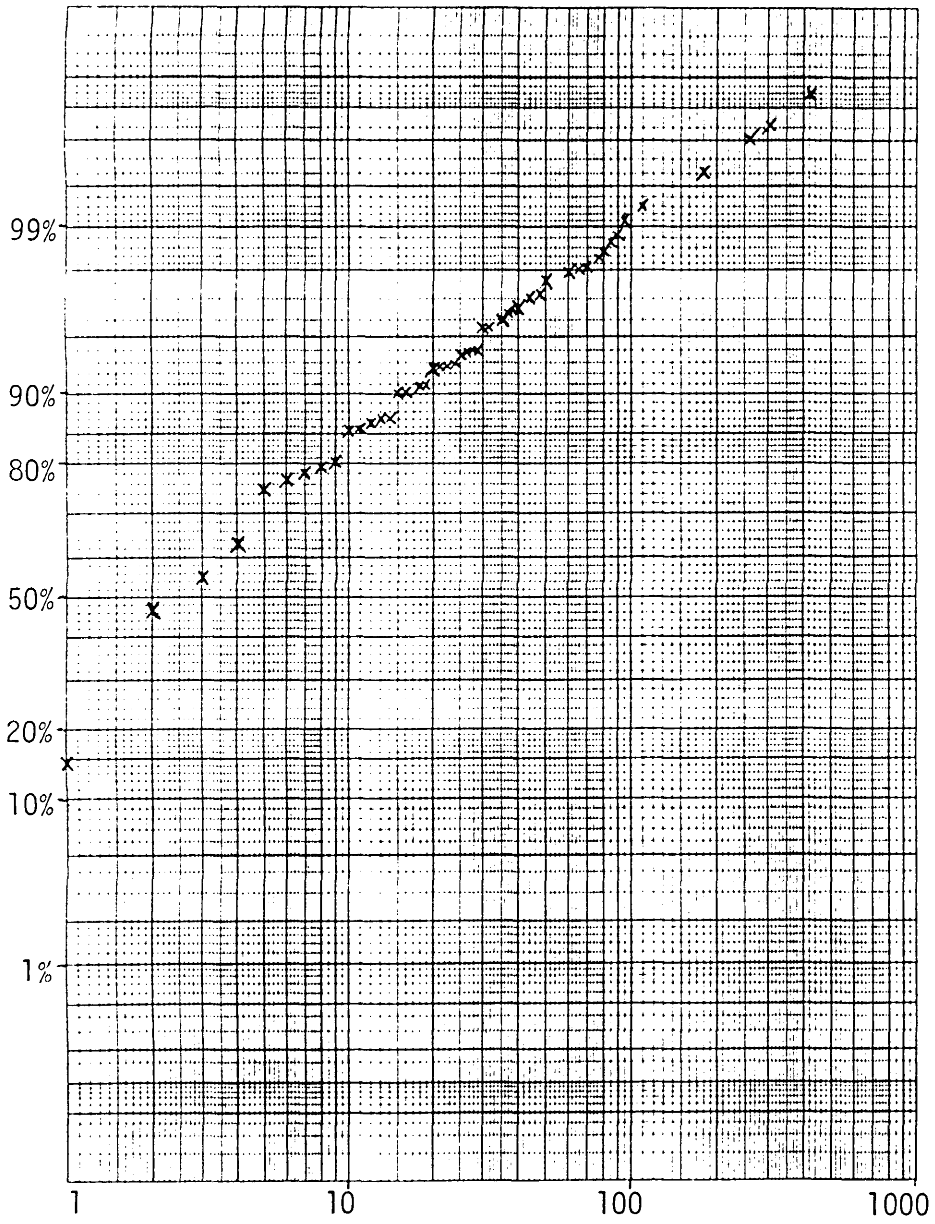
Graph 3 Plot of All Incidents with Downtime



Graph 4 Plot of All Incidents in Factory A

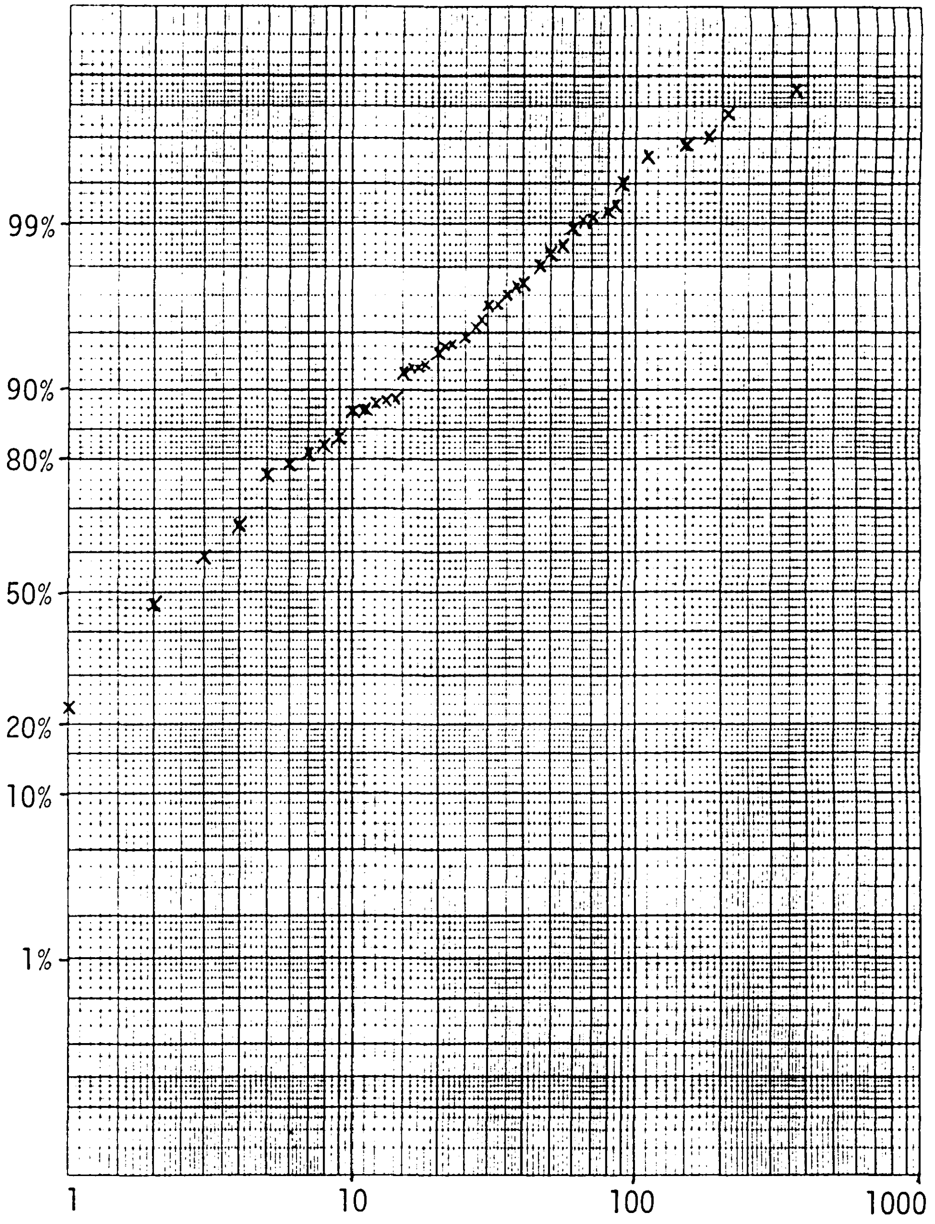


Graph 5 Plot of All Incidents in Factory B (System 5)



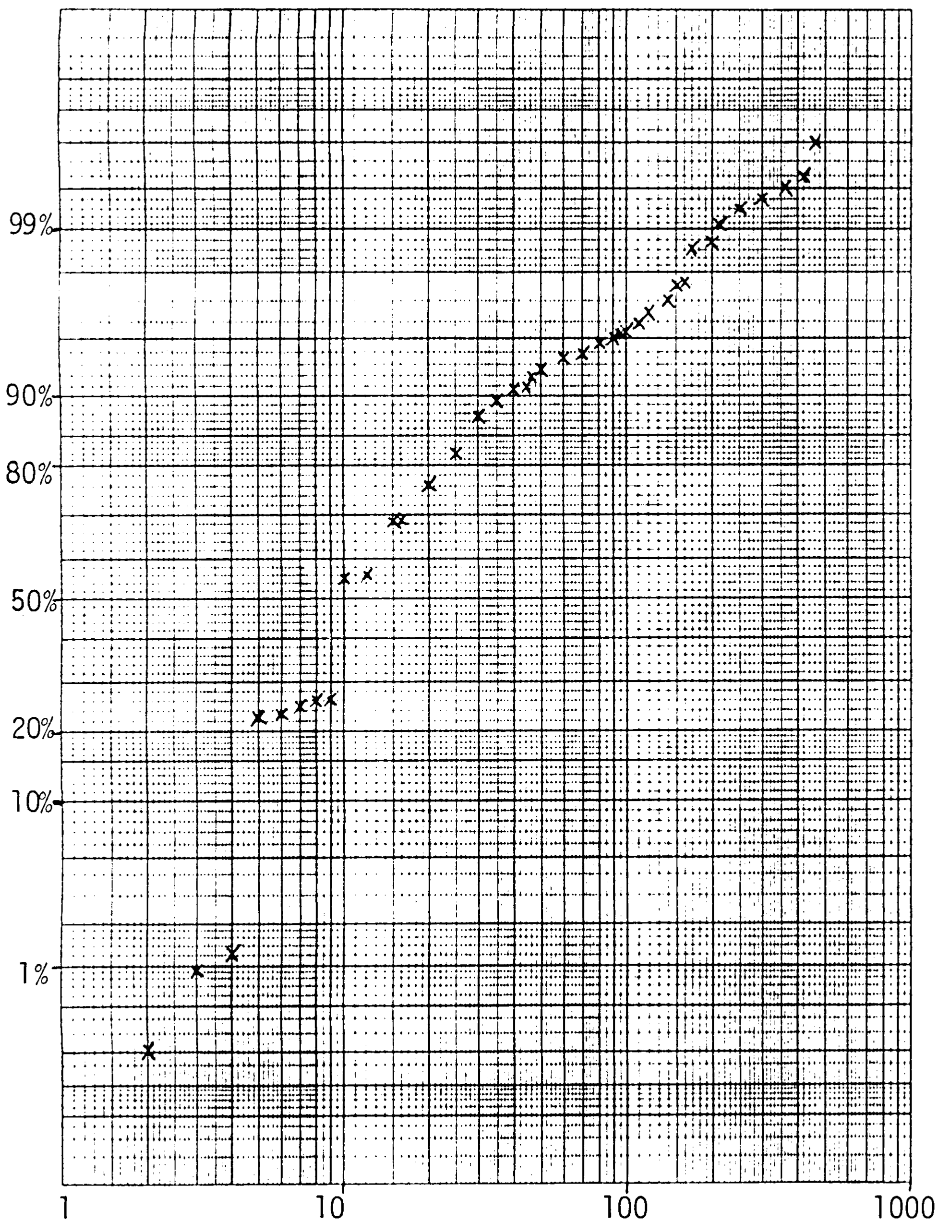
μ = 1.364, σ = 1.05, Skewness = 1.113

Graph 6 Plot of All Incidents in Factory B (System 6)



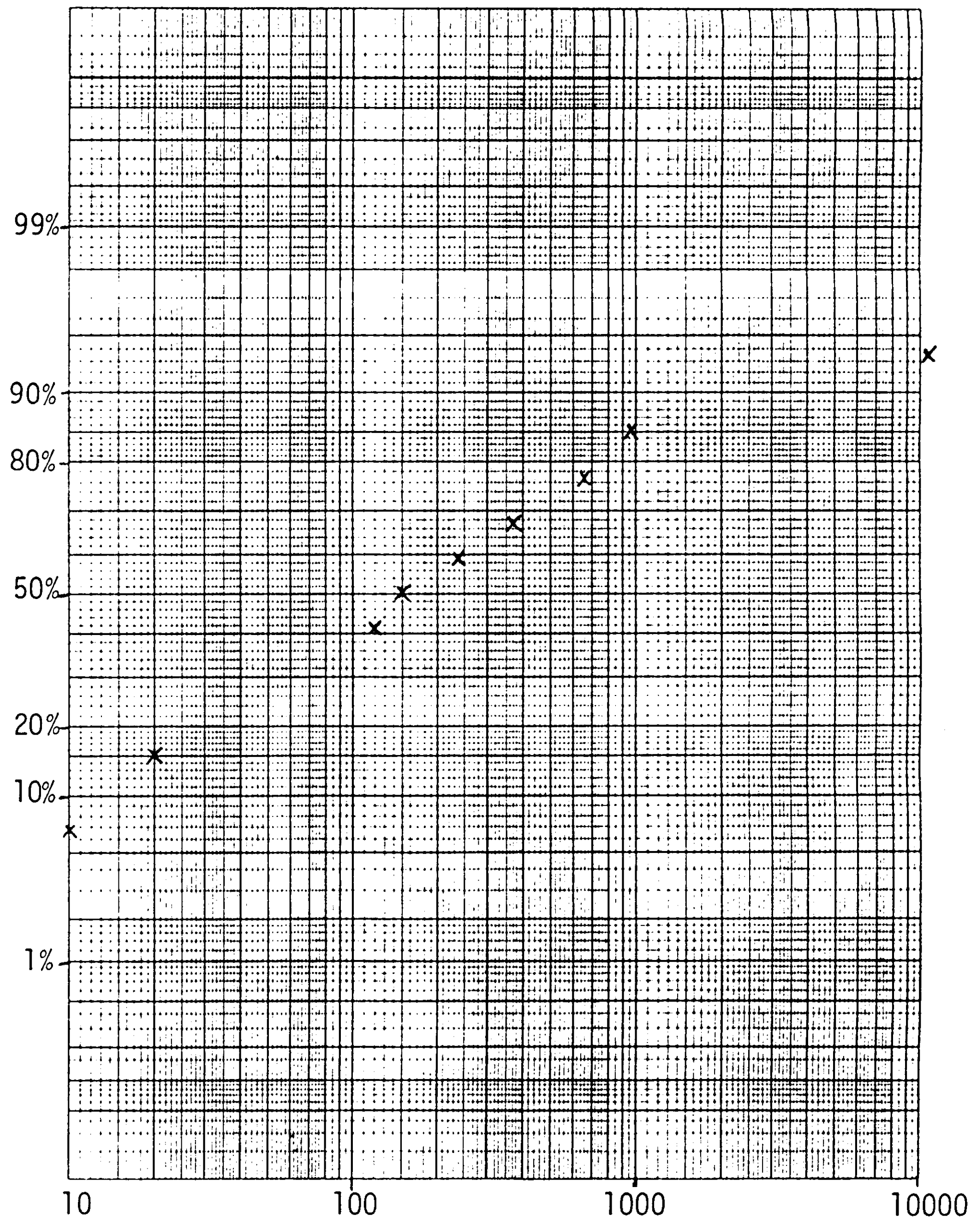
μ = 1.211, σ = 1.036, Skewness = 1.026

Graph 7 Plot of All Incidents in Factory B (System 7)



μ = 2.615, σ = 0.896, Skewness = 1.144

Graph 8 Plot of All Incidents in Factory F



μ = 5.331, σ = 1.869, Skewness = 0.452

Graph 9 Plot of All Incidents in Factory H and a straight line. In F the points appear to fall on two straight lines of quite differing slopes.

In H the small number of incidents with downtime (11) makes the use of percentage points an inaccurate measure (see Smith, 1976). Median ranks are used to place the points on the graph paper. The result is a very good approximation to a straight line, with the exception of the last point. This, at 10320 minutes is well above the top value that could be expected from the other points. A value of about 2,500 minutes for the longest duration for an incident would give a very good linear plot.

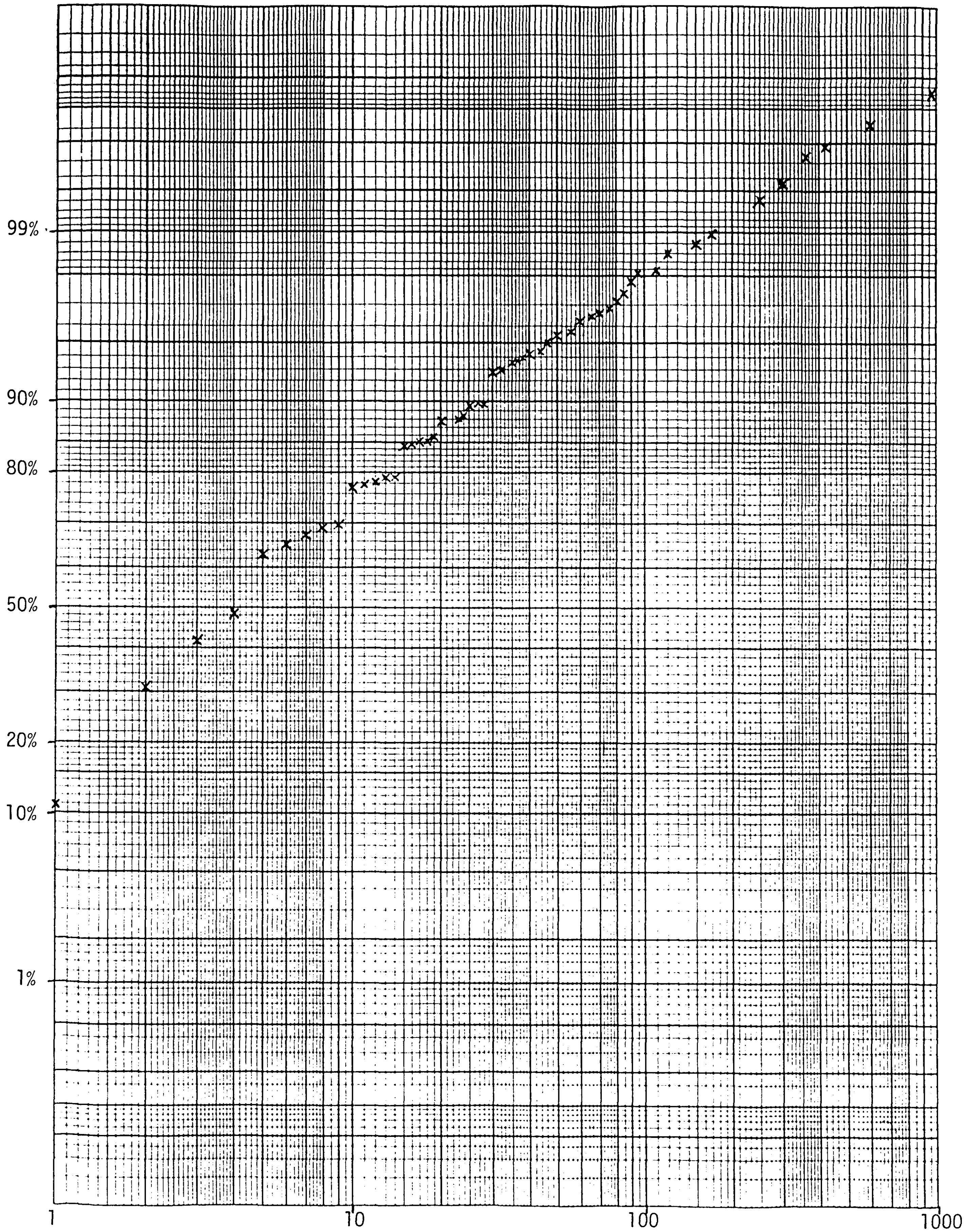
From Graphs 4-9 one can see that the distribution of downtime in each system can be approximated to the log-normal distribution. A similarity between A and B5, not shown in the mean of downtime in Appendix D is more apparent here.

The applicability of a single distribution is suitable to most systems (A, B5, B6, B7 and H) but not to F. In F there appears to be the possibility of a combination of distributions.

Robot related incidents. There are 1635 robot related incidents of which 1435 have a record of downtime. However, one of these has a downtime of 0 minutes and so only 1434 incidents are valid here. Graph 10 shows the plot of all robot related incidents on log-probability paper, showing a slight curve towards the higher values. A line drawn by visual inspection appears to be a reasonable approximation to the points. The mean, standard deviation and skewness of the computer analysis is also given. Once more the distribution is skewed to the positive (+0.994), arising from the slope of the points at high values.

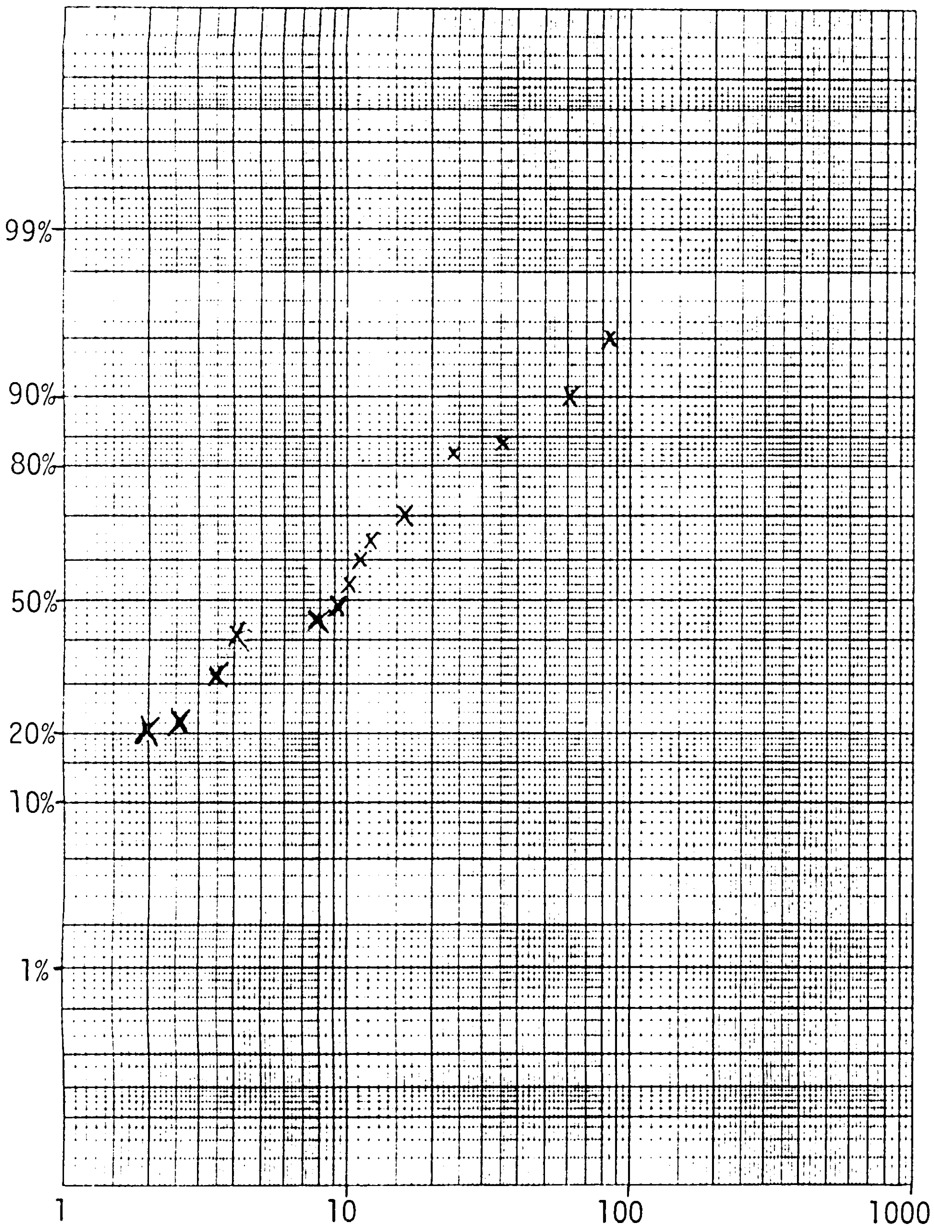
Plots of robot related incidents in each system do not approximate to a straight line as well as the overall figures for each system (see Graphs 11-16). Once more F shows the worst approximation to a log-normal distribution. However the log-normal distribution is still a fairly close representation. A and B5 are once more very similar, with means of the logarithm of downtime equal to 2.569 and 2.475 and the standard deviation equal to 1.584 and 1.256 respectively. This similarity is not shown clearly in the ordinary statistics, where the means differ by nearly 20 minutes. The mean of the logarithm of downtime for F is also similar to these two, but the standard deviation is only 0.906. The similarity between B6 and B7 in the ordinary statistics is supported by the plots and in Graphs 13 and 14.

μ = 1.672, σ = 1.189, Skewness = 0.994



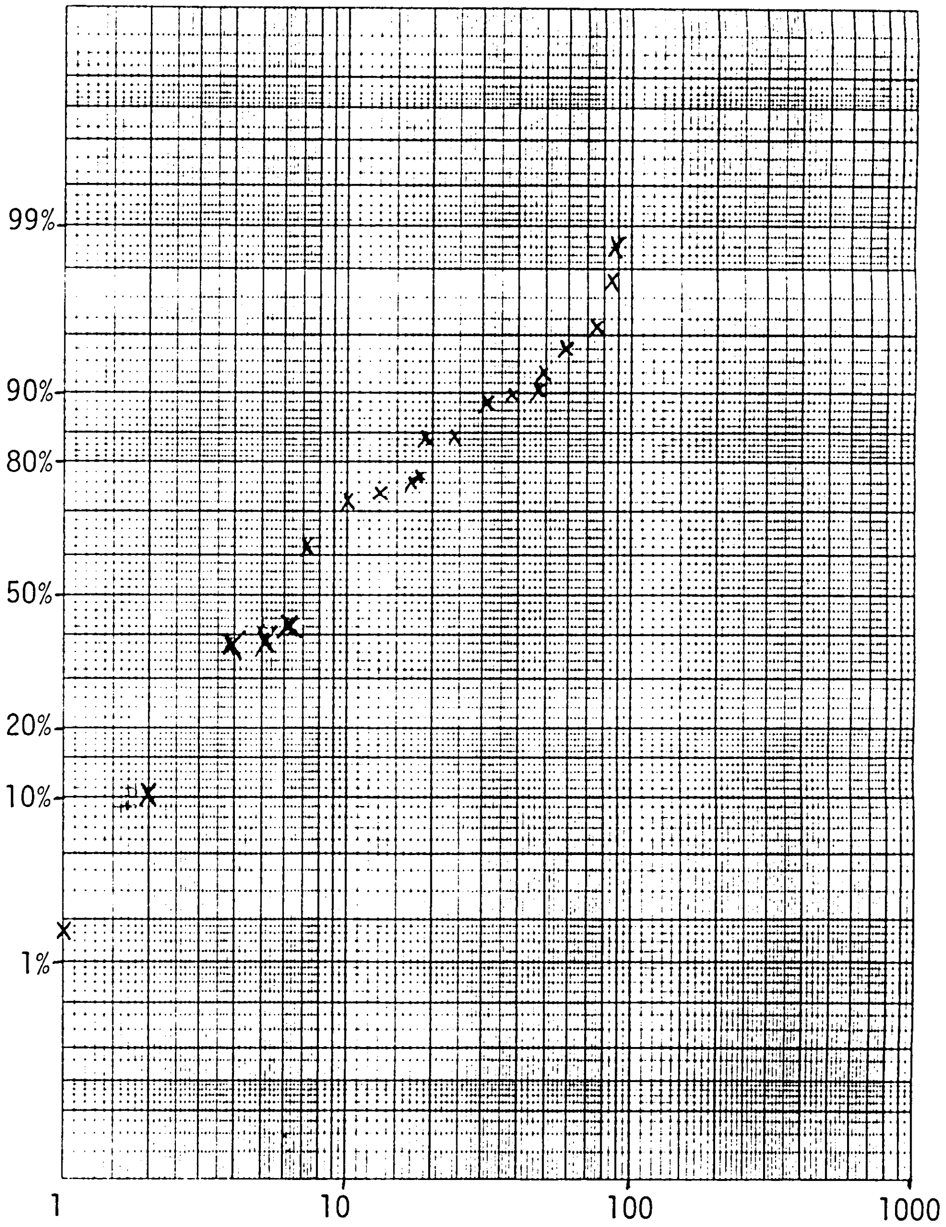
Graph 10 All Robot Related Incidents

μ = 2.569, σ = 1.584, Skewness = 0.59



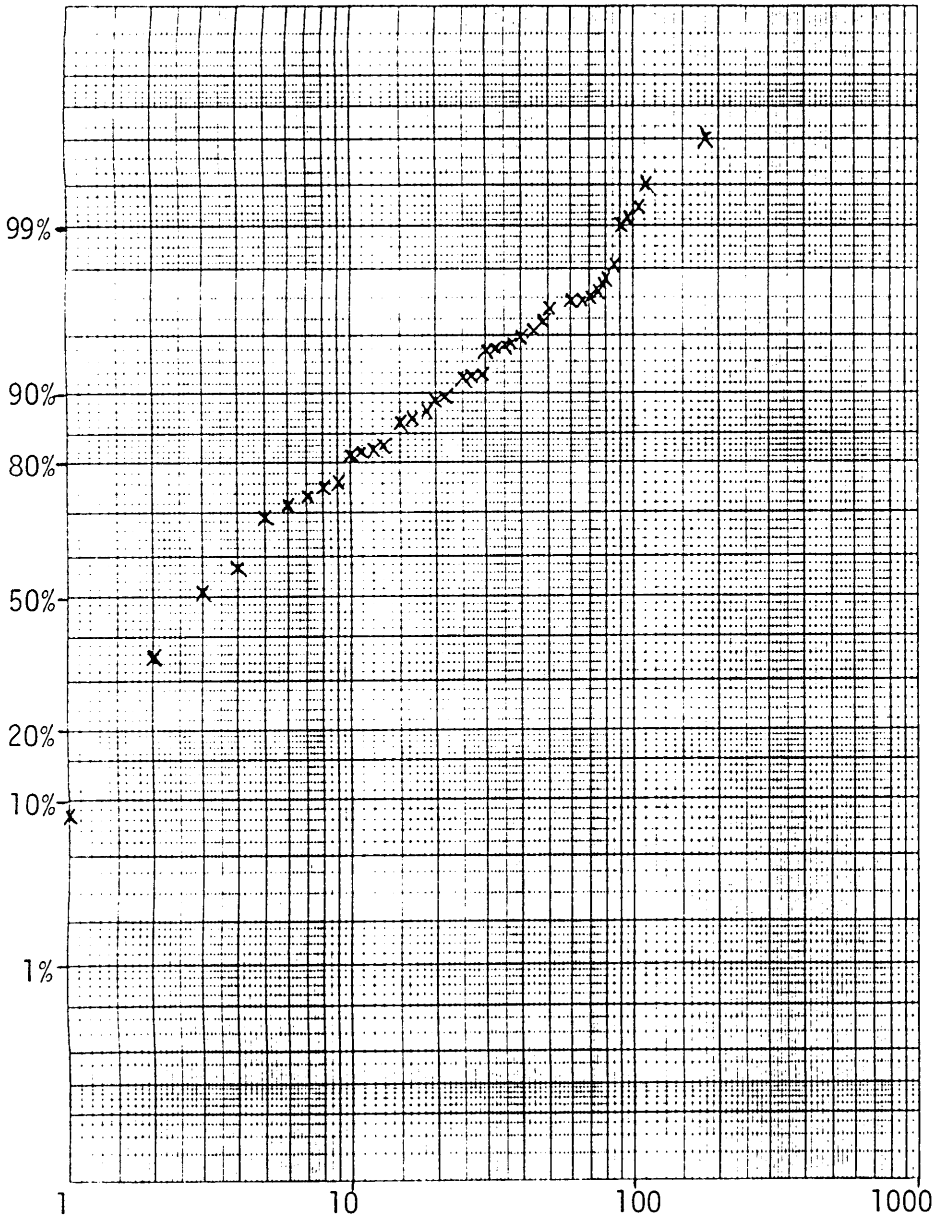
Graph 11 Robot Related Incidents in Factory A

μ = 2.475, σ = 1.256, Skewness = 0.619



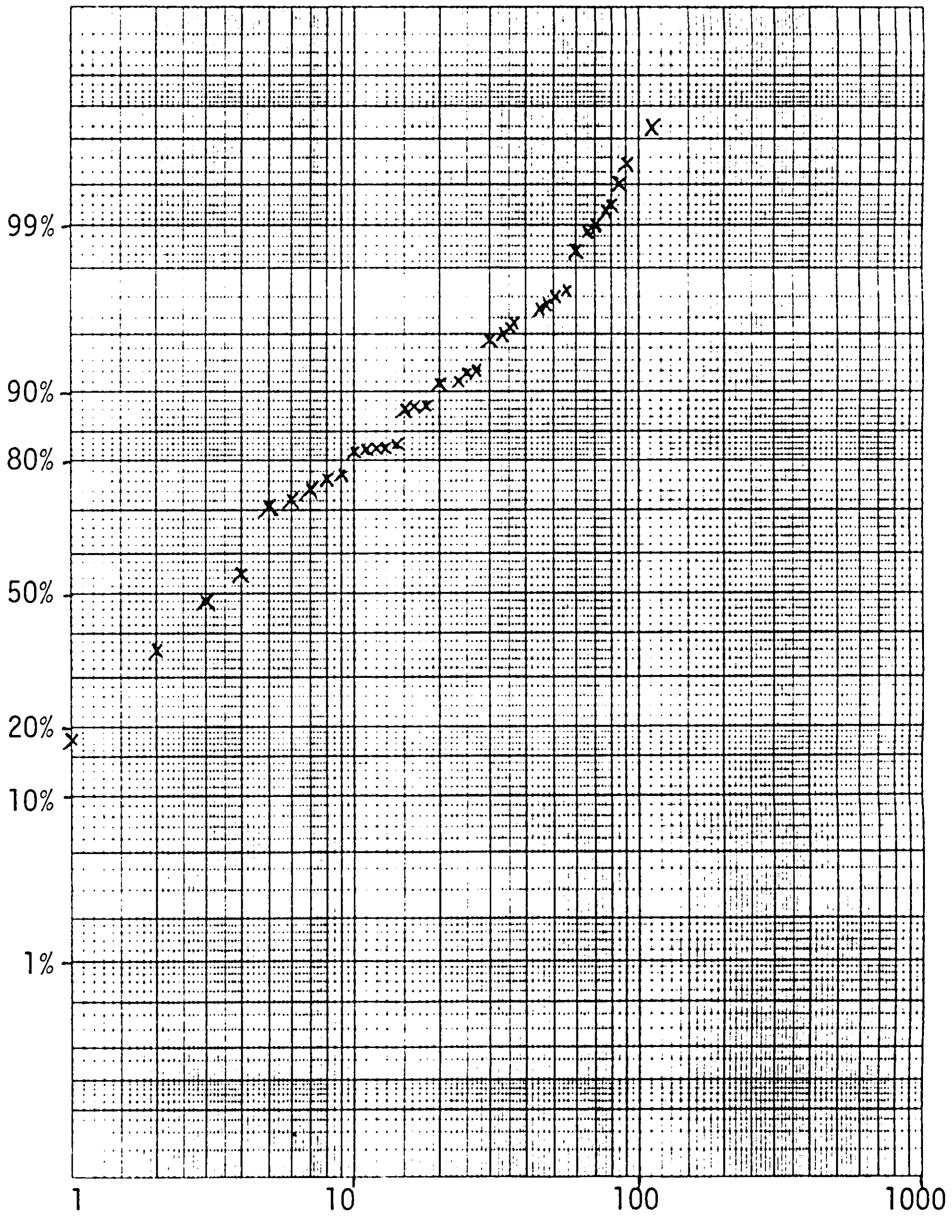
Graph 12 Robot Related Incidents in Factory B (System 5)

μ = 1.531, σ = 1.088, Skewness = 1.001



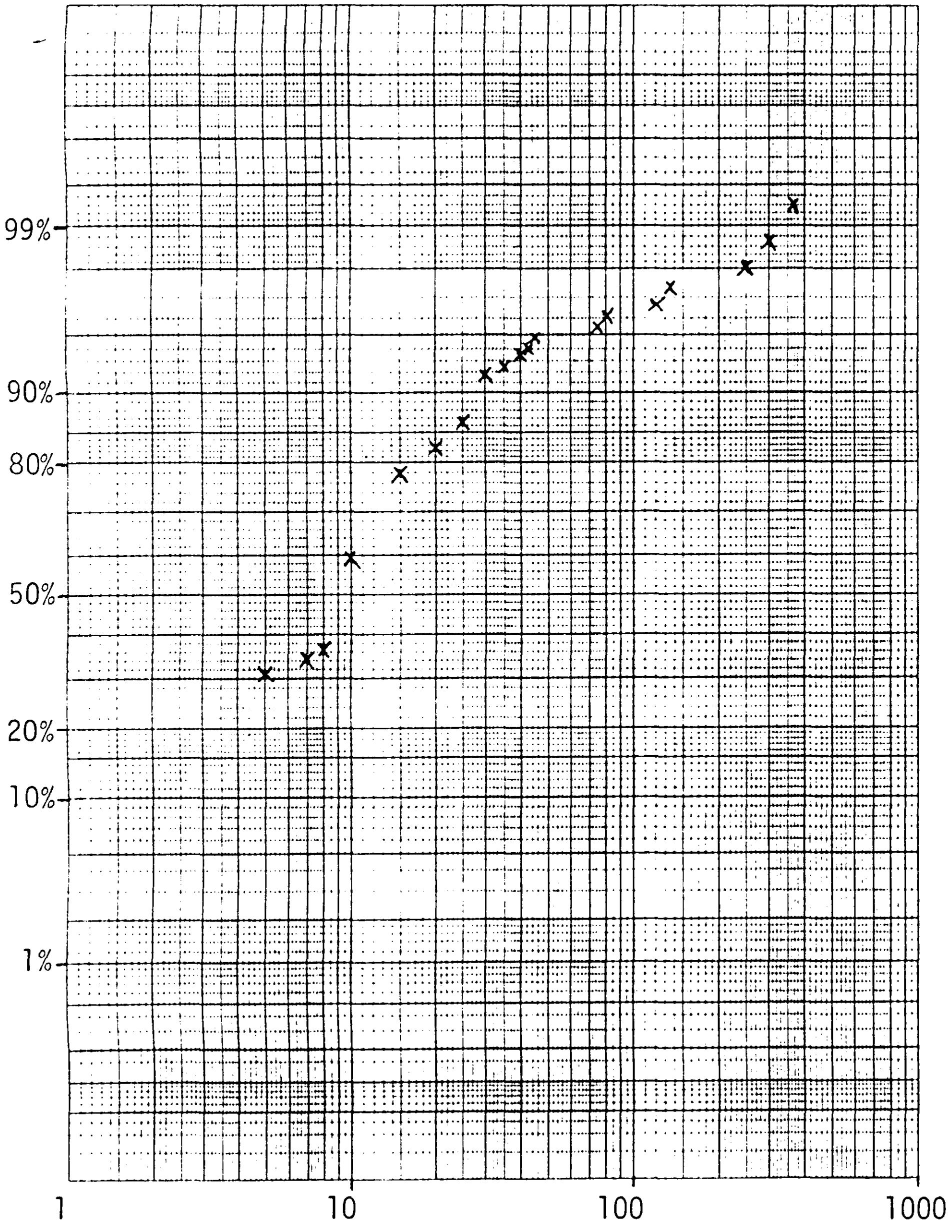
Graph 13 Robot Related Incidents in Factory B (System 6)

μ = 1.436, σ = 1.087, Skewness = 0.697



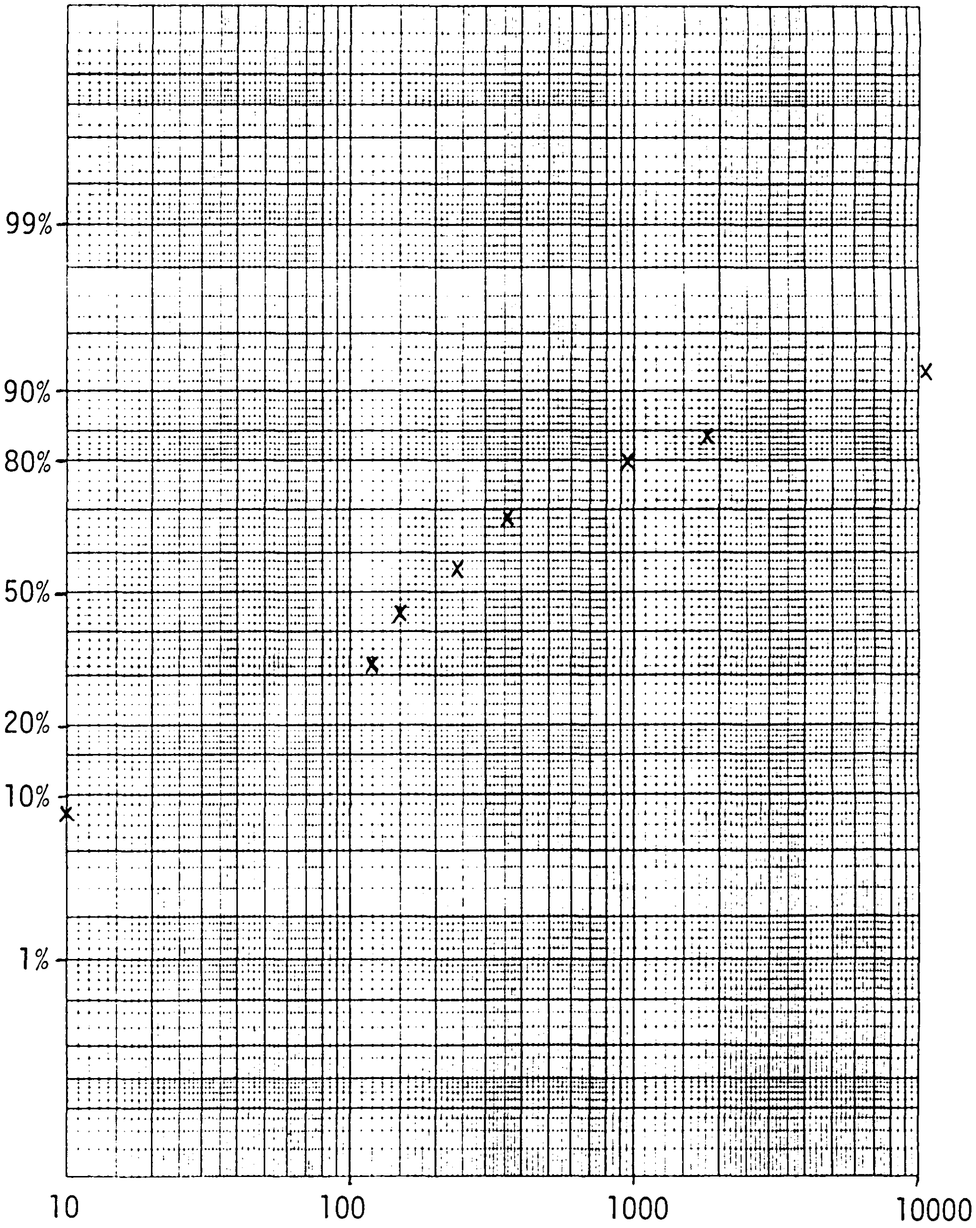
Graph 14 Robot Related Incidents in Factory B (System 7)

μ = 2.471, σ = 0.906, Skewness = 1.714



Graph 15 Robot Related Incidents in Factory F

μ = 5.545, σ = 1.981, Skewness = 0.434



Graph 16 Robot Related Incidents in Factory H

Robot types. The downtime for robot related incidents for the 4 robot types are plotted on log probability paper in Graphs 17-20. A good approximation to a straight line is possible in each case, although markedly less well in Graph 18 for Type 2 robots. Graph 18 matches Graph 15 (for F), where the variation from a straight line is noticeable. It should be emphasised that the majority of robot related incidents for type 2 robots occur in F. The skewness value for type 2 robots is much larger than for the other 3 types, at 2.26 compared to about 0.85 for each of the others, supporting the graphical presentation. The means of logarithm of downtime for the three electrical robot types differ only slightly from each other, varying from 1.5 to 1.8. Type 2 robots have a mean which is considerably higher.

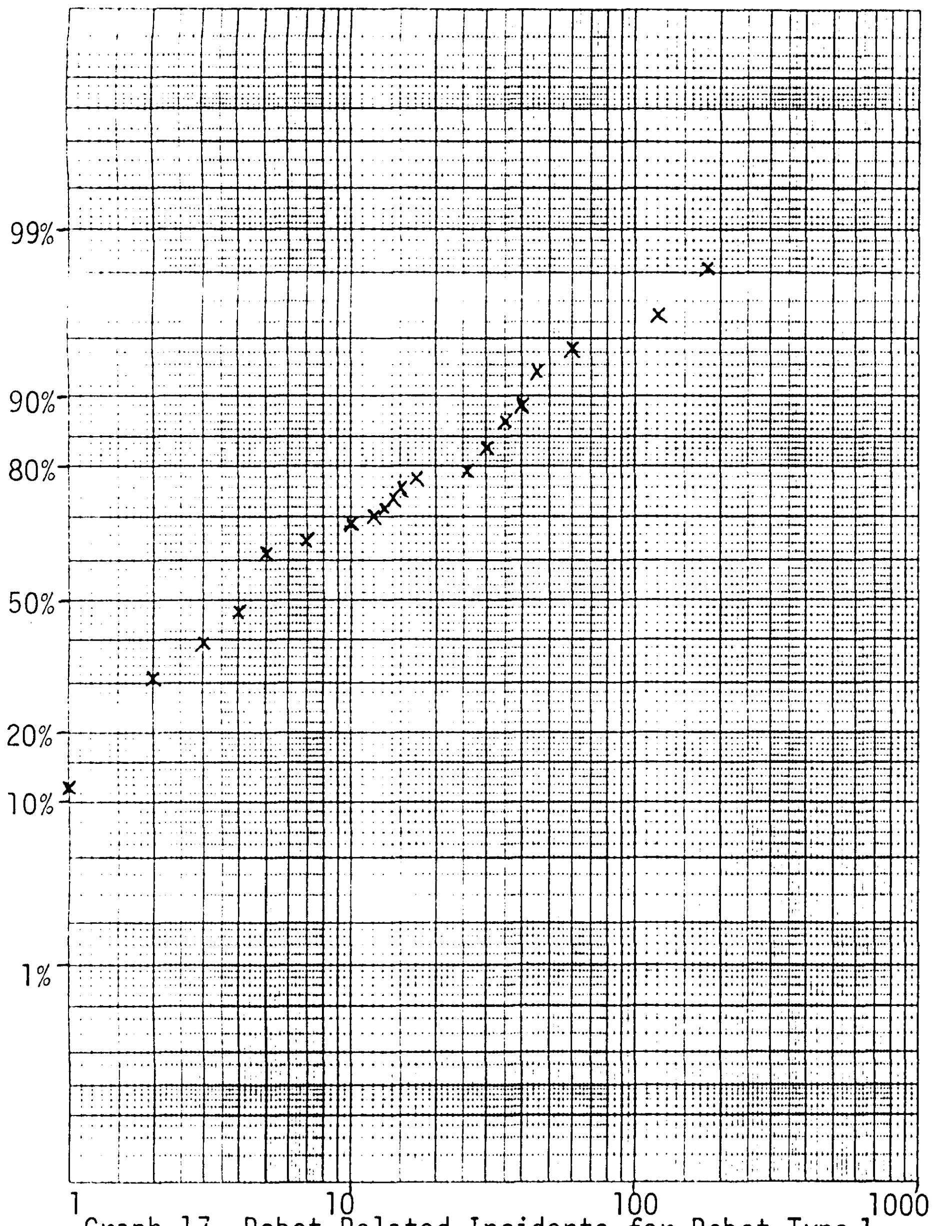
Classification of incidents. Appendix E shows that the 5602 incidents in this study can be split between 7 classifications of the severity of occurrence, with 34 incidents in which the classification was not given. Of the incidents which have a valid classification (5568), 4409 have downtime given. However, of these, 77 have zero minutes recorded as downtime. These must be excluded from this analysis of downtime, leaving a total of 4332 incidents with valid downtimes.

The table in Appendix E for accidents to people contains only one incident. Naturally it is impossible to produce a distribution for one incident, so 6 graphs are produced for each of the classifications of the severity of the incidents, once more on log-probability paper. Graphs 21-26 show a fair degree of agreement between the points and a log-normal plot.

The worst plots are those with the highest skewness values, graphs 22 and 24. Both of these have skewness values in excess of 1. This value is not particularly high and so the log-normal distribution is once more a reasonable approximation. Graph 23 is unusual in that the skewness value is negative. For this classification category, the small number of incidents have a peak in the distribution above the mean value.

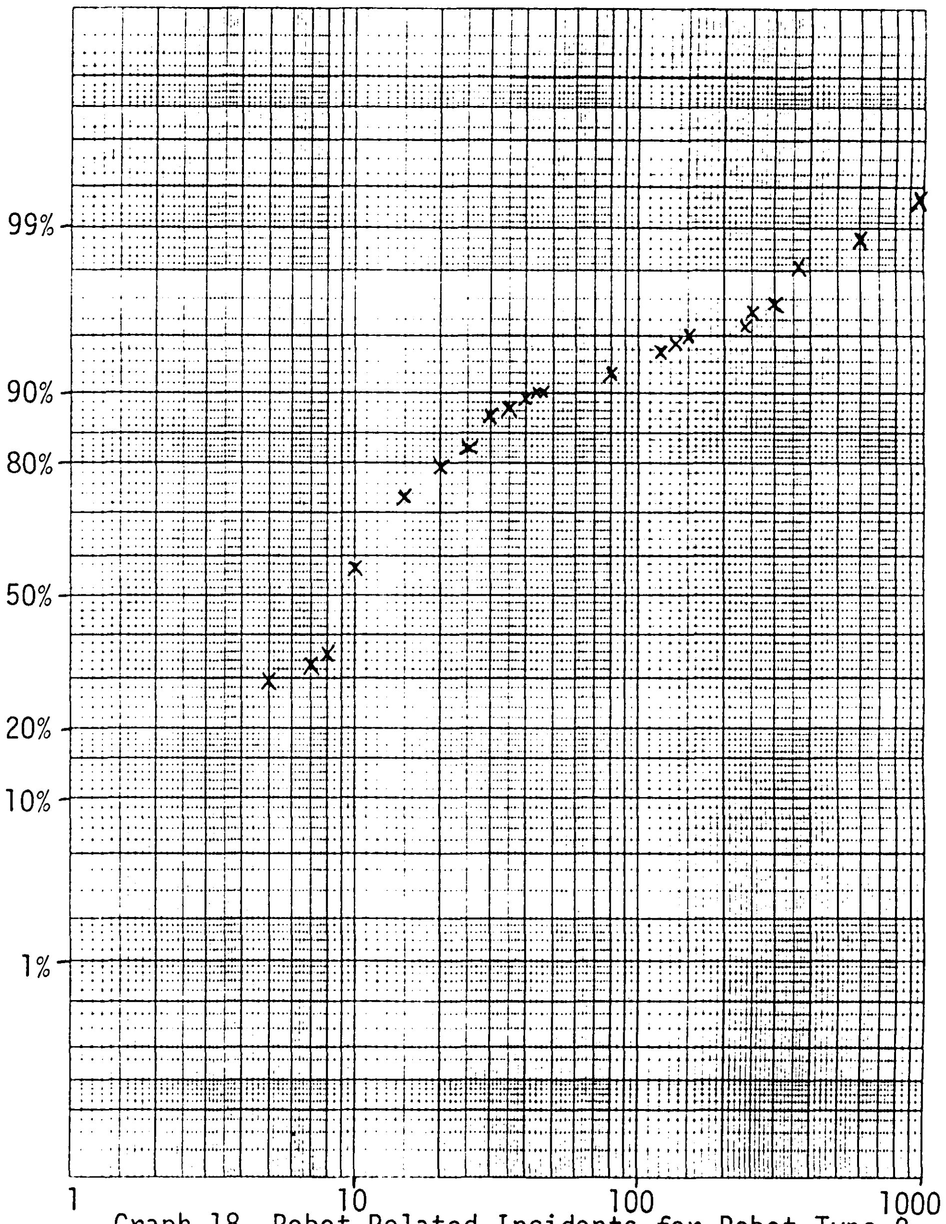
There is no great similarity between the distribution in these graphs, with the highest means being in graphs 25, 23 and 21, in decreasing order. The mean values' order has altered considerably from what was presented in Table 5.17. Whereas accidents involving no damage had the highest mean in Table 5.17, it is ranked fifth in the means of the logarithms of the downtime. Several other categories also alter their position

μ = 1.878, σ = 1.439, Skewness = 0.849



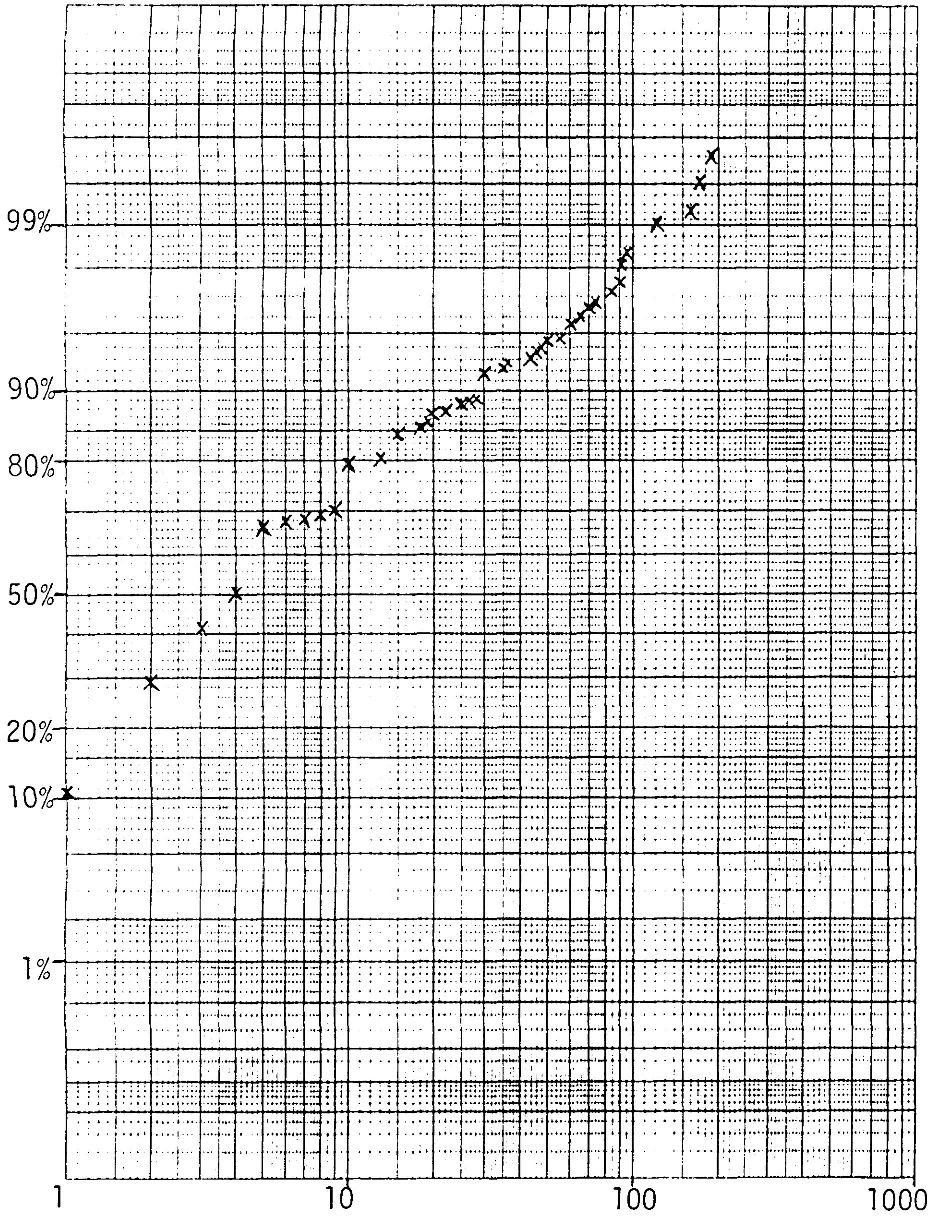
Graph 17 Robot Related Incidents for Robot Type 1

μ = 2.624, σ = 1.183, Skewness = 2.259



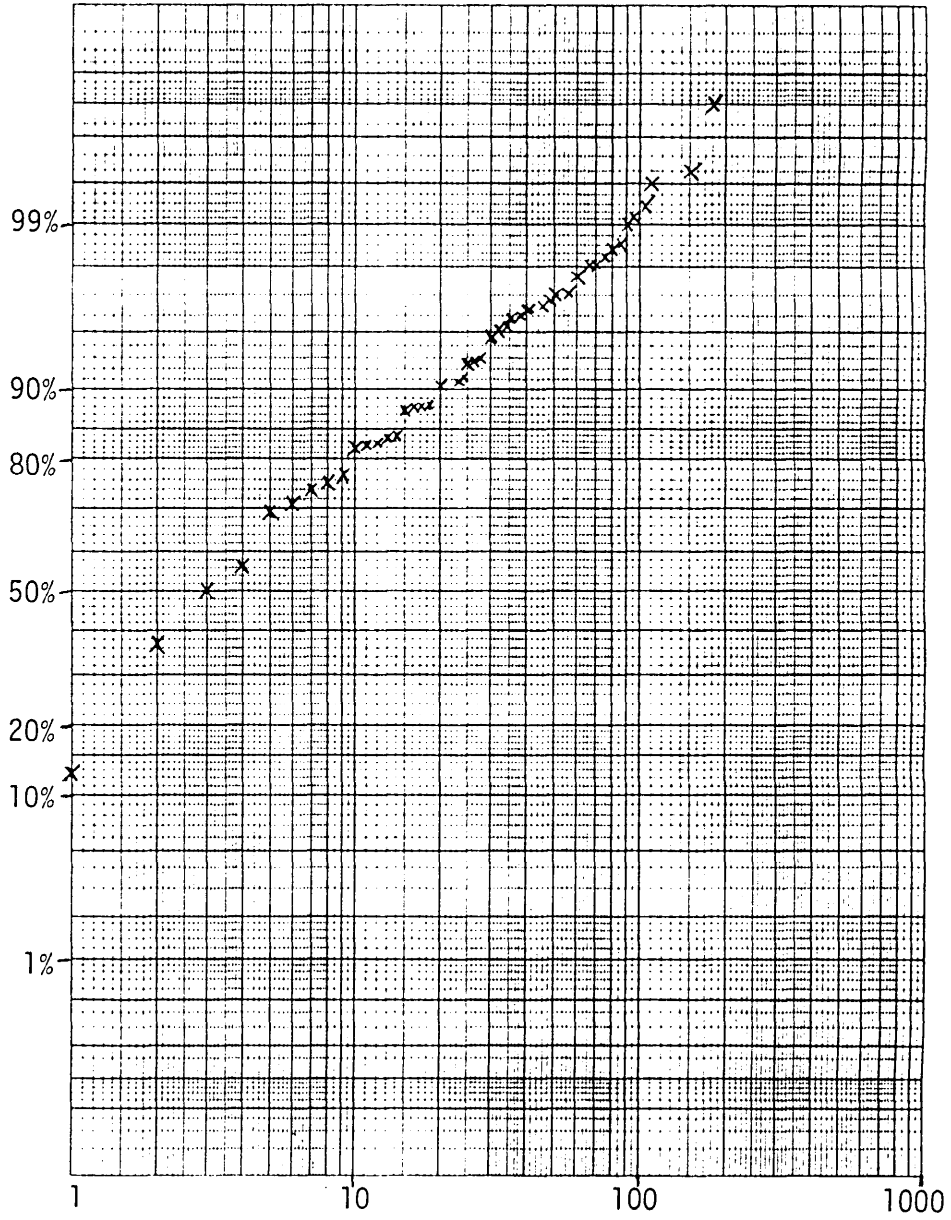
Graph 18 Robot Related Incidents for Robot Type 2

μ = 1.66, σ = 1.164, Skewness = 0.842



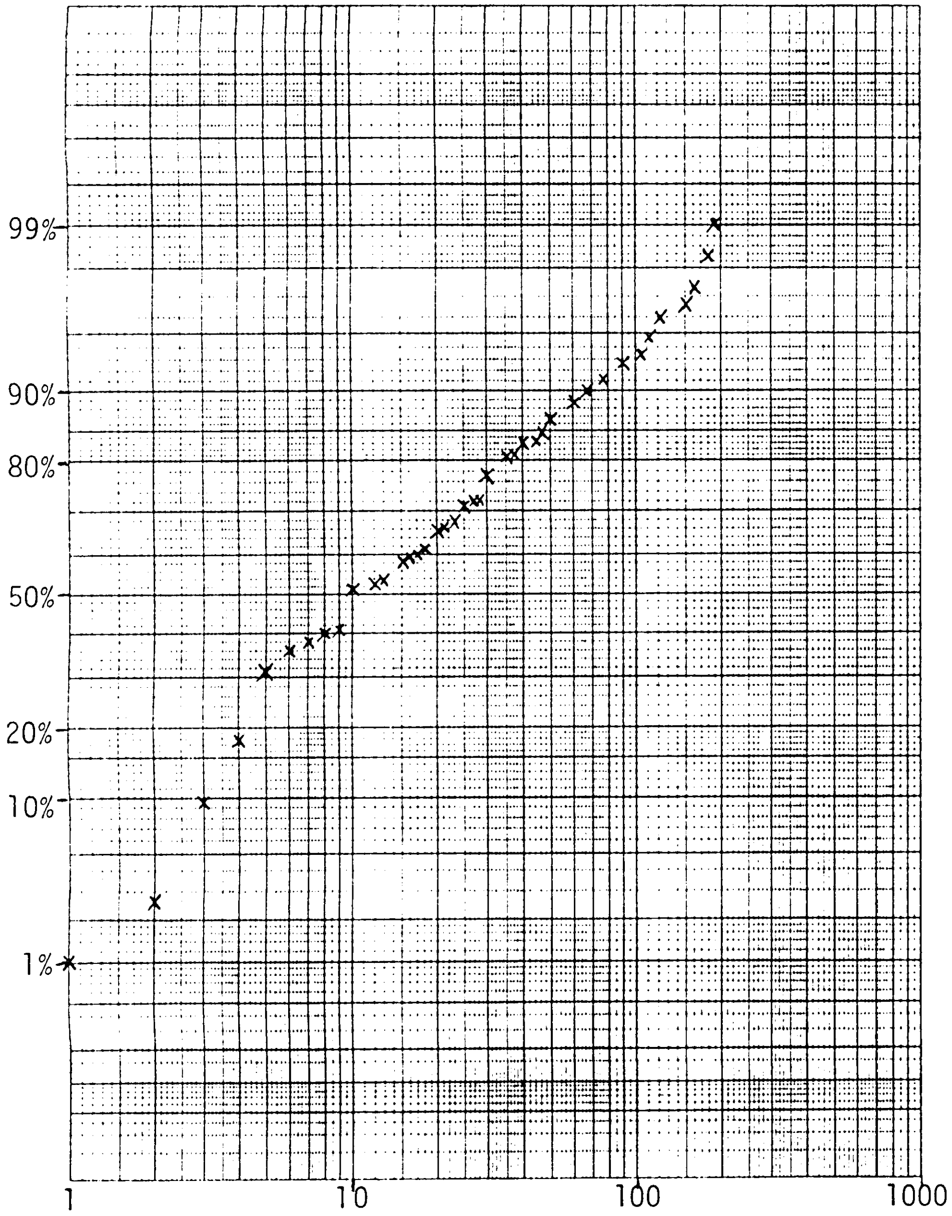
Graph 19 Robot Related Incidents for Robot Type 3

μ = 1.475, σ = 1.086, Skewness = 0.854



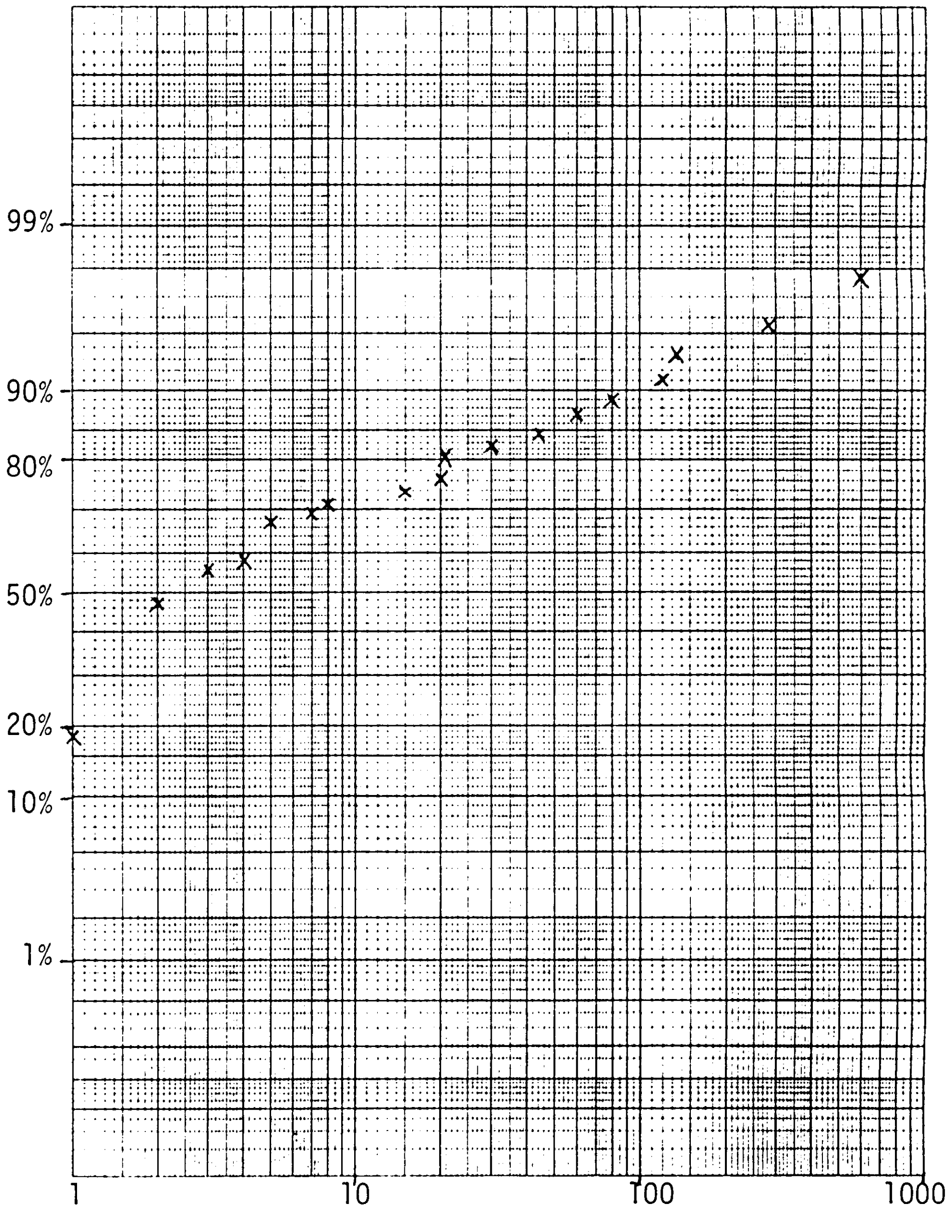
Graph 20 Robot Related Incidents for Robot Type 4

μ = 2.612, σ = 1.185, Skewness = 0.468

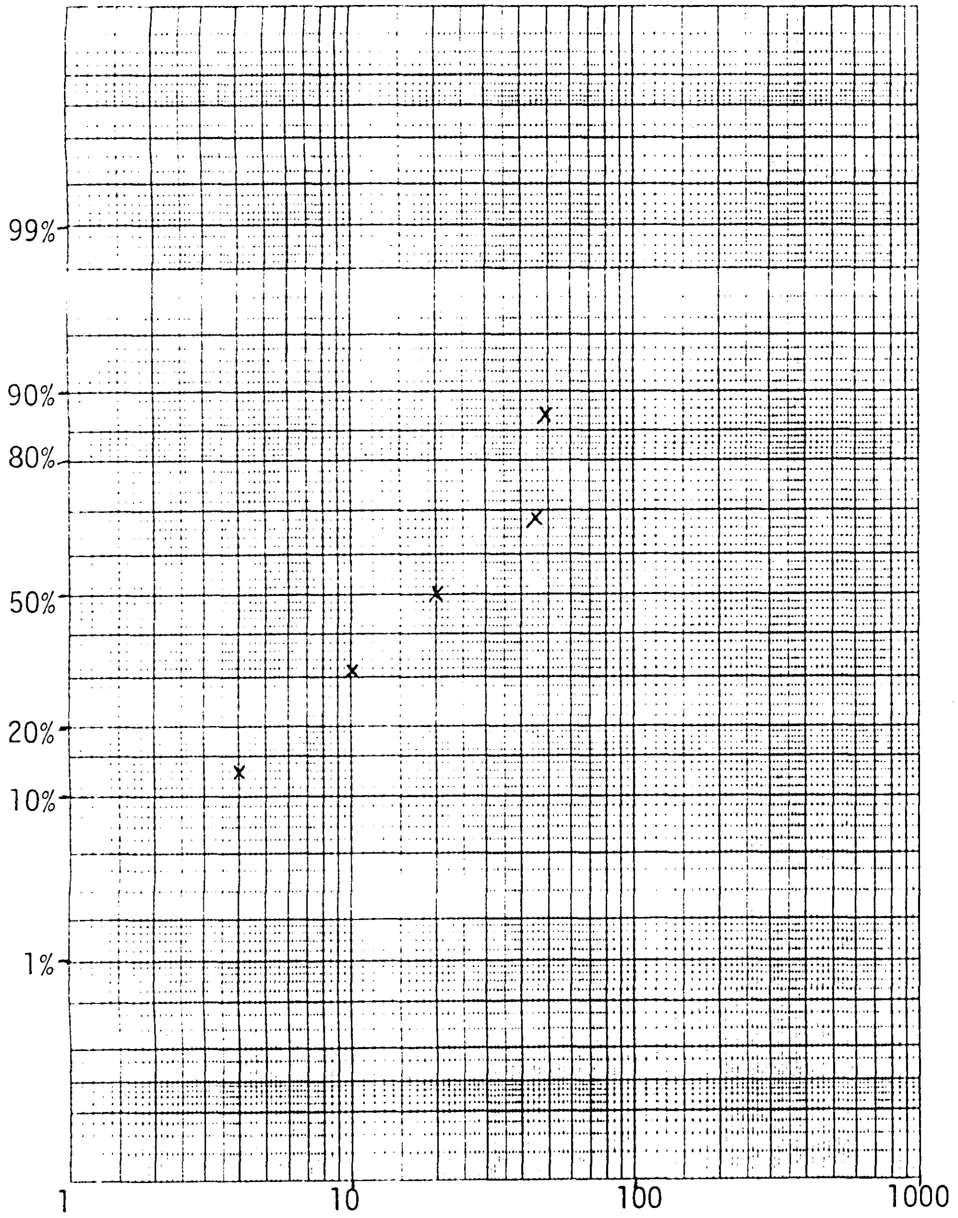


Graph 21 Accidents with Damage to Machinery

μ = 1.862, σ = 2.012, Skewness = 1.674

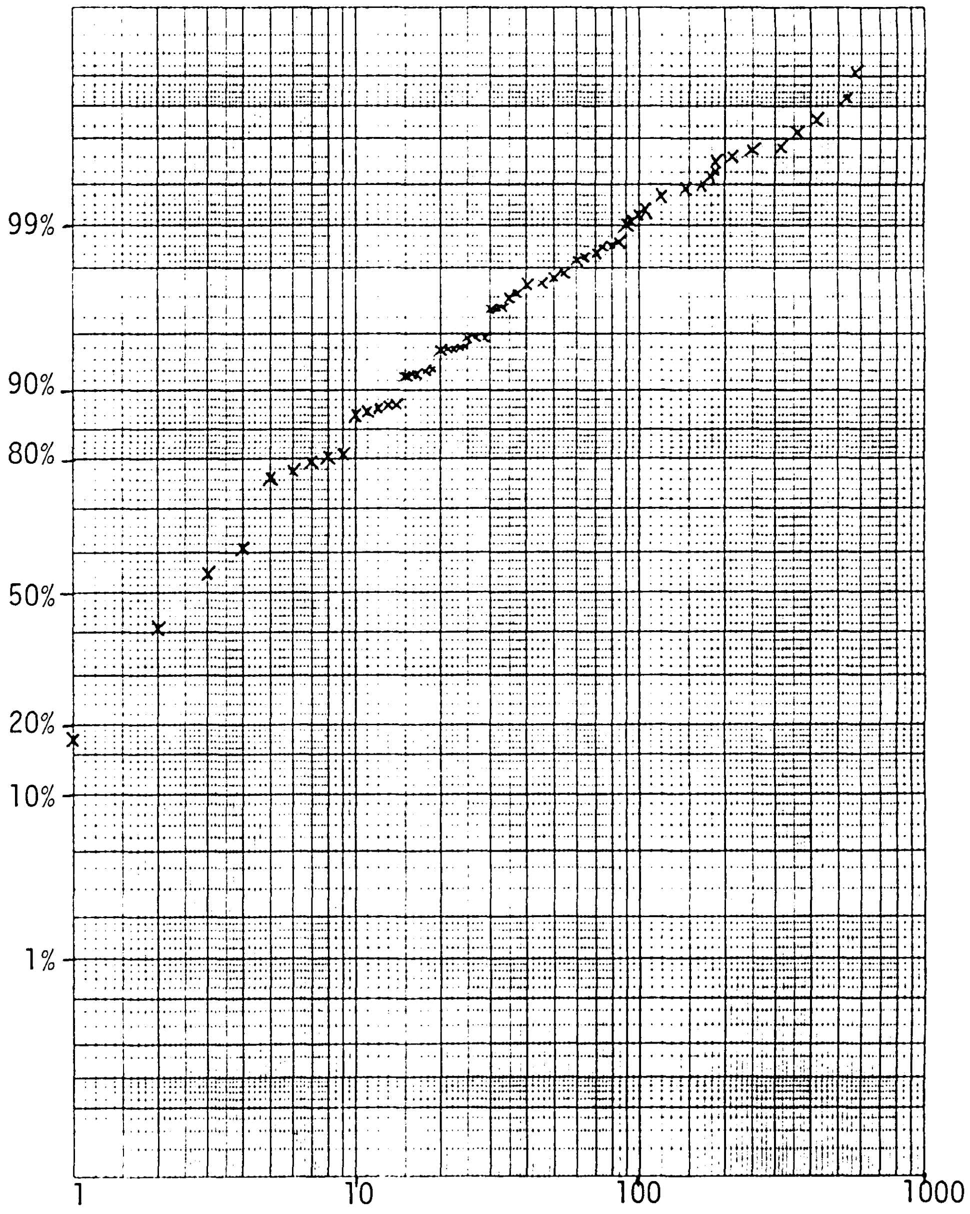


Graph 22 Accidents with No Damage



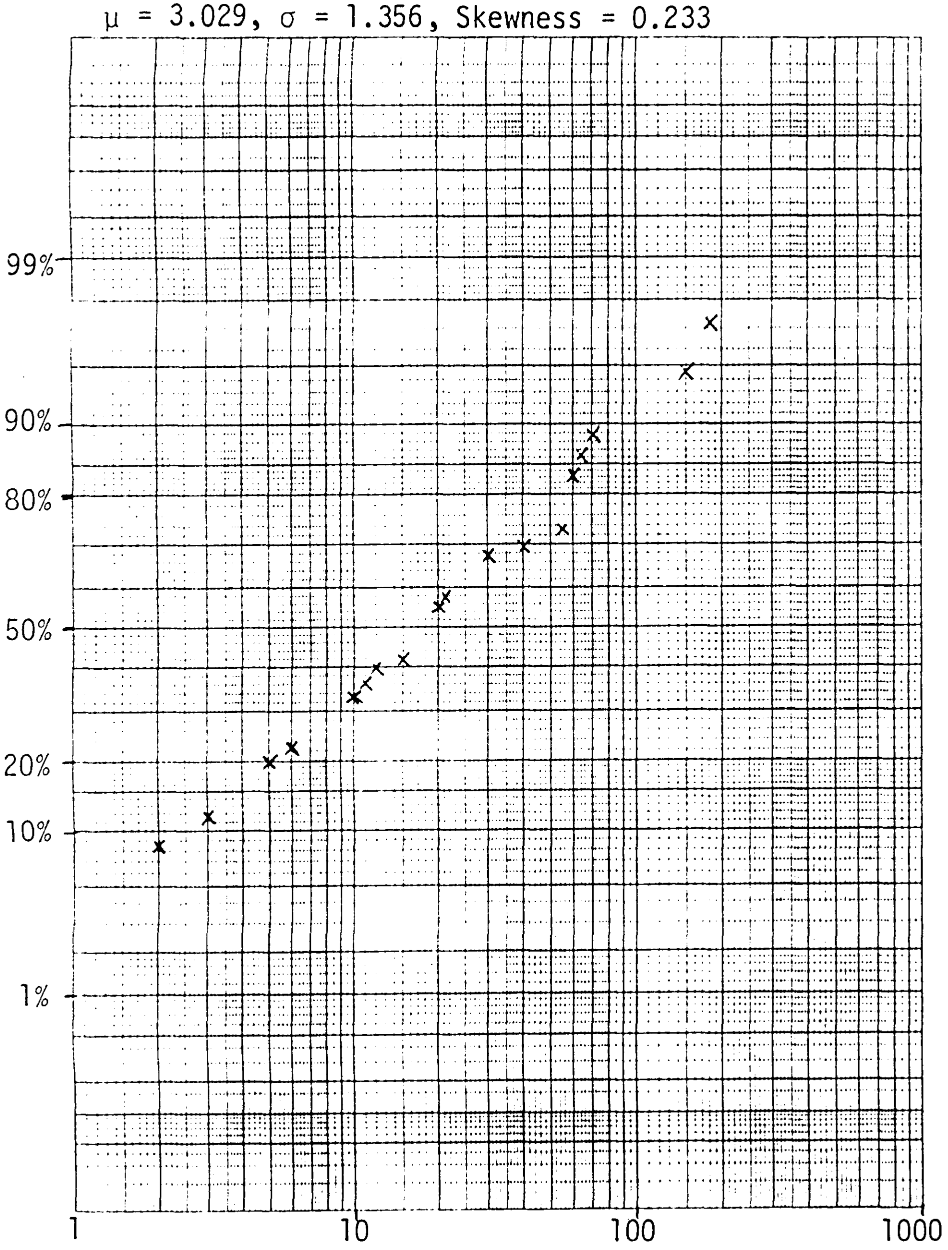
$\mu = 2.921$, $\sigma = 0.979$, Skewness = 0.393

Graph 23 Near Misses

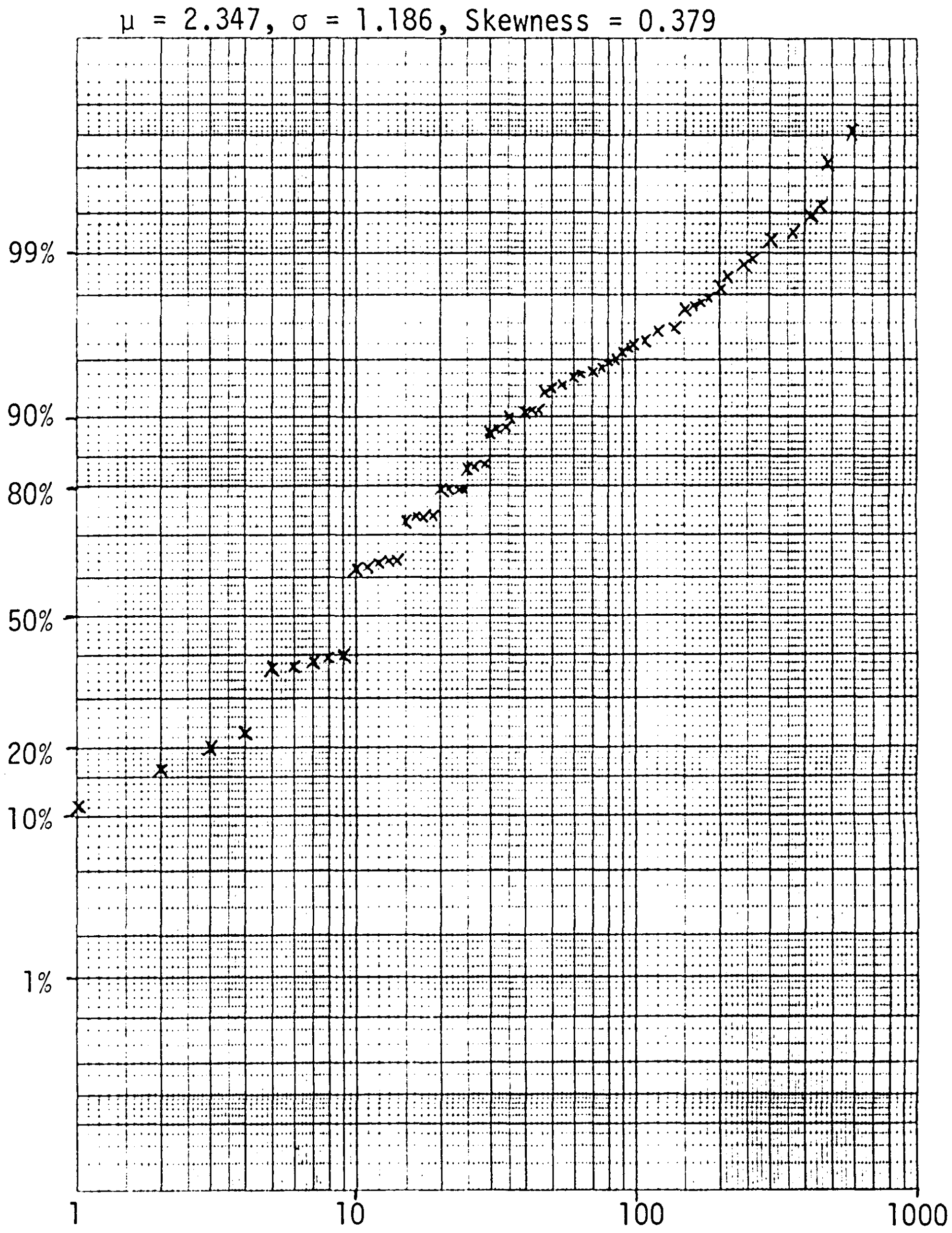


$\mu = 1.319$, $\sigma = 1.037$, Skewness = 1.101

Graph 24 Incidents with No Damage



Graph 25 Anticipated Hazards



Graph 26 Incidents with No Hazard Likely

such as near misses (graph 23). This has the second highest mean for the logarithms of the downtime but had the fourth largest ordinary mean.

The change in the ranking of means occurs because of the different effect of single incidents with large downtime when converted to logarithms. For example, the largest single amount of downtime was 10320 minutes (in H). The natural logarithm of this is 9.24, whereas the natural log of, say, 100 minutes is roughly half this value (4.605). Two events of 100 minutes contribute as much to the total as one event of 10320 minutes when the natural logarithms are considered. The longest single period of downtime resulted in an accident without damage, which explains the marked drop in the rank of the mean of the logarithms of downtime for this category when compared with the rank of the mean of downtime.

Underlying reasons. Rather than provide numerous graphs of the various underlying reasons in each system, the computer analysis of each reason with the 6 systems is presented in Table 5.28.

The computer package (SPSS) required two valid incidents in each category for the standard deviation and 3 valid incidents to obtain a skewness value. Thus there are numerous missing values in this table. The applicability of the log-normal distribution to the data is of importance here rather than any consideration of variation in values. The "degree of fit" of data to the log-normal distribution can be assessed from the values for the skewness of the log-normal time values.

Only 3 underlying reason categories in all the systems have skewness values of over +2.0. These are:- 'part variation' in B6 and 'robot no detail' and 'services problem' in F. Each of these categories contain an incident with downtime well in excess of the other incidents in the same category. For example, in B6 the second longest duration of an incident in the category of 'part variation' has a downtime of 32 minutes. Whereas the longest has 542 minutes. Thus the high values for skewness are almost entirely due to the effect of one value.

Even with these 3 and a further 26 values (out of a total of 98) in the 1.00 to 2.00 range, there is still a large amount of agreement between the distributions and a log-normal distribution. Therefore, the log-normal distribution can be taken as a good overall representation.

Summary of the analysis. This analysis shows that the log-normal distribution is a good representation for the downtime figures. This agrees with previous studies on production reliability of robots and N.C.

System A Underlying Reasons	No. of Valid Incidents	(Log-values) Mean	Standard Deviation	Skewness
10	4	1.409	0.927	0.952
11	1	2.565	-	-
12	0	-	-	-
13	-	-	-	-
14	1	5.193	-	-
15	-	-	-	-
16	3	0.924	0.40	1.732
17	1	6.040	-	-
18	2	4.171	0.871	-
19	1	2.303	-	-
110	-	-	-	-
120	5	2.428	1.141	-0.247
130	2	3.194	0.511	-
140	-	-	-	-
150	-	-	-	-
22	3	1.290	0.556	-0.754
33	13	1.795	1.993	1.063
34	11	2.693	1.01	-0.434
41	18	2.715	0.757	1.069
42	14	2.277	1.075	0.640
43	19	3.825	1.374	-0.240
44	7	2.987	2.174	0.056
55	5	3.142	1.156	-0.912
66	58	2.508	1.590	0.908
77	6	1.092	1.001	-0.039
88	8	2.150	1.436	0.232
200	172	1.541	0.721	0.196
210	31	2.534	1.752	0.402
All	385	2.107	1.355	0.994

Table 5.28 Results of Statistical Analysis of Underlying Reasons in Each System

(Cont'd)

System B5 Underlying Reasons	No. of Valid Incidents	(Log-values) Mean	Standard Deviation	Skewness
10	11	2.845	1.212	0.676
11	1	2.303	-	-
12	-	-	-	-
13	4	3.387	1.251	1.281
14	3	3.497	1.671	-1.403
15	-	-	-	-
16	22	1.602	0.703	-0.580
17	1	3.332	-	-
18	5	3.401	1.151	0.546
19	-	-	-	-
110	-	-	-	-
120	19	2.779	1.284	0.609
130	2	1.151	0.648	-
140	-	-	-	-
150	-	-	-	-
22	10	3.143	1.187	1.102
33	5	2.062	1.317	-0.212
34	-	-	-	-
41	-	-	-	-
42	8	1.576	0.787	0.686
43	22	1.934	0.964	0.067
44	36	0.73	0.911	0.909
55	3	2.228	0.129	-1.732
66	137	1.920	1.152	0.539
77	-	-	-	-
880	2	3.310	0.851	-
200	9	0.967	0.768	0.372
210	18	2.207	1.280	1.545
999	4	2.967	0.605	-1.740
All	322	1.951	1.247	0.547

System B6 Underlying Reasons	No. of Valid Incidents	(Log-values) Mean	Deviation	Skewness
10	19	1.461	1.153	1.436
11	66	1.261	0.843	0.630
12	8	2.396	0.941	0.211
13	13	2.610	0.582	-0.197
14	16	2.892	0.733	0.286
15	11	2.619	0.693	-0.422
16	216	0.945	0.593	1.194
17	11	2.514	1.488	0.250
18	30	2.895	1.263	0.146
19	-	-	-	-
110	-	-	-	-
120	133	1.922	0.976	0.964
130	9	1.873	1.231	0.291
140	42	1.150	1.269	1.553
150	-	-	-	-
22	32	2.650	1.133	0.918
33	19	1.233	1.271	0.515
34	-	-	-	-
41	-	-	-	-
42	125	1.207	0.825	2.065
43	41	2.258	0.923	0.595
44	10	2.501	1.396	-1.313
55	13	2.272	1.153	-0.271
66	447	0.977	0.862	1.573
77	3	2.804	0.556	0.754
88	9	0.892	0.726	0.450
200	44	1.407	0.570	1.053
210	17	1.264	1.082	-0.134
999	4	0.922	0.977	1.304
All	1338	1.364	1.050	1.113

System B7 Underlying Reasons	No. of Valid Incidents	(Log-Values)		
		Mean	Standard Deviation	Skewness
10	25	1.764	1.550	0.728
11	83	1.014	0.742	1.088
12	4	0.749	0.660	0.502
13	21	2.636	1.030	-0.102
14	4	3.849	0.543	0.460
15	6	2.188	0.747	0.863
16	207	0.919	0.743	0.620
17	9	2.781	0.714	-0.227
18	23	2.601	1.210	-0.346
19	-	-	-	-
110	-	-	-	-
120	204	1.696	1.011	0.204
130	8	1.074	1.300	1.137
140	17	1.918	1.216	0.358
150	-	-	-	-
22	29	2.729	1.193	0.656
33	81	0.611	0.783	1.317
34	-	-	-	-
41	-	-	-	-
42	170	1.021	0.844	1.938
43	22	1.781	1.485	0.905
44	15	1.836	1.343	0.305
55	19	2.255	0.816	0.072
66	480	0.963	0.849	1.091
77	-	-	-	-
88	10	0.935	0.344	1.102
200	61	0.837	0.844	0.538
210	-	-	-	-
999	5	1.277	1.319	1.567
All	1503	1.364	1.050	1.113

System F Underlying Reasons	No. of Valid Incidents	(Log-values)		
		Mean	Standard Deviation	Skewness
10	6	3.456	1.493	2.074
11	2	3.545	1.184	-
12	-	-	-	-
13	8	3.530	0.986	0.565
14	3	5.032	1.178	-1.547
15	-	-	-	-
16	7	2.063	0.448	0.073
17	3	4.034	1.461	1.583
18	43	2.409	0.568	0.361
19	-	-	-	-
110	51	1.964	0.593	1.719
120	18	2.604	0.604	-0.347
130	1	2.303	-	-
140	-	-	-	-
150	11	2.496	0.303	1.554
22	136	3.005	1.228	0.551
33	-	-	-	-
34	1	2.708	-	-
41	-	-	-	-
42	29	2.486	0.811	0.213
43	184	2.491	0.449	0.593
44	21	2.644	0.565	-1.046
55	19	2.687	0.788	2.007
66	249	2.599	0.920	0.746
77	3	2.207	0.556	-0.754
88	7	2.926	0.731	-0.655
200	-	-	-	-
210	9	2.194	0.497	0.078
999	3	2.743	0.459	0.342
All	804	2.615	0.896	1.144

System H Underlying Reasons	No. of Valid Incidents	(Log-values) Mean	Standard Deviation	Skewness
13	1	5.886	-	-
14	1	6.867	-	-
16	1	4.787	-	-
17	1	9.242	-	-
18	2	4.899	0.158	-
120	2	3.892	2.247	-
22	1	6.492	-	-
88	2	3.892	1.267	-
All	11	5.331	1.869	0.452

machine tools (see Chapter 1). However, some groups of incidents do not produce as good a fit to the log-normal distribution as others. For example, incidents in Factory F or robot related incidents with Type 2 robots appear to form a combination of log-normal distributions. These two differences are connected; hydraulic robots are relevant to both sets of figures. This poor agreement is in keeping with the findings elsewhere in this chapter. The figures for this system and this type of robot have numerous differences from corresponding results in other systems or for other robots.

The distribution figures also show some similarities between groups. A and B5 downtime figures are shown to be very similar, as are the robot related figures in B6 and B7.

One other significant feature is the change in the order of the means for downtime for classification categories. This change is due to the different effect of long duration incidents on natural logarithms figures from their effect on ordinary figures.

THE SAFETY IMPLICATIONS OF THE DATA ON PRODUCTION INTERRUPTIONS

Several areas covered in the production problem data give rise to safety implications. To understand these fully, one must link the production problems data with the descriptions of system designs and working practices presented earlier. This section deals with these safety implications by reviewing the analysis of the production data. It is divided into a number of areas along the same lines as the previous analysis and using the same data categories.

The Safety Implications of Actions Taken

Since the actions taken with each system are highly dependent on system design and the process, their safety implications must also be related to the specifics of each system. Actions involving access within the robot systems can expose workers to hazards from the process and from equipment. The hazards are closely linked to the practices adopted by personnel. Whether machinery is capable of automatic action during periods of close proximity of people and equipment is also important. The potential for harm is significantly higher where people work without attention to the hazards of a robot system and where close proximity to operational equipment is possible. Close proximity to operational equipment is possible where safety interlocks or other physical safeguards are circumvented, where the system design does not ensure a separation of worker and machinery.

Examples of hazardous practices were found where workers turned their backs on operating equipment, gathered in a cluster around a robot as it was being programmed or moved frequently within the fencing of a system to observe the process at close quarters.

The frequencies for the actions taken in each system show that some actions recognised as particularly hazardous are also quite frequent (see Chapter 3 for a discussion of robot hazards). Maintenance, fault finding and reprogramming are recognised by a number of authors for presenting workers with the greatest hazards, because of the need for equipment to be operational during these tasks. Unplanned maintenance appears more hazardous than routine maintenance or adjustments (Sugimoto and Kawaguchi, 1985). The powering up of a robot after the replacement of faulty equipment is also potentially dangerous.

The hazards posed vary from one system to another, because the operating state of equipment during access also varies. Equipment needs to be operational to some extent for only reprogramming and fault diagnosis but depending on the system design and working practices, equipment may also be active during other actions. The robot systems in Factory H are unusual among the robot systems in that the robot is the only piece of equipment in the system capable of independent motion. Thus hazards are only posed by the robot.

Reprogramming occurs in a sizeable number of incidents in each system. However in F, the hazards are likely to be greater than elsewhere because other equipment is not prevented automatically from moving. Working practices in A mean that equipment remains in a operational state during programming. The hazards from other actions are similarly worse in these two systems than in the other factories.

The systems in A and F have already been assessed as having high levels of hazard. This discussion on the way in which actions are performed reinforces this view.

The Safety Implications of the Reasons for Actions

Reasons for actions with safety implications (namely erratic robot, dropped part and the threat of damage to robots, people or machinery) are quite rare in each system. Erratic robot motions occur with only a few robots in any system. Erratic motions are not necessarily major movements off the programmed path, although they are sufficient to cause problems for production. As a result, they are usually more closely associated with quality problems than any threat of damage.

Where 'dropped part' occurs as a reason (in 4 of the 6 systems) the incidents are not directly linked to any robot. These incidents are generally the result of transfer devices releasing parts out of sequence.

Seventy incidents with the threat of damage to robots occur overall, with 44 of these in F. This high concentration of incidents in one system is the result of a number of cases of hydraulic power failure. The Type 2 robot arm can collapse under power failure and action is required to prevent damage occurring.

Threat to persons occurs in only one system (F), with 2 incidents associated with the transfer device. Both of these incidents arise from falling equipment. On one occasion, a loader was hit by a perspex guard and on another a light fixture came loose and fell near an operator.

The threat of damage to other machinery comes both from robot actions and actions of other equipment. Incidents with the threat of damage to machinery are linked to possible minor damage to the robots, as well as to tools and drive mechanisms.

Erratic robot motion was a cause of a number of incidents with possible damage to parts in B6 and B7. Such incidents were less frequent elsewhere. Collisions between robots in B6 and B7 also gives rise to a concern for safety. Both erratic robot motion and collisions present a certain amount of danger to workers within reach of the robot arm. However both types of incidents were rare occurrences.

The threat of damage to other machinery without damage to robots in the main concerned far less severe incidents than those involving erratic robot behaviour. They were mostly cases of machine over-run, parts damage or poor sequencing. These occurred during automatic operation and would have produced only minor hazards for any worker who was present at such times. It should be stated that the automatic operation of equipment would usually present a greater hazard at such times.

This discussion shows that not only are incidents rare whose reasons are safety related but also that when they occur, the hazards they imply they are not major. Thus the need for safety is rarely a reason for action on robot systems.

The Safety Implications of the Means of Interruption

The discussion and analysis of interruptions to production show that a major source of hazard concerns sequencing problems. The use of emergency stops as a means of personnel intervention also tends to be linked to problems which arise from sequencing. Thus the systems were interrupted for safety largely as a result of system sequencing problems.

The Safety Implications of the Classification of Incidents

The discussion and analysis earlier on the classification of incidents show that incidents which result in accidents or have the potential to do so are not a frequent cause of interruption to production. Automatic operation is thus rarely associated with the potential for or the realisation of accidents. However, for those incidents which do have some hazard potential, no special ability is found in any system to anticipate hazards.

The discussion earlier also identifies robot related problems as more likely to be hazardous than other causes of interruption. The systems with the most frequent occurrences of hazardous classifications (B6 and B7) also have a high proportion of robot related incidents among these classifications. Though these systems appear more prone to hazardous occurrences, the system design ensures that equipment is more at risk than personnel. In contrast, hazardous classifications which occur in F are of more concern, since there is a lower level of protection for people. It is worth noting that F has the one incident of actual harm to a person and has incidents where action was taken because of a threat of harm to persons. This suggests that the lower safeguarding level of system design and the informality of working practices contributed to a less safe environment.

Certain robot related incidents are shown to be frequent amongst hazardous classifications which also involve hazardous actions. For example 'erratic robot' or 'robot collision' could require reprogramming of the robot involved. The discussion on robot hazards in Chapter 3 shows that hazards before and after an incident are not entirely independent of each other. The predominance in the hazardous classifications of certain robot related reasons which require hazardous actions suggests that the hazards of such incidents are augmented. Persistence of the problem which caused the accident or its potential would make recovery difficult and would place the workers involved at a high risk.

The Safety Implications of the Involvement of Personnel

The personnel involved in identifying and sorting out problems with the robot systems are those workers most exposed to the hazards of robot production. The types of tasks performed by the different personnel and their training are thus highly relevant to the hazards experienced by these personnel. The frequencies for involvement given in Table 5.15 need to be considered in the light of the practices in each system and training of each grade of personnel.

In A maintenance workers and the foreman receive extensive training and also performed most repair tasks and re-programming tasks on the system. The rare presence of other workers means the hazards are presented almost exclusively to maintenance workers, who are also the most highly trained. A similar picture appears in Factory B (in all three systems). In F, much poorer training is given and to a far fewer number of workers. The figures in Table 5.15 also show that a wider range of personnel are involved in F in both identifying and sorting out problems. Thus these personnel are exposed to hazards in a range of tasks for which they are not always fully trained. In H, operators play a major role, but had received training for only operation and programming. Their involvement in sorting out problems takes them beyond this training. The maintenance workers, by contrast, are trained for such repair tasks.

Thus in F and H, personnel are exposed to greater hazards than in A or B by virtue of their lack of training and experience.

The Safety Implications of the Underlying Reasons

Observation shows some occasions where workers and machinery are in close proximity during automatic operation. However, the vast majority of interactions occur as a result of an incident of interruption to production. Thus the safety implications of the underlying reasons arise mostly from the actions which follow an interruption to production.

For certain underlying reasons, the only actions which would normally be required would be resetting or some minor adjustments. This applies to such robot related problems as 'robot out of synchronisation', 'robot in E stop', 'robot won't move' and 'stiffness in robot arm' (the last to only a limited extent). For the first three of these, the usual action would be to restart the robot by resetting it. Sometimes the robot would need to be re-referenced when synchronisation problems occur and this would involve moving the robot under teach control to its home position - in effect re-programming the robot to its start position. When a robot fails to move for some reason, the usual solution would be to reset it and only in the unusual circumstances of this failing would any maintenance or fault diagnosis need to be carried out.

When stiffness in the robot arm is the underlying reason for an interruption the robot normally goes into a control halt. It would need to be freed from this by resetting the controls and then the stiffness in the arm would need to be overcome by increasing the current limit settings to the relevant axis motor (note: this problem only occurs with electric robots).

More extensive actions are needed with some problems, such as erratic robot, which would require some reprogramming. With problems in tools, the likely actions would be some form of adjustment or cleaning (with some replacement of faulty equipment). Some reprogramming may follow if the position of the tool has been disturbed.

For incidents involving robot failures (that is 'cable problems', 'component failure in arm', 'blown fuse', 'fault in cabinet', 'fault in teach pendant' and 'power supply fault'), the replacement of faulty equipment is required and some extensive maintenance could follow. Reprogramming may also be required if the programme path has been disturbed. Thus quite extensive actions would follow these failures. Power supply faults are an exceptional category here, since they only occur with the hydraulic robots in F. The usual action for such an occurrence is to allow the system to resettle, replace the hydraulic fluid filter and reset the system.

For the other reasons, two categories involve mainly inspection. These are 'system checks' and 'check on parts'. The robot system and the parts progressing through it would be checked with the system made inactive. These occur almost exclusively in A, and can be seen as a product of the prevention by system design of outside inspection.

For 'part variation' and 'quality problem', some action is carried out to correct the problem, usually involving reprogramming of the robots to some extent. For 'process problem', 'system failure' and 'servicing problem', some adjustments and minor maintenance may need to be performed, to be followed by the resetting of the equipment. For 'other equipment problems' and 'component failure' some maintenance could be carried out as well as the replacement of faulty equipment in the case of component failures. The maintenance could be very extensive in some cases. A safety function problem would require the safety equipment involved to be investigated with some corrective maintenance performed if necessary. Human error can produce a whole range of problems, but of particular concern here are the errors in loading parts into the systems. These could cause damage or more likely prevent the system from operating at some stage. The whole system would then need to be reset subsequently. Weld failures occur when the robots stop because of a failure to carry out the welding process. The problem has to be identified and the robot reset at the same spot in the programme. An investigation of the interruption is followed on occasions by reprogramming.

The final category of underlying reason, 'sequence fault', has particular safety implications because of the possible damage which can result from the misplaced equipment when considerable potential or kinetic energy is available. These faults create major problems for resetting on some occasions since the sequence of the process may have to be reversed to remedy the problem. Usually these incidents also require some fault diagnosis to identify the cause, and some corrective action in the form of maintenance or adjustments.

From this short description of tasks associated with underlying reasons, one can see that certain robot related problems would involve major work, for example robot failures, but that these form a minority of incidents. The frequency of occurrences for each reason shows that only a minority of recorded robot related problems need major work to be performed. The recorded frequency of other underlying reasons, shows that a number of other hazards are the result of underlying reasons which are not robot related. For example, sequence faults in A are quite frequent. The safety implications of this underlying reason, with as high a frequency as 6.1% is a potential cause for concern with this system. B5 also has a sizeable percentage for sequence faults. Indeed, an overall frequency of 1.6% of all the incidents in the six systems for such a hazardous occurrence is a cause of more general concern with robot systems. Thus system operation and the interactions of equipment in a system create hazards which make those from purely robot problems only a small part of all the hazards from system operation.

One further source of safety problem can be identified. It is clear that occasionally the underlying reason for an incident can be difficult to ascertain. The systems could stop production without an identifiable underlying reason. Personnel were aware of the problems of identifying a problem wrongly and undertaking inappropriate maintenance. This phenomenon is similar to Turners' 'decoy problem' (see Chapter 2). Personnel could become exposed to hazards whilst correcting what they consider to be the problem. The hazards against which they have protected themselves relate to the underlying reason they have identified. If another reason resulted in the incident then a different and possibly worse set of hazards may be present. Therefore the difficulties of identifying underlying reasons for problems create their own hazards.

SUMMARY AND CONCLUSIONS

This chapter has provided a description of the robot systems in the empirical study, the analysis of interruptions to production and the analysis of their safety implications. The description of the robot systems covered seven topics: the physical environment, the system layout, the safety features, the hazards of the systems, the working practices, the training provisions and accident statistics from two factories. These descriptions showed the unique character of each system. The complexity of design was shown to be greatest in Factories A and B and least in Factories C and H.

A preliminary assessment of the hazards in each system was made, based on the system design but without a full consideration of the safety features. The systems in A and B were found to have the highest level of hazards but these were largely controlled by the separation between people and the process achieved in the system design. The hazards to which workers were exposed were found to be highest in Factories C and F because workers and the automatic equipment were not separated effectively. The working practices of operators in Factory C were noted as largely routine and following a continuous cycle governed by the equipment. The role of behaviour of these workers matched the 'pre-programmed' mode described by Kay and thus workers were susceptible to the causes of accidents which Kay identified. This finding would apply to any similar repetitive task in the other factories but was most clearly exemplified by the action of workers in Factory C.

Accidents were neither severe nor very frequent overall. Nevertheless the evidence of accidents in the empirical study corroborated the surveys of accidents and statements on industrial robot hazards (see Chapter 2). Similar types of accidents were shown, even though the empirical study provided a small sample.

Some support was shown for Zermeno-Gonzalez's conclusion that robot use was largely experimental (see Chapter 1). Robots were a new and untried method of undertaking the process in Factories A, D and H and a certain amount of experimentation took place. Robot use was more established for the processes in the other three factories and so experimentation was not so necessary.

The major part of the analysis in this chapter dealt with the recorded incidents of interruptions to production in six of the systems studied and identified the major influences on variations in production availability. In particular, system design, task, work organisation and robot type were found to be important in some of the significant differences in the production problems, notably in the variation in mean downtimes and underlying reasons for interruption.

A large number of incidents of production interruption and a high system unavailability were found with each system. The arc-welding application in Factory A had a particularly high amount of downtime, but all the systems showed significant difficulties in maintaining continuous production.

Systems B6 and B7 had similar patterns with low mean downtimes and a high frequency of incidents. High relative availability was maintained by prompt corrective action, for which well trained and experienced personnel and a system designed for prompt and safe access were beneficial. Further analysis of the downtime for separate underlying reasons showed a narrower band of mean downtimes for B6 and B7, in the proficiency with which problems were handled.

The types of actions required with incidents were linked strongly to the system design and process. However, resetting and other corrective actions were frequent overall, indicating the need for frequent corrections to problems with robot systems. The industrial robots in some systems were found to be more prone to the need for unplanned maintenance than overall. A practice of responding to actual faults with the robots was the reason for this phenomenon.

Reasons for actions which were concerned directly with the performance of individual pieces of equipment predominated, notwithstanding the dependency on process conditions and system design. The variations in reasons for robots in the same systems indicated the differences in the requirements made by the system on each robot.

The means of interruption in each system also showed a dependency on system design and operation. In particular, the way in which the robots are incorporated into the system operation played an important role in deciding the frequency of the different means of interruption. Personal actions formed a minority of incidents. However, on the rare occasions when serious hazards were prevented by the pressing of emergency stops, sequence problems were involved. Thus the few hazardous problems for which the emergency stop is necessary are caused by the actions of the systems as a whole.

Tight coupling and complexity of robot systems was indicated by the role of sequence problems in incidents requiring the use of emergency stops and in incidents involving damage to machinery. The latter consideration indicated how the system designs in B6 and B7 in particular were tightly coupled. However in these two systems, the design had taken into account the possibility of damage and the majority of these incidents of damage were corrected rapidly.

The vast majority of interruptions to production in each system did not result from hazard realisation or even its potential, so the problems of tight coupling could not be considered a major cause of interruption to production. Nevertheless, no particular ability was found in any system to anticipate hazards.

The personnel involved in incidents was decided primarily by the work organisation for each system, but a shift was found in the solution of problems in some systems towards more experienced and well trained personnel.

Robot related incidents were found to have a more serious effect in terms of downtime than in their relative frequency of occurrence, except where more serious problems were encountered with other equipment in the system (Factory F). The analysis of robot related incidents showed more evidence of the difficulties experienced by robot systems. In particular, tool problems and robot control interruptions were persistent problems. Each robot type had a unique pattern of underlying reasons and downtime, with hydraulic robots suffering the longest periods of downtime. However, the influence of robot design could not be isolated from features of system design.

The analysis of robot failures isolated the six failure categories and considered them for each system and robot type. The overall mean time between failures was less than 350 hours of production, which is well below the figures provided by Sugimoto and Kawaguchi (see Chapter 1). The failure categories and the times between failures for hydraulic robots showed considerable differences from those for electric robots, thus showing once more the differences between robots of the two types of power supply.

An analysis of the distribution of downtime re-emphasised the predominance of incidents of short duration, which suggested that personnel were able to deal with the vast majority of problems with relative ease. A statistical analysis showed that a log-normal distribution was applicable overall. The downtime in Factory F and for type 2 robots (large hydraulically powered robots) approximated less well to this distribution, showing once more that hydraulic robots perform differently from electric robots. However, a log-normal distribution was still a reasonable representation for these robots.

This chapter concluded with an assessment of the safety implications of the production problems. The previous analysis of production problems and the system descriptions in the four systems were used to develop this assessment.

The assessment showed that some hazardous actions were quite frequent and reinforced the view on the high levels of hazard in Factories A and F. However the need to ensure safety was rarely a reason for action in any system.

The previous analysis identified the higher than average proportion of hazardous classifications in B6 and B7. However the equipment was more at risk than the personnel in these two systems. Hazardous classifications were of more concerned in Factory F where there was less protection for personnel. Concern was also shown for incidents which involved hazardous actions and were also in hazardous classifications. The hazards of the actions were increased by the possible persistence of the problem which led to the hazardous classification.

The poorer training of personnel in Factories F and H raised the hazard level, especially when these personnel were involved in solving problems for which they had received little or no training.

The assessment of the underlying reasons showed that robot related reasons were not the major source of hazards. The system operation created significant hazards rather than any single piece of equipment. The problem of incorrect identification of the underlying reason for an incident was shown to have some potentially serious effects upon personnel safety.

CHAPTER 6

THE ANALYSIS OF THE SAFETY STRATEGIES

INTRODUCTION

Detailed analysis of the strategies in the 6 case studies towards ensuring safety in the robot systems is given in this chapter. A framework for analysing hazards and the strategies for their control, developed by Dawson et al (Dawson et al, 1982 and 1983) and presented in Chapter 2 is used in this analysis. It describes the strategies in a number of separate steps and highlights the technical and organisational processes involved.

In summary, the framework identifies a number of actions which may be taken by management to control the hazard sequence, beginning with the identification of the hazards. Several complementary strategies are available, either in anticipation or as a reaction to hazard realisation. The process of deciding upon the steps to be taken must be seen in terms of the organisational context in which the process operates, with the availability and allocation of scarce resources and the role of key interest groups being particularly important. Technical control measures to ensure the successful development, implementation and later adaptation must be employed at the point of risk as well as much wider motivational control measures for the whole organisation.

The descriptions of the robot systems in each factory show that there are a number of similarities in the approach to ensuring safety in the robot systems (see Chapter 5). For example, each attempted to develop anticipation strategies for containing the hazards in some way, particularly through physical safeguards. However, the extent to which hazards were identified and then strategies developed and implemented varied considerably. A large number of adaptations and problems were also found. The variations between the factories are considerable and so each section of the Dawson et al framework is considered in detail in this comparative analysis. The analysis follows the order of classification categories given in the description of the strategy framework (see Chapter 2).

THE IDENTIFICATION OF HAZARDS

A number of sources of information are available for the identification of hazards for a particular robot system. Prior experience of the use of robots is one obvious source, as well as expertise within the company or even factory on robot systems. Other sources, from outside the company (such as literature on robot safety or particular robot systems) may also be used in this process. Each of these sources was used to some extent by at least one factory. Figure 6.1 summarises the processes of identification in the 6 factories.

Previous knowledge on the use of robots was available only in Factory B. The previous systems in B were not as complex as the systems studied here but nevertheless used robots for similar tasks. The expertise and experience of problems generated in the past could be called upon by those involved in the implementation of these systems (Manufacturing and Plant Engineers, Safety Engineers and Production Management). Experience elsewhere in the company was also available by the exchange of information and visits to these other sites. This intra-company assistance was also available in Factory A where the Company's Senior Safety Manager became deeply involved in the development of the safety requirements for the new system. Production technology specialists were also brought in on a long-term basis to work on the robot systems and these also had a great deal of experience of other robot systems.

In three of the factories (A, B and F) the systems were installed and commissioned with the considerable involvement of engineers from outside the company, belonging to commissioning companies. These commissioning companies have become a feature of the industrial robot industry in the U.K. and have built up substantial experience of robot system installation. Indeed, one of the commissioning companies in Factory F was also involved in the robot system implementation in Factory A (ProdEng Ltd.).

The level of involvement of commissioning companies varied considerably between the three factories. In A and B, the commissioning company's engineers worked alongside the production technology specialists and engineers to develop the system and overcome problems. In B, the specification of equipment was done by Factory B's engineers, with the commissioning agents involved in the detail of the operation of the equipment. In

FACTORIES					
A	B	C	D	F	H
Assistance sought from elsewhere in the company (Senior Manager, Production Technology specialists). Commissioning company on system for lengthy period and introduced fencing and safeguards.	Visits to other sites in company, exchange of information on experiences elsewhere and also within the plant used prior experience. Formal identification process by safety engineers and committees. Involvement of commissioning company in system development as well as factory engineers. Well developed knowledge of robot hazards. Robots systems classed as high risk.	No clear process, although conventional hazards of welding and turntable motion well understood. No attempt to gain information from elsewhere on robot hazards. Minor role of commissioning company on one system.	Qualitative analysis - recognition of systems hazards and needs of injection moulding machine safeguarding.	No clear process of identification. Commissioning companies produced systems and installed safeguards.	Visits to other users by Works Services. Use of technical literature and MTTA guidelines. Safety Services involved from beginning.

Figure 6.1 Summary of the Identification of Hazards

Factory F, the fewer resources available on-site meant the commissioning companies were instructed to develop and instal the systems from the specification provided the factory's production engineers. Thus the operation of the system and the physical safeguards were decided by people outside the company. A large proportion of the systems in F was equipment designed and built by the commissioning companies. Since the experience and abilities of the commissioning agents were relied upon, no clear process of hazard identification took place within Factory F at the installation stage.

The other three factories (C, D and H) had no access to previous experience from within the company or from external agents. Each implemented the system solely with their own engineering resources. This does not mean that information on hazards was not sought from elsewhere. In Factory H, personnel from Works Services and Safety Services used a number of information sources to aid their decision making. They visited a number of robot systems similar to their intended design, consulted a number of publications in the technical press and referred to the MTTA guidelines on safeguarding industrial robots (MTTA, 1982). This helped to assess the hazards presented by robot use and gave a well-grounded indication of safeguarding techniques. Works Engineers in Factory D were also aware of robot hazards from technical publications, but were more concerned with the impact of the use of robots with an already high risk system - that of an injection moulding machine. The Factory Inspectorate's assistance was obtained in assessing the hazards produced by the introduction of robots and in deciding on how to incorporate the use of robots within an industrial Code of Practice on Horizontal Injection Moulding Machines (British Plastics Federation, 1984). The robot supplier was also involved in advising on adaptations to equipment design. The robots were seen to add to the hazards of injection moulding and needed to be treated within the scope of the regulations as an extension of the injection moulding machine.

There was little evidence of an attempt to gain information about the hazards only in Factory C. No clear process of hazard identification for robots was noted, although the more conventional hazards of arc-welding and turntable movement were recognised. Indeed it seemed that the hazards produced by robot-turntable and turntable-human interactions were considered more significant than robot-human interaction, since fencing was provided for the one robot system with a turntable. This system was exceptional in another respect, in that the supplier companies were involved in bringing the system to operational status. However, their involvement did not include the identification of hazards or the prescription of safeguards.

In some companies, safety department personnel began assessing and inspecting the systems from the earliest stages of system development. Their role was one of collating information on robots at an early stage in the development of anticipation strategies. Although the main responsibility for developing the system remained with the factory engineers in each case, it was clear that the identification of hazards was greatly assisted by the early involvement of the safety department.

In Factory A, safety department involvement was mainly in the form of the Senior Safety Manager who had experience of robot use elsewhere. In Factory B, the Technical and Fire Prevention Supervisor and one other safety engineer assisted in the system development and in assessing the hazards of the equipment. A formal structure for hazard analysis of safety equipment existed in Factory B within company-wide committees and along with the assessment of the completed system by the Factory Safety Department, this made the process of safety problem identification part of the initial decision making process. In Factory C, no involvement of the Safety Officer took place at the identification stage. It was usual for him to become involved later, through his roles as Chairman of the Safety Committee Meetings and as Works Study Engineer. In Factory D, the Safety Officer at the time of the systems' introduction was not heavily involved, leaving the matter to the Works Engineers, in liaison with the Factory Inspectorate and the robot supplier. Factory F had no safety department on site and as the system introduction and implementation was left to the commissioning companies, it was unlikely that much consideration to safety was given by other personnel at the identification stage. In Factory H, the close involvement of Safety Services from the onset was unusual, since they became involved usually at the implementation stage and thereafter. This factory is the clearest example of the close cooperation between factory engineers who designed the system and the safety department. The results of the hazard identification process can be seen in the production of a safety booklet on the systems.

Thus, different means were adopted in the factories to overcome the lack of knowledge of hazards. It is clear that the knowledge of hazards was well developed prior to introduction in only one case, that of Factory B, where considerable previous experience was available. The measures taken in the other factories differed in degree and method and as the discussion above has shown, some factories were more successful than others in developing a pool of experience within the factory.

Different decisions were made about the hazards posed by the systems. Although the identification process in the 6 cases varied and was more complete in some than in others, it would be expected that the hazards identified would be different. The hazards of each system are produced as much by the other equipment in the systems as the robots and the interaction between these different parts. It comes as no surprise that the systems in Factory B were considered high risk, not for the presence of the robots but for the whole system design and their interactions. In contrast, the Safety Engineer in Factory A stated that the hazards of robot use were no different from that of other equipment, apart from the possibility of rapid and unexpected movement. This response shows an approach to hazard identification which does not consider the system as a whole, but considers each piece of equipment almost in complete isolation. The expressed concern of the Safety Officer over the high speed of the robot arm during teach mode motion is a sign of some hazard consideration. However, his involvement in the initial hazard identification was minimal, which may reflect his unfamiliarity with the need to take a system-wide perspective.

ANTICIPATION STRATEGIES

It is always possible that the risks posed by robot systems be considered acceptable after the completion of the process of hazard identification. The probability of hazard realisation and the severity of the consequences may be considered minor enough to be left uncontrolled. However, none of the factories studied came to the conclusion that actions to control the hazards were unnecessary. In each, a combination of the three options, Elimination, Containment and Mitigation of the Likely Consequences of hazard realisation, was considered. Containment strategies were the most frequent with a particular emphasis upon physical safeguards. Overall an attempt was made to eliminate hazards from workers not required to be in direct contact with the robots and to contain them for the other workers.

The process of deciding upon the anticipation strategies to be adopted varied in the degree of formality. The top half of Figure 6.2 summarises these anticipation strategies. In A, the decisions were largely made by the production engineers and the Senior Safety Manager. In B, a more formal structure of committee meetings to discuss system designs meant that decisions about safety strategies were made to some extent whilst discussing safety equipment. It should be noted that M & PE staff were the true decision-makers on types of equipment and their operation with the safety department making the subsequent choice of the safest design. Moreover, this decision making process applies only to physical safeguards. Other forms of hazard anticipation were undertaken in a less formal manner.

In Factory C, no formal anticipation process occurred, with only a few safeguarding options arising as the systems were designed. In Factory D the strategy development process was more one of iteration with several improvements being introduced. In Factory F, the whole task was given to the commissioning companies so no process of deciding upon strategies took place before the onset of system operation. Some later adaptations were dealt with by factory management through the factory's formal procedures. In Factory H the anticipation process culminated in the production of a safety booklet, describing system design, the operation of safeguards and the correct way for people to work with the system. The systems' layout were also specified in some detail in the form of blueprints. The example of one system described in the technical press was followed with visits to other users before the system design was finalised.

The overall purpose of the anticipation strategies can be understood in the four factories with some form of formal process of decision making. In Factory A, the initial strategy was an attempt to contain the hazards within secure fencing, with no contact between live machinery and personnel possible (with the exception of robot motion under teach control). In

FACTORIES					
A	B	C	D	F	H
ANTICIPATION	ANTICIPATION	ANTICIPATION	ANTICIPATION	ANTICIPATION	ANTICIPATION
No formal process of strategy development. Strategy development by Senior Safety Engineer and Commissioning engineers.	Formal identification and analysis of options. Manufacturing and Plant Engineering developed strategies.	No formal anticipation stage.	Piecemeal addition of safeguards, mostly to protect machinery.	System design was given to commissioning companies.	Safety Brochure produced to describe hazards and means taken to control them. Work Services developed strategies.
ELIMINATION	ELIMINATION	ELIMINATION	ELIMINATION	ELIMINATION	ELIMINATION
Choice of maintenance workers (highly trained & experienced) for hazardous tasks. An attempt to achieve safety by design of system. Control of welding hazards by the use of robot system.	An attempt to achieve safety by design - remove people from direct contact with the process. Maintenance workers (highly trained and experienced) chosen for hazardous tasks.	None. Workers not seperated from the process by robot introduction.	Completely enclosed robot system with no workers in the vicinity.	None. Hazards of process not fully controlled by use of robots.	Restricted area to keep people away from robot area.

Figure 6.2 Summary of Elimination Strategies and Some General Points on Anticipation Strategies

Factory B, the high risk systems were designed to contain the hazards whilst maintaining ease of access and a high level of safety integrity. In Factory D, the system was also considered high risk and hazards were contained or eliminated by complex system design. In Factory H, the system was meant to ensure authorised access only and to remove hazards during periods of contact with the equipment.

Elimination

The use of robots introduces a separation between people and the hazards of the processes being undertaken. This is in itself a form of hazard elimination, by removing the source of the hazard - the interaction between people and hardware. If it were complete, it would eliminate most of the hazards of the system. However, certain workers still need to come into contact with robot systems, as the descriptions of the robot systems show. For these workers, the use of robots produce further hazards in addition to those of the process (see Chapter 3). Any claim that robots are an effective means of eliminating hazards needs to be tempered with the realisation that robots cannot wholly eliminate hazards.

A separation between people and hazardous processes was found in all cases, but in two this process was not really successful. The second half of Figure 6.2 summarises the elimination strategies in each factory. In Factory C, the robot operators did not have to carry out the arc-welding tasks themselves, but they did have to work in close proximity whilst the robots did the welding. It is arguable whether the process hazards were actually increased in this factory, as the normal eye and face protection worn by manual welders was not worn by the robot operators. In Factory F, the spot-welding system offered little protection from flying sparks except the larger distances between worker and welding equipment. The arc-welding system was better, in that the bright light and spatter was controlled by cloudy plastic screens. The success of both these systems in Factory F in eliminating process hazards was diminished by the frequent access within the systems during automatic operation.

In the other arc-welding system (A) the system design was quite successful in eliminating the hazards of the process from the surrounding area, as were the spot-welding systems in Factory B and the routing and drilling robot systems in Factory H. The designs went some considerable way in eliminating the hazards of the process from the majority of workers in the vicinity. The most successful case was in Factory D, which went the furthest in designing to eliminate hazards. The robot system was completely enclosed and no-one was required to come close to the injection moulding machine to unload it.

The use of fencing to eliminate the hazards of the robots and the process has already been touched upon above. It is a second form of hazard elimination, in that the robots' own hazards are prevented from affecting those outside the system. This was effective in Factories A, B, F and H, since the access to the live system was controlled by fencing. It was even more effective in Factory D where the complete enclosure of the robot within fencing ensured that the robot hazards were eliminated to those outside. The use of any means of access was designed to make the system completely inoperable. Since the use of fencing is really a form of containment of hazards to within the confines of the system, it is dealt with more fully below under the heading of Containment.

Elimination strategies concentrated upon the interaction of people and hardware. However, strategies focussing on people were also implemented. The choice of certain well trained personnel for the tasks requiring close contact with the systems eliminated the exposure to hazards of other workers less familar with the systems. This was done in Factories A, B and D, in their decision to utilise maintenance workers for tasks such as programming, alterations and adjustments. These workers had a high degree of competence, good knowledge of the systems and were experienced with the technology. Thus, the major hazards were eliminated from the rest of the workers around the systems and restricted to those personnel considered responsible and experienced.

The elimination of hazards from certain personnel was achieved in one further way in Factory H. One of the systems (System I) was placed in a restricted area, so that only people with some reason to be in this area would be near the robot system. This went some way to ensuring only authorised personnel would have access to the system.

Elimination of hazards was therefore particularly successful where fencing was used to contain the hazards within the systems, where maintenance workers were employed for the more hazardous work activities and where unauthorised access was restricted. Thus, the elimination of hazards was most developed in Factories A, B and D. However, problems with the system design may lower the effectiveness of the hazard elimination. This proved to be so particularly in Factory A, as described later in the Problems and Unanticipated Consequences section later in this chapter.

Containment

The analysis of the containment strategies distinguishes between the three options of concentrating upon hardware, on people and on the interactions between people and hardware and thereby focusses on the use of physical safeguards, the provision of training and information and the adoption of systems of work. The main points of these containment strategies are summarised in Figure 6.3.

Physical safeguards

This term denotes all hardware means of enclosing machinery and forms of safety devices as additional features on a system. The use of such equipment was very common and in this respect a number of similarities were found between the strategies in different factories.

A great deal of time and effort was expended on the design of physical safeguards for most of the systems, with a plethora of types of equipment and operation modes. These have restricted the access to the systems and contained the hazards for personnel both inside and outside the systems.

The commonest form of physical safeguard was some type of fencing, although the size and material varied. The most common material was a thick metal wire mesh, of either 1" or 2" grid. This was used in Factories B, D, F and H and on one robot system in Factory C. The one fenced system

FACTORIES					
A	B	C	D	F	H
Physical Safeguards 2m high sheet steel fencing. Weld monitoring. Interlocked gates. Photo-electric guards. Roller bars. System of Work Notice from Safety Engineer prohibiting access to live system. Permit to Work system. Training 16 people on 2 week course at suppliers site. Held at beginning of system life and no refresher course. No training for Safety Engineer of safety	Physical Safeguards 2" wire grid fencing 2m high. Perspex screens over some areas. Double limit switches on access doors. Photo-electric guards. Lock pins for pneumatically powered equipment. Sensors on transfer mechanisms. System of Work Procedures for manual welding. Formal practices for maintenance tasks - in flowchart form. Training Continuous and in-house. Films, videos and booklets available on wide range of topics.	Physical Safeguards 1 system - 3m high wire mesh fence with interlocked sliding gate. Safety curtains. Sequence control buttons. Safety feature on weld torches to robots 4-7. No Formal System of Work Training Extremely limited. Foremen and maintenance only. On-the-job training for operators.	Physical Safeguards Modifications to robot. Safety interlocks, pressure sensitive matting. Fencing completely surrounding system. No System of Work - hazards controlled well by physical safeguards. Training At suppliers and at factory. Large numbers received training. No refresher courses. Trade Union representatives trained.	Physical Safeguards System I:- 3m fencing. Limit switches. Safety visors and perspex barrier on loading area. System II:- 3m fencing. Rollerbars. Sequence buttons. Cloudy plastic screen. System of Work (later modification) Presence of 2nd person and E-stop covered. System of 1 chargehand to minimise hazards. Training: Patchy. Some trained on different robots than those on which they worked some not at all. 3 weeks on one robot type. 3 days on other. At supplier site.	Physical Safeguards Wire mesh fencing and perspex upper part to fencing. Interlocked doors. Black and yellow hazard area. Extraction pipes. System of Work Specified in safety booklet. Training Extensive, 1 weeks suppliers course as a 'primer' then on-site refresher courses. More trained than necessary. Robot Instructor. Safety signs.

Figure 6.3 Summary of Containment Strategies

in C was different in that a far finer wire was used, making the fencing considerably less sturdy. The fencing was also not effective in containing the hazards.

The height of the fencing was between 2 and 3 metres in each case with the added feature in Factory D of fencing overhead of the same wire mesh to make a complete enclosure. The fencing in each case offered some separation between people and the hazards of the process and equipment. However each system was designed to allow access to personnel within the system and as such the fencing only contained the hazards to within the system and to those that entered.

Access to the system was through gates in the fencing. Where there was no fencing (as in Factory C) there was no physical restriction on access to the systems. In most cases the access gates were interlocked in some manner to control the hazards present within the system during periods when people could be present.

In Factory A, the interlocked gates removed power from all equipment except the robot, but this was restricted by software to teach mode operation only. In Factory B each access gate had a set of two limit switches which acted via hardware and software to stop all movement in the affected section. On the simplest system studied in Factory B, Station 5, the access gates were also locked. In Factory C, the one system with fencing had a sliding access door which was interlocked to the motion of the turntable. In Factory D, the one access gate in each system was interlocked via a key system to the robot and the injection moulding machine. This interlock removed all hydraulic power to the system and prevented movement of the robots and the moulding machine.

The only fenced systems which did not also have interlocks were in Factory F. In this factory the containment of hazards achieved by the fencing was diminished by allowing access through the gates. The systems in Factory H had two gates each, both with key interlock mechanisms. This system of double interlocks allowed access to the robot controls (for authorised personnel) but prevented access to the operational robot.

A number of other safety devices were in evidence, mostly concerned with controlling hazards for people on the periphery of the systems. Photoelectric sensing devices were present in two cases, in A and B, to protect people performing manual tasks on the system, such as loading and unloading parts. In Factory D, a p-e device was introduced across the conveyor belt exit from the system and another across the access area to the moulding machine on the robot side. These served to protect equipment rather than workers.

The loaders on some systems had other devices for their protection. In A and F (System II) roller bars with interlocks prevented the motion of equipment near the loaders. The equipment controlled by this interlocked safeguard were in the immediate vicinity of the workers. In A, the roller bars also acted as a physical means of preventing motion of the jig truck by locking it in place in the 'out' position. Some protection for loaders was provided with System In in F by interlocked movable perspex screens on the loading areas. However, these screens were only in place when spot welding was not taking place. Safety visors were also available for the loaders but were used infrequently.

Perspex screens were used in two other systems as a means of controlling the spread of by-products of the process and to afford good visibility. In B, the screens were placed over the wire mesh fencing at a number of places where sparks which reached the fence could be produced. In H, the perspex screens formed the upper part of the fencing. Any swarf which was produced would thus remain within the system. Cloudy plastic screens were used in Factory F (System II) for a similar purpose. In Factory C the safety curtains on the majority of systems and the green plastic screen on the turntable also served to control the spread of hazardous effects of the process,although in this factory the emission of light was controlled, not the 'spatter' from the welding. Other process hazards, such as ozone, noxious fumes production and noise were not controlled.

Some robots had special safety features which acted to protect both personnel and equipment. All the arc-welding robots in Factory F and the 4 most recent in Factory C had a microswitch at the joining of the weld torch to the robot arm. Robots of one type in Factory B (Type 3) also had a form of anti-collision safety device. The actuation of this device caused a emergency stop condition and not a control halt as in the arc-welding robots above.

The restriction of robot movement to slow motion only under teach control was common. This restriction was achieved mostly through an interlock with the access gates but was achieved in Factory D by another means. In D, the robots had undergone some modifications, so that the only motion possible when a person was within the system was under teach restrict control. This was the only example of system hardware design safeguarding a person locked inside the systems.

Manually selectable safeguards were not common but did form part of the system design in Factory B. The pneumatically powered equipment could be locked in place by hardware means when access was required.

The majority of systems showed the signs of build-up of deposits from the process being performed. In only one case were extraction measures given a prominence. In Factory H extraction pipes were built into the design to remove most of the swarf and thus contain the hazards produced by these sharp pieces of material.

The control sequencing for the movement and action of equipment in each system also acts as a form of safeguard, in that the types of interaction which can occur under normal working are constrained. In some cases this constraint was achieved by an overall controller, in others, by the robots own controls along with interfaces to the other equipment. Positional sensors, in the form of either limit switches, encoders or proximity switches were very common in sequence control of the robot systems. In Factory A, there were many proximity switches on the jig truck, the hoists and the other jigs. There were also limit switches on the rest stand for each robot. The main controller also monitored the welding action of each robot. In Factory B, there were numerous sensors throughout, on the transfer devices and on the parts holders (lifter tables and turnbucks). The only sequence buttons were on the initial loading sections in Station 5. Systems halts could be initiated by the signals from the sensors on the other safety devices. In Factory C, only system No. 6 had complex sequencing, with a special interface control between the robot and the turntable. The other systems were controlled by the sequence buttons, with signals from rotating jigs in some systems. In Factory D numerous interlocks aided the sequencing of both the robots and injection moulding machines. In Factory F, both systems had sensors on the parts holders. There were also limit switches in System I for the rest position of the two robots. Factory H was the simplest in respect of sequence control, in that no sensors were used for this purpose.

Training and information

The variation in scope, length and focus of training is much wider than the variation in options for physical safeguards. Although all the factories provided training for workers to some extent, some did far more than others. Variations occurred in the length of periods of training, the numbers and types of employees given the training, the site of training, its timing in relation to system introduction and the safety content. Other types of information available to workers varied similarly.

Formal training periods extended from 3 days to 3 weeks. The longer training courses were in Factories A and F, with 2 weeks in A and 3 weeks with one robot supplier in F. The shortest courses were in Factories D and F (with the other robot supplier). For the others, 1 weeks training was the approximate norm.

The numbers attending training courses in each factory reflected to some extent the numbers involved with the robot system. In some cases more were trained than was absolutely necessary. In Factory A, 16 people from engineering departments and maintenance were trained, of which only 6 were seen to use the skills gained in this training on a regular basis. In Factory B, all the maintenance workers were given appropriate training in the company's own training scheme, as were the loaders/operators. In Factory C, only the welding foremen and maintenance were sent on any training courses. In Factory D, more maintenance workers and programmers were trained than were really required. Factory Trade Union officers were also sent on the training courses. In Factory F not all the system supervisors were trained, although production engineers were sent on extensive courses. In Factory H, all robot operators and relevant maintenance workers were sent on training courses.

The choice of location is an important feature of training, Factories A, C, F and H chose to use the robot suppliers site. Factory B had their own extensive facilities for training with a training centre and booklets, films and videos available on relevant issues. Factory D started with training at the suppliers but discovered that more benefit was gained from training on the systems used by the workers. As a result, 3 days out of the 4 training days given to each worker were at the factory. In Factory H the suppliers training was a primer, which was built upon by training on site from a Robot Instructor. Thus some factories not only opted for on-site training but developed on-site facilities of their own.

The majority of the training took place at the beginning of the systems' use and thus the recall of information given during training could become impaired over time. Workers in a number of factories where no further training was given after system introduction commented on the deterioration of their knowledge and of the benefits of refresher courses. Such continuous training was available in Factories B and H with their on-site training facilities, but were not in the other factories. However, in Factory C other workers were sent on training courses well after robot system introduction. For example, a maintenance electrician was sent on a more intensive 2 week course than the others in the factory had received. This took place well into the lifetime of the systems' operation. Subsequent training for new workers was also found in Factory H.

The content of training dealt with many matters besides safe robot use. Fault-finding, programming and some level of maintenance were the main areas covered. In fact, safety played quite a minor role in the whole training. By and large safety training was given alongside correct operating, programming and maintenance procedures. Factory B, D and H's training programmes had the clearest forms of safety training in terms of the requirements of the Code of Practice in D or the established training provided by the Robot Instructor in H or films for safety training in B. In those cases where training was on-site, the training was not restricted to considering the robots as stand-alone pieces of equipment. The interaction and operation of the whole system were considered.

Those who did not receive formal training but nevertheless came into contact with the robot systems received their training in a more formal and less effective manner. The loaders in Factory A were only taught the order of parts to be placed in the jigs and how to fasten them in the correct position. In Factory C, the robot operators received some on the job training from the foremen, but learned how to work with the robots by spending 1 week alongside another operator. What is more, by their own admission, the foremen in C also had learned a lot by trial and error. In Factory F, the chargehands who were not trained formally also resorted to learning from the others and by trial and error. Maintenance also were not fully trained on the systems and attempted to supplement their knowledge by watching the service engineers who came to repair parts of the systems. Given the low level of knowledge one can presume that such visits were frequent at the beginning of production. The loaders/unloaders were given some tuition by the senior production engineer. Formal training was not given to the safety engineers in any case, although T.U. officers did get some training in D.

The patchy pattern of training in some factories has some safety implications. When coupled with the informal practices observed with these systems, a number of circumstances can be identified where workers were not fully aware of the problems and hazards involved in the tasks they were performing. The lack of extensive training for certain types of employees in some factories signifies a low priority for training.

Training of a formal or informal nature is not the only source of knowledge of the hazards of the system. For example, each factory was supplied with manuals on the robots and in some on the other equipment as well (for example the main controllers). In those factories where training was well developed (A, B, D and H), the manuals provided were very detailed. In Factory C, the more detailed manuals were only released when the maintenance electrician received an intensive 2 week training course.

Other sources of information were available in 3 factories. In Factory B, the company had developed a large library facility on-site which contained a large amount of information on the systems. In Factory C an information board with instructions for operators was present in the first robot system, although it was clear that it was not referred to frequently. In Factory H, the procedure of developing safety booklets for guidance and standardising procedures acted as a source of information to a number of people, including safety representatives. There were also a number of safety signs around System I in Factory H which referred to possible hazards involved in robot use.

Though the provision of training and information varied considerably, a pattern emerges from this diversity. Where provisions were made for continuous training, these facilities also provided training on safe use. Where training appeared more as part of system introduction, the provisions were less extensive and less directed at issues of safety. On-site training also appears more successful,with greater flexibility for subsequent refresher courses and information.

Systems of work

The focus of the containment strategies upon the interactions of people and hardware was developed to a lesser extent than those upon hardware or people. Only in two factories had significant amounts of time and effort been expended on developing systems of work. Other formal statements of working practices existed in another two.

It is clear that a number of potentially hazardous states remained in each system after other safety strategy options were applied. It is therefore perhaps surprising that in only 2 of the 6 factories were clear forms of systems of work adopted. It is less surprising that these two systems of work differed considerably from each other.

In Factory A the Safety Engineer prohibited all access to the live system initially, except for 3 senior members of staff. None of these were directly involved in carrying out on-the-spot maintenance. Later, an attempt was made to bring actual practices in line with formal ones by the establishment of a form of Permit to Work system. This attempted to control practices involved in close contact with live and sometimes also operational machinery. Authorisation was given to the maintenance team on a daily basis. Protective clothing and equipment was provided and certain procedures were to be followed by workers at particularly hazardous times.

It is somewhat inaccurate to call this procedure a Permit to Work system, since it does not contain important elements normally specified in one (see the HSE Guidance on Entry into Confined Spaces, HSE, 1977). Moreover, it does not conform to the guidance provided in the MTTA guidance (see Chapter 3) nor does it appear to fall wholly within the terms of reference of the Unfenced Machinery Regulations, 1938 (see Chapter 2). The authorisation applied for the whole shift and not for particular hazardous occasions. Normally the hazardous circumstances are specified on a PTW form along with safeguarding measures to be adopted. None of this was specified along with the system of work adopted in Factory A. Instead it gave authorisation for maintenance workers to do what they considered necessary within certain general constraints on behaviour.

In Factory B, a system of work for maintenance workers was designed around a flowchart of possible safeguarding options. Although a number of physical safeguards operated automatically, it was recognised that a procedure was required to utilise the manually operated safeguards when necessary. This procedure was developed by Manufacturing and Plant Engineering and presented to the Factory Safety Committee for formal agreement. It was displayed prominently over the whole of the area as well as given to each maintenance worker. Maintenance workers decided the answers to questions posed in the flowchart and then acted accordingly.

The actions of other workers in loading parts or carrying out manual welding were not included in the flowchart and since these workers' actions were heavily constrained by the operation of the equipment there was clearly little need to develop a system of work specifically for these workers. For example, a decision had been taken that physical safeguards (such as photo-electric safety devices) contained the hazards to an acceptable level for the loaders, so that formal procedures were unnecessary.

There were formal specification of working practices in two other factories, but not to the same extent as above. In Factory F, the safety committee decided that a procedure similar in some respects to that in Factory A should be introduced. Whenever a person was within an operational system, proper supervision was required and a second worker was to cover an emergency stop button. This procedure had the added support of possible disciplinary action for contraventions. A less formal system was developed by one chargehand to reduce the possibility of hazard realisation during periods of access. However, this only applied to one system and to the shift worked by this chargehand.

In Factory H, the Safety Booklet produced on one of the systems contained sections on the correct procedures to be followed during various operations.

In the other two factories, little was done to control the interaction between people and machinery. In Factory C, the working practices of foremen, maintenance and robot operators were developed informally, with no clear separation between tasks or an attempt to control hazards. The information board prepared by one foreman for the operators' use did contain information on the correct procedures to be followed, stating safety issues which were relevant and what should be done to avoid hazards. However, this was not really used and so was not an accurate representation of working practices. In Factory D, the hazards were largely considered to be controlled by other means, notably physical safeguards. Therefore those hazards resulting from periods of close contact during maintenance were considered to be sufficiently controlled not to warrant a system of work to contain the possibility of hazard realisation.

Mitigation of Likely Consequences

All the factories had introduced some means of reducing the likely consequences of hazard realisation although it was clear that this was not a major emphasis. The upper part of Figure 6.4 summarises the measures taken. In the main mitigation of likely consequences was provided as a "last ditch" safeguard. Each system had emergency stops to remove power from the equipment in the event of a hazardous occurrence. In each case, these emergency stops acted to remove all power from the systems and to stop all operations.

Factory H had an additional feature in the form of emergency doors on each system. These allowed access in an emergency. The proper access doors also acted as emergency doors. Each of these had a break-glass bolt both on the inside and outside. This interesting feature is the sole example of a system incorporating a means of dealing with hazards which might be produced for those within the system, other than by the pressing of an emergency stop button. The ability to open the doors by the same means from the outside also ensures that someone coming to the aid of an injured worker would not also be exposed to the same hazards.

REACTION STRATEGIES

The mitigation of actual consequences is similar to the anticipation strategy outlined above, but differs in that it is not directed at identified hazards. The mitigation of actual consequences acts through the provision of general facilities and resources for hazard realisation. The clearest form of this is some type of accident and injury treatment centre in the factory, such as a surgery or first-aid treatment centre. The lower part of Figure 6.4 summarises the measures taken in the 6 factories.

Each factory had some form of treatment centre, but this varied from the extensive to the barely adequate. In three cases (C, D and F) the first aid treatment was given by shop-floor or staff personnel with first-aid training. In C, there were first-aiders amongst the shop-floor workers in each section of the factory, often combining this duty with being safety

FACTORIES					
A	B	C	D	F	H
<u>MITIGATION</u> Emergency stops.	<u>MITIGATION</u> Emergency stops. Emergency power-off and sequence stop.	<u>MITIGATION</u> Emergency stops.	<u>MITIGATION</u> Emergency stops.	<u>MITIGATION</u> Emergency stops.	<u>MITIGATION</u> Emergency stops and emergency access doors on system.
<u>REACTION</u> Emergency - full time nursing staff.	<u>REACTION</u> Medical Department and surgery facilities - full time nurses.	<u>REACTION</u> First aiders (shop-floor workers).	<u>REACTION</u> First aid facilities-shop-floor personnel.	<u>REACTION</u> Surgery - inadequate in an out of the way part of the factory. First aiders drawn from workforce, mostly staff and security personnel.	<u>REACTION</u> Medical Department. Full-time nurses.

Figure 6.4 Summary of Mitigation Strategies and Reaction Strategies

representatives. In D, the first aiders were also manual workers in each section. In F, the majority of first-aiders were staff or security personnel. The treatment centre was in an obscure part of the factory and thus not wholly appropriate to dealing with injuries in the main factory area.

In the other factories more extensive facilities were available. In A, one full-time nurse was available to treat all employees in a well equipped surgery. In B and H a large medical department was available with full-time nursing staff. The better facilities in these three can be explained by the size of the companies of which the factories were a part. More resources could be allocated to the capital expenditure for purpose-built treatment centres and the employment of full-time staff.

OVERVIEW OF THE STRATEGIES IN EACH FACTORY

The strategies match the guidance reviewed in Chapter 3 closely. Containment strategies predominate, particularly physical safeguards. Most of the major items of physical safeguards in the systems confrom to the explicit guidance given on these items. The poorer development of training and systems of work in the majority of systems is also in accordance with the less detailed presentation of guidance on these subjects.

The discussion of anticipation and reaction strategies shows that certain factories have a far better set of measures to control hazards than others. In particular, Factory B developed strategies within each category considered above. In contrast, Factories C and F developed few strategies. Thus steps taken to identify hazards affect the extent of strategy development. The poor identification of hazards in C and F can be seen to have a detrimental effect. The lack of knowledge on hazards appears to have inhibited the development stage of safety strategies in these two factories.

THE ROLE OF KEY INTEREST GROUPS AND THE USE OF SCARCE RESOURCES

Dawson et al state that two important components to the overall organisational context of health and safety are the role of key interest groups in the company and factory and the use of scarce resources. The general availability of scarce resources, in particular technical and specialist knowledge, finance and time for line management decide the capabilities of the various key interest groups, but the allocation of these resources to health and safety and to the robot systems will determine their relative availability. To analyse these issues, the roles of each key interest group identified by Dawson et al and the availability and allocation of scarce resources is considered. Figure 6.5 summarises the information in this section.

Key Interest Groups

Corporate management

The involvement of management beyond the factory in decisions on the safeguarding of robot systems varied mainly according to the normal senior management involvement. Certain compaines operated with strong vertical control over the operation within the factory, but these were in a minority. It was more common for virtually all operational and some strategic decisions to be made at factory level.

In Factory A, the company subsidiary normally had complete autonomy of action. Factory A's own actions were controlled by the decisions of this subsidiary. However, in the case of the robot system, the decision to invest was taken at a higher level by the company's senior management. This was not the only involvement of corporate management in the decisions, since the Senior Safety Manager of the whole company was involved in safeguarding the system.

In Factory B, there were a number of company-wide departments to co-ordinate and facilitate communication between management functions at factory level. There was a Safety Department which acted as an advisory body on Company Policy towards such matters as safeguarding. A National Health and Safety Committee, set up with the recognised Trade Unions also assisted in

FACTORIES					
A	B	C	D	F	H
KEY INTEREST GROUPS					
Senior Manager present initially. Factory Management delegated to technical specialists. Maintenance team worked continuously on the system.	Company-wide Health & Safety Committee. Safety Dept. at H.Q. Factory management delegated to technical specialists. First line supervision not much in evidence. Safety committee involved in approval of formal working practices.	Group Risks Manager. Production Manager heavily involved with robot systems. Foremen involved in problem solving.	Works Manager and Senior Works Engineer heavily involved with robot systems. First line supervision not much in evidence.	Personnel Manager's role in co-ordinating health and safety. Major role taken by commissioning companies. First line supervision involved in problem solving. One production engineer involved in robot programming and problem solving.	Works Management involved in implementing safety booklet on robot system. First line supervision not much in evidence. Works Services, Production Engineering and Manufacturing and Development involved with robot systems.
THE USE OF SCARCE RESOURCES					
Tight financial constraints. Technical and specialist knowledge in short supply in factory. High demands on line management's time.	No shortage of technical and specialist knowlege. Finances not found to be tight. Line management given time to develop and participate in health and safety strategies strategies.	Tight financial stra- constraints. Shortage of specialist knowledge. Little time for line management to participate in safety strategies.	Technical and specialist knowledge spread throughout the factory. Finances freely available for safety on robot systems. Works management involved in strategy development.	Small technical and specialist knowledge base in the factory. Little fresh investment available subsequent to system introduction. Line management had little involvement in participating in safety strategy development.	Technical and specialist knowledge widespread in factory. Flexible financial constraints. Line management initiated safety strategy and participated thereafter.

Figure 6.5 Summary of Role of Key Interest Groups and the Use of Scarce Resources

establishing appropriate measures at factory level. The role of co-ordinating did not stretch to making the decisions for the factory management. Each factory was allowed to act independently, except on matters of major strategic importance. This applied as much to health and safety as it did to the whole range of other operational decisions.

In Factory C hardly any involvement of corporate management took place. Most strategic decisions were taken by the subsidiary company management, with operational decisions being made on site. Corporate management became involved in health and safety with the visits of the Group Risks Manageer who assessed safety measures for possible company liability.

In Factory D, the parent company had a minor role in decisions taken at the factory, particularly on health and safety. The decisions surrounding the use of robots and their safeguarding were made within the factory.

In Factory F there were a number of company-wide managers, one of which, the Personnel Manager, dealt with co-ordinating health and safety. Decisions on the finance for the robots were made by the company's senior management, but details of their operation were left to the factory. Some safety issues came to the attention of the Personnel Manager in his attendance at safety committee meetings, but he was not directly involved in the solution of these problems.

In Factory H, virtually all decisions - operational and strategic - were taken at divisional level. In effect this meant that the decisions were taken at factory level, since the two sites involved here were two of the three sites which constituted the division. Management was structured largely on a divisional rather than a factory basis.

Thus corporate management took a minor role overall in the decisions involved in robot system design, implementation and the related safety strategies. Factory A was an exception in this, with corporate safety management involved in the system implementation stage. In B and C, company management could affect the safety strategy with the advice of company safety personnel in B and the advice of the Group Risks Manager in C, but this would be subsequent to the decisions within the factory. With the exception of A the decisions on the robot system were initially made by factory personnel.

Factory management

The Safety Policy Document for each factory placed primary responsibility for health and safety upon factory management. In all but one factory a senior member of factory management acted as chairman of safety committee meetings. The exception was Factory C where the Safety Officer/ Works Study Engineer fulfilled the role of Chairman of the safety committee.

The involvement of factory management in health and safety matters implies an involvement in the introduction of the robot system and subsequent safeguarding. Although factory management were involved to some extent in each case, the level of involvement and the role played varied. In Factories A and B, overall responsibility lay with senior factory management, but their involvement was not high. The design and implementation of the system was left to the technical specialists. In A this meant the specialists from elsewhere in the company as well as those in the factory and from the commissioning company. In B this meant the engineering specialists within the factory and the commissioning company.

In Factory C, the Factory Manager was not much involved, but the Production Manager could often be found on the shop-floor dealing with issues. The latter manager was heavily involved in the robot system introduction and also had responsibility for the implementation of the Health and Safety Policy.

In Factory D the Works Manager and a senior works engineer became deeply involved with the design of the robot systems. These senior staff members also had responsibility for health and safety. Indeed both played a part in a new Safety Committee structure.

In Factory F both the Factory Director and the Manager had formal responsibilities under the Health and Safety Policy of the company, but had not played an important role in the introduction of the robot systems. The decision to leave the major proportion of implementation to the commissioning companies played a part in this lack of involvement. The senior management also delegate a large part of day-to-day responsibility for the production facilities to the production engineers in the factory.

In Factory H, works management were given the main responsibilities in the Health and Safety Policy Document. They were the main instigators of the drive towards the preparation of a Safety Booklet on the first productive robot system and took an interest in the safety issues raised by robot introduction.

From this brief description, the pattern emerges of a key role for factory management where specialist assistance is not available within the factory or company or from commissioning companies. Senior factory management played the least important role in F, where commissioning companies implemented the systems. Where expertise was available within the factory, senior management delegated their involvement to these specialists.

First-line supervisor

The involvement of first line supervision falls into two clear groups:

a) those where their involvement was high because of a continuous involvement with production problems

b) those where they were not much in evidence.

The two groups have an equal frequency. In A, C and F, foremen or chargehands are part of the production team working on the systems. In A, the foreman and four maintenance workers were allocated on a permanent basis to the system. In C, the foremen were the main workers dealing with problems which arose. In F, the chargehands entered the systems to sort out nearly all problems. In these 3 factories they tended to accept the status quo and did not attempt to instigate major changes. In the other 3 factories, the foremen dealt with a much larger area than the robot systems studied here and so were not much in evidence at any one spot within this.

First-line supervision therefore either exerted no major influence on the safety of the system because of their absence or tended to work in the same manner as the others and thus exerted no corrective influence on the adopted practices.

Technical specialists and safety officers

With the exception of Factory B the introduction of the robot systems was the first of its kind in the factory and also for the most part in the companies. Under such circumstances, one would expect technical specialists to be involved a great deal, with a role in safety matters as well as overall system design and operation. Where technical specialists were involved one can similarly expect a great deal of power and influence from safety specialists in the decisions on safety strategies.

In Factory A, nearly all technical specialist knowledge come from outside the factory, mostly from elsewhere in the company. The role of the Senior Safety Manager in the system would tend to suggest that the main source of influence on safeguarding came from this person and not from people in the production technology specialist subsidiary. The transfer of authority to the factory Safety Engineer can be seen as lowering the level of specialism. This is especially so when one considers his lack of involvement in the system introduction, the lack of training on robots and his opinion that robots do not differ greatly in terms of their hazards from other equipment. Technical specialists were required mostly for the system introduction.

In Factory B, technical specialists were available on a continuous basis on-site from the Manufacturing and Plant Engineering department. They were heavily involved in all stages of system design, implementation and operation. They were also involved in safety matters, as can be seen from their role in the incorporation of physical safeguards and the adoption of a system of work for maintenance workers. The factory's Safety Department was also involved in the technical specification of the system and in subsequent inspections of design and operation. There was no shortage of availability of technical specialists in this factory.

In Factory C the only technical safety specialists in the factory was the Safety Officer. That this role was concurrent with Works Study Engineer and that his general role was mainly satisfying legal requirements rather than advising on new safety techniques, suggested a low status for this position. Correspondingly, any influence he had was also diminished. For example, the Safety Officer usually did not see plans for new production systems prior to introduction. The design of systems was the responsibility of the Production Manager. It was more common for the Safety Officer to come into contact with the new systems in his role as Works Study Engineer.

In Factory D the main technical specialists came from works engineering. They maintain equipment in the factory and were the main force in deciding on the design of the robot systems including the safeguards and the subsequent incorporation of modifications to the system design.

The importance of the safety function had been enhanced shortly before the study be an increased authority for the Safety Engineer and a safety committee structure with a wider workforce representation. The improved role of the Safety Engineer in the factory signifies an enhanced position with greater power and influence than was present at the time of the robot system introduction. However this improved influence did not affect the robot systems greatly, since they were considered already well guarded.

In Factory F the production engineering department were the only technical specialists continuously available and were involved a great deal in the robot systems. The production engineers were the main source of technical expertise on the system design and operation along with the specialists from the commissioning companies. There was no full-time Safety Officer in this factory, with the duties of such a post being part of the Factory Manager's overall responsibilities. Thus there was no person within the management team to consider the safety issues, to advise or to try to influence the consideration given to safety by the Factory Manager.

In Factory H technical specialists are within Works Services, Production Engineering and Manufacturing Development, all of whom played a major part in the robot system design, introduction and operation. Safety issues were advised upon by the Safety Services Department. This last specialist group had a number of staff members and considered itself influential in the factory. They played a significant part in the standardisation of approach for the two robot systems and in assessing the systems prior to their introduction.

Thus technical specialists and safety officers played a major role in only three factories, B, D and H. The expected high level of involvement is not found in three factories where previous experience of robot systems was either minor or non-existent. Though some factories had specialist involvement in system introduction, this expertise was not maintained subsequently.

Workforce safety representatives

Worforce involvement on safety and system introduction can take place at all stages in the development and implementation of the systems. They could be consulted or informed at the design stage and play a part in the formulation of safety measures, or become involved later when problems arise in system introduction or operation. Clearly the stage of involvement and the form the involvement takes are important in an understanding of their role. The committees could participate in the decision making process or be merely a source of information transfer between management and workforce about plans or actions near completion.

In Factory A no one safety representative had taken formal responsibility for the robot system, although one had decided to take up issues concerning the system. The committee meetings were not consulted about the introduction of the robot system, but were informed of its imminent arrival. Issues concerning the effect of the system on the surroundings and workers in the area were raised subsequently and some had been acted upon. The safety representatives did not consider that they had a great deal of influence, which was illustrated by the slow response to issues they raised.

In Factory B, the safety committee was involved towards the end of the design in agreeing to the formulation of the systems of work as a flowchart. They were informed of the design of the system but were not greatly involved subsequently.

In Factory C the safety committee was a management initiative with safety representatives elected according to a pattern set up by the management. Meetings were held irregularly (unlike all the other cases where regular intervals were laid down and maintained - usually once a month) and poorly attended. Thus it is perhaps not surprising to note that the representatives had little influence. They were not consulted or informed over the robot systems and found that safety issues had to be raised repeatedly before they were acted upon.

In Factory D, the safety committee at the time of robot system introduction was informed of the robots but were not consulted. This position changed with the new committee structure as consultation and the degree of influence was increased. However in common with the view of the Safety Engineer in this factory, the systems were considered to be of less immediate concern than other equipment.

In Factory F the safety committees were set up as a result of a union initiative, well after the robots were introduced. The general feeling about the part played by committees amongst workforce representatives was that they resulted in reaction to steps taken by management rather than the development of commonly agreed procedures. A high level of conflict of purpose was reported by both management and union representatives on the committee. However the representatives were informed of future plans for the expansion of the number of robot production systems. A disciplinary procedure also existed for contraventions of certain safety committee decisions. Thus the influence of the representatives had grown since the days of the robot system introduction.

In Factory H the safety representatives were very active. This may have been connected with the fact that they were all trade union representatives who were also concerned with health and safety matters. However, issues concerning the robot system had not arisen and the representatives admitted to a general lack of knowledge on robot safety.

Factory C was the only factory in which workface safety repretatives were not supported by a trade union structure. In all the others the representatives were either elected separately to the two posts or were trade union officials with a particular interest in health and safety matters. It is possible that all the representatives suffered from a lack of knowledge of health and safety in general and of robots in particular. This was reflected by the low level of awareness of robot hazards shown in the issues raised at committee meetings and could be explained by the lack of the training on robots for safety representatives. In only one factory (D) did Trade Union representatives receive specific training on the robots.

The Use of Scarce Resources

The role of key interest groups and their influence on issues of safety and robot systems have to be linked to the general availability of scarce resources and the application of these resources to robot systems. Three important types of scarce resources have been identified (see Chapter 2). Each factory is considered in terms of these to identify the available options.

In Factory A the overall availability of resources was restricted. Technical and specialists knowledge was in short supply in the factory and was supplemented by resources from elsewhere in the company. The Safety Engineer of the factory had responsibilities for two other factories. Finances were considered to be tightly constrained and were blamed by safety representatives for the slow action on safety issues. Difficult market conditions of this subsidiary served to exacerbate this limitation. Line management and maintenance supervision in the robot system area were not able to participate throughout the development of health and safety strategies, since a large proportion of energy and time had to be spent on keeping the factory and company viable.

In Factory B resources were not found to be tight or particularly scarce. There was no shortage of technical and specialist knowledge and no difficulty was noted in allocating these to the needs of the robot systems. For example, visits to other company sites were carried out by the Safety Department and other engineers to investigate alternative safeguarding strategies. Finances were not tight and no shortage was apparent in the design of the systems (which formed a major part of the company's investment programme). Line management (i.e. maintenance supervision) was not under noticeable time pressure, but had to cover a wide area of the factory. As a result they were not greatly involved in the health and safety strategies, nor in the supervision of the system of work for maintenance personnel.

Resources were found to be tight overall in Factory C. Technical and specialist knowledge was minimal in the factory and none was sought from elsewhere for the needs of robots or health and safety. The Safety Officer had only minor secretarial support, with one secretary shared between 3 senior managers. Authorisation for major investment came from the parent company. Few resources were found for ensuring safety on the robot systems. Senior production management were intimately involved in minor issues and the welding foremen were under tight time constraints. Consequently there was little opportunity for participation in safety strategy development. This may be a major reason for the simple safety strategy developed in this factory.

In Factory D, resources were not particularly tight. Technical and specialist knowledge was widespread with a high proportion of engineering staff in the factory. Considerable time and effort had been expended on the robot systems and in particular on their safeguarding. Finances were not tight but it proved sensible to develop extra safeguards for the equipment, which was worth over £100,000. The works management were involved in safety strategy development of the safeguards on the system.

Resources were found to be particularly scarce in Factory F. Technical and specialist knowledge was sparse with a small production engineering department. One of the production engineers worked with the robots on a full-time basis because of the importance attached to them. The asbence of a full-time Safety Officer in the factory can be seen to contribute to the lack of attention to safety issues. Finances were also noticeably scarce with little available after the initial system introduction. Line management had little involvement in the safety strategy development as this was passed to the commissioning companies.

No shortage of resources was found in Factory H. Technical and specialist knowledge was widespread with a highly technical workforce in a technologically advanced industry. Health and Safety was also given appropriate resources. Knowledge was sought from outside the company when in-house expertise was found wanting. Financial resources constraints were found to be flexible, with resources given as appropriate. The lack of conflict between safety representatives and management supports this view. Line management were the original initiators of the safety booklet on the robot systems and so were involved in the development and implementation of the safety strategies. The development of controls and the introduction of equipment progressed at a relaxed pace, with line management involved throughout.

This summary shows that the variation between factories is consistent across the three main forms of scarce resources. The allocation of one resource to the robot system meant that the others were also available. The role of key interest groups and their influence on safety issues with robots were greater where resources were more freely available. In the factories where resources were tight some had found means of overcoming the problem. For example, A had managed to overcome these shortages for the robots by obtaining assistance from elsewhere within the company for system design and introduction. In F the help came from outside the company in the form of the commissioning companies.

Different influences for the relaxing of the availability of scarce resources can be seen. In Factory B, the overall company policy on providing resources meant that these were available for the robot system. In Factory D, works management had been committed to the system development and provided sufficient resources as well as supporting the improved safety committee structure. In Factory H, the policy towards safety and the favourable financial circumstances meant that resources were available for any necessary new development.

TECHNICAL CONTROLS

A study of safety strategies needs to consider the means of ensuring that strategies are taken beyond the initial development. Management have two forms of control measures, technical and motivational, at their disposal. This section considers the technical controls in terms of the stages of identification of the need for controls, their development, implementation, adaptation and maintenance. In the subsequent section the motivational controls are discussed in terms of the overall objectives, the definition of responsibility and authority of key personnel and the mechanisms for accountability and performance measurement. The first two stages of technical control have been dealt with to some extent under the identification of hazards and the development of the various strategies. An overview of these stages is presented here, before more detail is given on the implementation of controls and the adaptation and maintenance of strategies. Figure 6.6 gives a summary of the identification and development stages, and Figures 6.7 - 6.9 summarise the subsequent stages.

The Identification of the Need for Controls

Safety personnel took part at this stage in a number of factories, as did those responsible for developing the systems. Commissioning companies also played a role in three factories - A, B and F. Information was gained from a number of sources including previous experience, technical literature and other users' experience. Independent analysis was performed in some factories, D and H being notable in this as they had not previous robotic experience. It was clear that the process of identification was aided by safety personnel involvement.

Little was done in two cases C and F. Matters were left mainly to the commissioning company in F and not pursued actively in C.

The Development of Control Measures

The main choice of strategic options were those of hazard containment. A heavy reliance on physical safeguards was found in all cases.

Physical safeguards were developed by factory management in each case with production engineering specialists having primary responsibility in some factories. In the main, training followed naturally from the acquisition of the robots and decisions of numbers to be sent for training were taken by production management. Systems of work were mainly the joint responsibility of production management and safety officers. Safety committees were rarely involved at this stage. The exception to this was in B, where safety committees became involved in the approval of the system of work for the maintenance workers.

FACTORIES					
A	B	C	D	F	H
Identification Response to external pressure or legal requirement. Development System developed to operate safely. No involvement of safety committees.	Identification Advisory role of Safety Dept. at H.Q. Well developed understanding of need for controls with robots. Development Standardisation with other factories. Well developed and documented measures for safeguarding systems. Safety Dept. assessment of systems as they were developed.	Identification No clear process. Development Production Management responsibility. To some extent, decided few measures were required beyond a few minor safeguards and some training. Process of development hard to recognise.	Identification Recognition of special needs of injection moulders. Development Production Management responsibility.	Identification Performed mainly by commissioning companies. Development Physical safeguards developed by commissioning companies. Training poorly developed. Formal working practice developed within safety committee.	Identification Advisory role for Safety Services. Responsibility for Works Services. Development A standard approach to safety was developed. Specifications of safeguards well developed and documented.

Figure 6.6 Summary of Technical Controls - Identification and Development

The development of strategies was well specified in two cases, B and H. In both an attempt was made to standardise on equipment in all their systems. Both had good documentation of the planned installations and the operation of the physical safeguards. Factories C and F were the worst in developing control measures, which followed their failure to identify fully the need for controls. Controls were either few or developed mainly by the commissioning companies. The process of development of strategies in F was hard to identify apart from the development of the system of work.

The Implementation of Control Measures

The numerous safety strategy options outlined above need also to be implemented before they are effective. The people responsible for implementation and the timing of implementation are as important as the level of implementation achieved. In this section each factory's attempt is discussed separately and is summarised in the upper half of Figure 6.7.

In Factory A the responsibility for implementation rested with Production Management and to some extent initially with the commissioning company. Subsequently, the factory's own Safety Engineer took over some responsibility. The system design was completed at an early stage, with only minor alteration later, for example the closing of gaps in the fencing and restricting access to the stairways and unload areas. However, the implementation of the control measures was not complete. Some measures were not used consistently, such as the interlocked doors. The working practices did not concur with the formal system of work. The implementation of this particular control was left to the maintenance workers themselves and their foreman.

Factory management had primary responsibility for the implementation of control measures in Factory B, but had assistance from the Safety Department and from Manufacturing and Plant Engineering Department. Safety Engineers inspected the construction of equipment and the completed systems and also monitored their introduction. All the control

FACTORIES					
A	B	C	D	F	H
IMPLEMENTATION	IMPLEMENTATION	IMPLEMENTATION	IMPLEMENTATION	IMPLEMENTATION	IMPLEMENTATION
Incomplete implementation especially working practices. Implementation occurred almost exclusively at beginning of system life.	Fully implemented except system of work, whose implementation was left to the maintenance team. Implementation carried out at outset.	Controls implemented insofar as they were developed. No great concern over problems of implementing spirit of strategies.	No problems with implementation of control measures.	Systems implemented by commissioning companies. Formal working practices not implemented. Training incomplete. Safety visor wearing not enforced.	Slow implementation. System operative with safeguards incomplete. Not fully implemented in period of study.
MONITORING	MONITORING	MONITORING	MONITORING	MONITORING	MONITORING
Little monitoring of working practices. Permit to Work not monitored. Performance of system recorded by foremen. Product quality monitored. Surgery record of accidents.	Safety engineers performed general monitoring function. Downtime on systems are recorded, which acts as a way of monitoring performance. Personnel records of accidents kept.	No monitoring of robot operators or foremen working practices. Monitoring of equipment for generation of utilisation statistics.	Safety Inspectors. Investigation of accidents. Record of maintenance work kept by production department.	Extensive monitoring of product quality. Surgery record of accidents.	Robot Instructor carred out informal monitoring. Safety Officer 'kept an eye' on systems.

Figure 6.7 Summary of Technical Controls - Implementation and Monitoring

measures were implemented at the outset of system introduction, and were fully implemented with the exception of the system of work. As in A, the implementation of this was left to the maintenance workers. Even though Manufacturing and Engineering Plant department (M & PE) devised and then presented the flowchart to the maintenance workers, its implementation was not followed up by M & PE. The maintenance foreman could be expected to exercise some control over this behaviour, but his presence was neither regular nor frequent. However any variations from the system of work were not major.

In Factory C, the Production Manager had overall responsibility and was heavily involved in system implementation. Control measures in this case were few and were not particularly effective even though most were well developed and implemented. The one system with fencing did not have a fully implemented secure fencing and it was unclear whether the original intention had been to provide a secure fence. There was also no great concern shown over problems in implementing the spirit of the measures such as the use of dark glasses and safety curtains to overcome arc-eye problems.

No problems of implementation were found in Factory D. Once measures were decided upon, they were incorporated and fully implemented. Most of the control measures were implemented at an early stage with some additions later. Responsibility for the implementation rested firmly with works management.

Factory F had a variety of personnel responsible for the implementation of its control measures. The commissioning companies were responsible for the physical safeguards as part of the system design. Training was partly the responsibility of factory management with production engineers also playing an important role. The formal working practices were developed by the safety committee but was factory management's responsibility to implement. Of the strategy options, only the physical safeguards were implemented near to completeness. Training, which was carried out at the beginning of the system use, was not done fully or effectively. Some people were trained on the wrong robots. The workers involved with problem solving were not all given the appropriate training. The formal work practices were not found to have been implemented to any observable extent.

In Factory H, Work Services were responsible for control measure development and implementation, with support from Safety Services. For example, the interlocks on the access and emergency doors were to be tested by Works Services, while Safety Services would give the system the 'once-over' when implemented and in productive use. However the implementation of control measures was a slow process, whereas the development took place in good time before system introduction. As a result, productive work took place with incomplete control measures. Some control measures were still not fully implemented by the end of the period of study.

Overall, it was found that the level of implementation of control measures did not follow the level of their development. In Factory H, the development was well specified but the implementation somewhat lacking. However, Factory B was by far the most successful at both development and implementation of control measures. Factory D also did well at both of these stages. An important feature in D was the special nature of a system to be safeguarded according to a specific code of practice.

The Maintenance and Adaptation of Control Measures and Problems and Unanticipated Consequences

To consider how control measures were maintained and how adaptation occurred, the problems and unanticipated consequences of the control measures in operation on each system are also worthy of consideration. Each system differs from the others in such a diverse manner that the problems and unanticipated consequences need to be considered separately.

A discussion of the means of monitoring problems and unanticipated consequences precedes a discussion of these problems and consequences. This section concludes with the adaptations that were made to control measures when faced with the changed circumstances.

Monitoring of strategies

The main purpose for monitoring of each system was to check on the production and in some cases to generate performance data. Records of incidents of downtime were kept in each case but the level of data varied. The lower half of Figure 6.7 summarises the monitoring in each factory. At its best, the records contained the length of downtime, the causes of downtime and the actions carried out along with an indication of the severity of the incident. However, a very brief description was given in most cases. Product quality inspections also took place in a number of cases with destructive tests being used in Factories A and F. Production data was generated for parts completed only for those periods when production took place. In depth analysis of the results took place in only A and B, but this was only on machine and system performance, with little of direct relevance to safety. At best, analysis on the other factories took the form of the generation of some basic equipment utilisation statistics.

Monitoring of issues relevant to safety took place to some extent. Three areas can be identified: safety inspections, the inspection of workers actions (particularly by first line supervision) and the generation of accident data. Safety inspection took place to some extent in a number of factories. Formal inspections were carried out by safety personnel in two (B and D), but there was every indication that the robot systems were not a prime concern of these inspections with both safety departments considering the robot systems to be relatively safe in relation to the other parts of the factories.

Production and factory management in some factories monitored in a more informal manner. In H, safety engineers kept a watching brief on the system to identify any problems as they occurred and the Robot Instructor also checked on personnel actions. In A, the Safety Engineer stated that he inspected at intervals but was seen to do so only when accompanied by the Factory Inspectorate.

First line supervision were potentially in a position to monitor and thereby control the action of workers on the systems in all cases. However, it has already been shown how supervision was deeply involved in problem solving actions on some systems, and were thus not in a good position to monitor. They tended to have the same working practices as those they were meant to be monitoring. This occurred in A, C and F. In the other factories the ability of first line supervision to monitor was hampered by the lack of time spent near the systems. Thus safety monitoring of the robot systems was not extensive in any factory.

Accident data was collected in each case, mainly to obtain records of personnel injuries. In Factory D and H it was stated that one of the duties of the Safety Department was to investigate the causes of accidents to see whether preventative action should be taken. In other cases the actions were more defensive in ensuring the distinction between the person's and the company's liability and in preparing a defence in the event of prosecutions. For example, in Factory B, the records of accidents were filed alongside the people affected and not according to the factory areas or the equipment involved. In Factory F the records were kept in the surgery and not used for any other purpose if no further action was taken by the injured person or prosecuting authorities.

In all the factories, it was noted that the safety committees played a minor role in monitoring. A number of issues were raised concerning the various systems, but on the whole these dealt with rather mundane matters such as housekeeping practices, ventilation and parts handling problems. Where more technologically advanced issues arose, the representatives were clearly aware of the inadequacies of their knowledge. As the next section shows, a large number of problems arose in each factory which were not dealt with by the implemented safety strategies and so the lack of major issues raised at safety meetings is not the result of few such issues.

Problems and unanticipated consequences

Each system showed a number of problem areas and unanticipated consequences of the use of control measures. These varied from the systematic circumvention of safeguards and contraventions of formal practices to the introduction of production problems by the incorporation of safeguards. The problems and unanticipated consequences are summarised in Figure 6.8.

In Factory A, the initial system design proved impracticable since a number of necessary adjustment tasks were made much more difficult. As a result, practices arose which circumvented the safeguards by means such as the use of 'fiddle keys' on the interlocked doors (keys which would open the door but did not come from the master panel of keys) and the disregard for prescribed practices. Workers developed the habit of remaining within the system for lengthy periods which were not absolutely necessary.

These bad practices were allowed to develop because of the lack of monitoring of the way people worked on the system and the lack of control exercised by the foreman who worked alongside the maintenance team. At certain times when the foreman was absent, supervision effectively became non-existent.

The introduction of the Permit to Work system (PTW) was meant to bring formal and actual working practices back into agreement but failed to do so because of the lack of monitoring and maintenance of the practices set out in the Permit to Work. Workers continued to use the means of circumvention at their disposal and spent a great deal of time within the fencing. The formal practices in the Permit to Work meant little hazard control for maintenance workers within the system, since the system could work automatically at such times. This was allowed since maintenance workers were considered responsible persons and there was meant to be a second person observing from outside the fencing near an emergency stop. However, since the practices laid down were not adhered to, even greater hazards arose. For example, the observation by a second person whilst covering the emergency stop was not followed and often was not physically possible because of the siting of the emergency stop buttons. Furthermore, the protective clothing and equipment provided with the PTW was not used consistently. The result of the introduction of the PTW system was to legitimise unsafe behaviour by the maintenance workers because its implementation allowed them to continue to work as before.

FACTORIES					
A	B	C	D	F	H
Systematic circumvention of safeguards and poor working practices. Ineffective Permit to Work System. Sequencing problems. Inexperienced loaders and the need for maintenance workers to supervise loading.	Incomplete monitoring of working practices by maintenance foremen. Manually operated safeguards not used as frequently as necessary. Experience and knowledge of serious problems limited. Robot collisions a relatively frequent occurrence.	Major problems with the robots. Poor maintenance. Little control exercised on robot operators and foremen. The use of young and inexperienced short-term workers as robot operators. Poor working practices.	Poor control over robot programming and working practices of maintenance workers. Some damage to equipment following sequence problems. Failures of physical safeguards a major cause of downtime.	Ineffective system of work. Poor enforcement of personal protective equipment (e.g. visors). Chargehands were main supervision and also main contravenor of safe practices. A number of serious sequence faults and accidents.	Systems used with safeguards not in place. Correct procedure for loading parts not followed. Severe hazard from 'abort button'. Black and yellow hatched area understated the reach of the robot arm and tool. Robot operators worked automatically for most of the time. Interactions between operators and robots nearly continuous at certain times.

Figure 6.8 Summary of Problems and Unanticipated Consequences

The interlocking between the robots, their rest stands and the controller was shown to be a cause of unsafe conditions on one occasion. The failure of a robot to leave its stand showed that the interlock only sensed the switch on the rest stand in its down position and did not show if the robot had moved to its working position. The resultant damage was costly as well as potentially dangerous. A number of other hazardous problems with the software were identified, particularly with the sequencing of the various pieces of equipment.

At the beginning of the study, the allocation of loaders to the system occurred on a daily basis. Different groups were present on consecutive days. This failure to build up a skill base in the loaders at the initial stage was responsible for a number of problems with the system, causing the maintenance workers to deal with more problems. Maintenance took on the supervision of the loaders as a result of this.

By comparison, Factory B had few problems with safety implications. Naturally problems with the systems arose at frequent intervals, but the safeguards were able to deal with them, being designed for ease of use and effectiveness of action. However, a number of areas did arise which pointed to deficiencies in the control measures. Maintenance foremen were not found to monitor maintenance worker performance to any great extent and the use of the system of work was much more a personal decision by each worker. There was evidence of some variation from best practices, with manually operated physical safeguards not being used as often as necessary. The use of danger tags and lock-off hasps whilst working on the systems was also omitted. Observation suggested that knowledge of the usual problems may have been high, but on more unusual (and also serious) problems,it was much lower. Incorrect actions were possible which could have led to hazards in some cases.

Safeguards built into the software of the main controller were not as good as initially intended. For example, the control exercised by the main controller on the robots to prevent collisions was not completely effective, since collisions between robots occurred on a number of occasions. No clear explanation of this phenomenon was offered by factory personnel.

In Factory C, major problems with the robots resulted from their movement to a new part of the factory immediately prior to the study. The causes of these problems were less clear but were quite possibly linked to poor maintenance over a lengthy period prior to the move. A large number of incidents of collisons between the robot and other equipment were noted with some serious damage occurring on occasions. Several other events arose with serious safety implications, for example the tendency of one robot to shoot off its programmed path at high speed.

Little control was seen to be exercised on the behaviour of robot operators and foremen. They were allowed to perform their tasks as they wished with only the constraint of the maintenance of production schedules as a modifier of practices.

The use of short term workers for the robot operators' tasks during a large part of the study raised serious safety questions. These short term workers were generally very young and inexperienced. They were given the task of loading robot welding stations because of the low skill content of this work. They were given rudimentary training as operators for this task. They were thus exposed to the normal hazards of welding operations as well as to the robots' own hazards, with only the basic safeguards available in these systems and with little training. The problems of short-term workers were exacerbated by a number of other problems identified in this factory. The safety curtains on six of the systems were less than totally effective, partly because of their position but mostly because of their poor condition. The problem worsened on one system following a redesign of the jig for a new component. The safety curtain then blocked out only part of the task when pulled fully across.

The working practices of operators and foremen in general suggested a number of problem areas. Both groups worked at times near or on robots which were operational. On one occasion a robot was operating when a foreman was attempting to adjust the wire feed speed from beneath the robot arm in a crouching position. A number of other occasions arose where operators or foremen were seen working very close to operating robots.

The one system which had safety fencing in Factory C was not fenced securely. A person could enter the system with ease.

These various problems with the systems and the safety strategy adopted gave a general air of complacency towards the hazards. This permeated from senior management right down to the shop-floor, as evidenced by the working practices of all involved in the systems' operations. It is therefore not too surprising that the susceptibility to accidents or injury for those working regularly with the robots should be higher than in the rest of the factory. Accident figures for this factory seem to support this view even though the accident rate is not very high (see Chapter 5).

In Factory D, few problems arose with the maintenance of the strategies in the period of study. No real control of the work of maintenance teams was found, but this may be a reflection on the level of control of the hazards by the physical safeguards. However concern was expressed over the large number of personnel who programmed the robots. The different ways in which programme alterations were made were not recorded. Thus all those concerned were not informed of the state of each robot programme. It was also considered probable that other workers made simple adjustments to the robot paths than those trained and allocated to these tasks. The manual workers in an adjacent area were suspected of being involved on some occasions. However the most serious outcome of the possible variations to proper practices had been damage to the robot gripper. An unanticipated consequence of designing a strategy with such a heavy reliance on physical safeguards was that the majority of problems with the systems were related to the inoperability of safety features.

In Factory F a large number of problems arose. The system of work was meant to control hazards for periods of contact with operational systems. Observation showed that such contact was frequent with people working in the vicinity of moving robots on a number of occasions. The formal practices were not enforced nor adhered to. Although access to live systems was considered inevitable, no attempt was made to maintain the best set of practices for such times. What is more, the safeguards were totally ineffective once a person was within the systems and possibly even counterproductive. An example of their counterproductive nature was found with the cloudy plastic screens on System II. It was difficult to see a worker within the system from outside. If the practice of having a second person observing whilst someone was within a system was not adhered to, it was possible to start the system and expose a person within the system to severe danger. The low frequency of wearing protective visors was another problem of a lack of enforcement.

The source of enforcement of all working practices on the shop-floor in Factory F were the chargehands. These were also the main workers on the robot systems, being heavily involved in dealing with problems of the systems' operation. Thus they were also the ones likely to perpetrate the infringements of the systems of work most frequently. The time constraints under which they operated could only exacerbate these matters. These constraints on time also encouraged the chargehands to enter the systems to observe the process whilst it was still operating. A number of interlocks on System I had been by-passed (because the connecting cables had become worn) in order to keep production going. This had interfered with the normal sequencing and resulted in a number of machine collisions and faults with clear safety implications. It is perhaps not surprising that accidents had occurred in this factory.

In Factory H, the implementation of the strategy took place at such a slow rate that robot systems were used with no physical safeguards for a while and for even longer without the interlocks on the access doors. On System II the key interlocks were in place at one stage but had been circumvented to allow unimpeded access. It was also possible to circumvent the internal fencing on System I without using the interlocked door. It also became normal for the table on System II to be loaded from within the fencing because of difficulties in removing the table for loading outside.

The presence of a special button for unsafe conditions - the "abort button" - turned out to be a severe hazard in itself. It caused high speed motion to occur in a direction away from the table and the part, but through an area where an operator might be standing. A further problem with the physical safeguards concerned the area marked out by Black and Yellow stripes. These were quite distinctive and purported to show the extent of the robot's reach. However these understated the reach of the tools attached to the robot arm.

The robot operators in Factory H were found to act autonomously with no formal check on their working practices. For example, eye protection was not worn at any time when the systems were observed. The operators also changed tools on the robot and did other similar tasks with the robot hydraulics still powered on, in direct contravention of formal practices. It was also found that interactions between worker and the robots were nearly continuous at some times, with reprogramming and part testing requiring frequent close contact between machine and operator.

It appeared that it had been decided that the safety strategy in Factory H would be implemented when the system went from development work to production. However there was a 'grey boundary' between these two phases as both took place concurrently during the period of study. A lowering of the level of safety resulted from this lack of decisiveness on the need to implement safety measures.

Overall one can see that the major problem areas concerned the failure to maintain safe working practices, which arose because of the unanticipated consequences from the system design and from certain physical safeguards. In certain factories (particularly Factory C) it was unclear that the safeguards were meant to be effective against all the possible hazards of the robot systems. As a further example, the robots in each factory except Factory B would collapse slowly if power was removed or an emergency stop button was pressed. This possibly presents hazards, such as the trapping of a person beneath the heavy robot arm.

Systematic circumventions of the safety strategies have been shown in three cases, A, F and H. However the actual practices this led to were unlikely to be as hazardous as those found in Factory C. Factories B and D had the least problems and showed the greatest success in development, implementation and maintenance of the strategies.

Fewer problems occurred where strategies with all three focusses (hardware, people and their interactions) were well developed and implemented. One can see a correlation here between problems with one strategic option and the successful implementation of another. For example, the poor development and implementation of a system of work in Factory A exacerbated the problems with the system design. Similarly, in F, poor training and working practices made the problems with system design more severe. Thus one can see that the three focusses of a strategy enhance the effectiveness of each other when fully developed and implemented.

Adaptations to strategies

The problems outlined in the previous section were dealt with to some extent by adaptations and alterations to the control measures. However, it should not be thought that all problems were removed. The adaptations are summarised in Figure 6.9.

A decision on the acceptability of the hazards posed by the problems needed to be taken by the management in each case and the decision could have been to accept the hazard level and not provide further control measures. An example of a decision to accept a hazard occurred over the identified problem of slow collapse of the robot arm during power failure or power removal. It was clear that this risk was considered acceptable and not in need of further adaptation, such as the addition of brakes on the robot arms.

In Factory A, the first adaptations to the system occurred as a result of safety committee and the Factory Inspectorate pressure. The safety committee requested that gaps in the fencing of the system be closed off. The Factory Inspectorate pointed out a number of areas, such as access to the observation gantry and unload area and commented upon the possibility of access within the system when part of it was operating. As a result the stairway and unload areas were closed off more securely and a notice issued by the Safety Engineer forbidding access within the system when it was operating. Later, safety committee requests for hoists in the loading area to assist with the movement of the heavier parts resulted in their addition.

The Permit to work system in Factory A was itself an adaptation, since the previous notice from the Safety Engineer had proved ineffective. However implementation of the PTW raised its own set of problems (see above).

In Factory C, no major adaptations occurred, although some minor ones did take place. The safety committee made repeated requests for changes which eventually produced some improvement in the poor state of safety curtains and the cable positions in some robot systems. No specific adaptation was attempted to take account of the hazards presented to the short-term workers.

In Factory D, adaptations to the physical safeguards were mainly additions to protect machinery. The safeguards already in place were considered sufficient for containing the hazards to personnel. The

FACTORIES					
A	B	C	D	F	H
Minor alterations to system design as a result of pressure from HMFI and safety committee. Instructions from Safety Engineer forbidding access whilst system operational. Permit to Work System.	No major adaptations.	Minor adaptations:- rerouting cables and replacing safety curtains.	Additional safeguards to protect machinery. Alteration to training to provide on-site experience.	Formal working system (ineffective).	'Abort button' removed. On-site training introduced and role of Robot Instructor created.

Figure 6.9 Summary of Technical Controls - Adaptation

The training provisions were altered by works management, with the purpose of improving the understanding of system operation and the equipment interactions.

In Factory F, the formal working practices were an attempted adaptation following an accident. This accident had served to illustrate the dangers of working within the systems with the possibility of starting them from outside. The general failure to implement the formal working practices was not followed up by any adaptation or other control measures such as disciplinary action.

In Factory H, little adaptation was made to the original strategy laid out in the Safety Booklet. However, the "abort button" on System I was removed as soon as its hazards were realised. On-site training was also introduced with a robot instructor to supplement the training of the robot supplier.

MOTIVATIONAL CONTROLS

The means of developing motivation for safety can be divided into 3 categories:- the general objectives, culture and atmosphere of the organisation (the 'overall climate'); the definition of responsibilities for safety and authority of personnel; the mechanisms of accountability and performance measurement. Each of these categories acts throughout the organisation and can be seen as a sort of "back-drop" for the safety strategies developed and implemented in each case. This section considers each category separately and discusses the relevant findings in each factory. Figure 6.10 summarises the measures in each factory.

FACTORIES					
A	B	C	D	F	H
1) General Climate Infrequent visits by Safety Engineer. Little encouragement for safer behaviour. Few safety signs. Poor overall conditions.	1) General Climate Headquarters Safety Department. Clean conditions well managed roadways.	1) General Climate Factory and Production Manager visit shop floor frequently. Factory generally dirty, cluttered noisy and high levels of fumes.	1) General Climate Safety Policy explicit of management's commitment to safety. Generally good environment.	1) General Climate Low priority given to safety. Safety Policy Document out of date. Factory conditions poor.	1) General Climate Factories safety conscious. Safety booklets. Excellent working conditions.
2) Definition of Responsibilities and Authority Unclear Policy Document. No clear definition of safety responsibility.	2) Definition of Responsibilities and Authority Responsibilities specified in broad terms.	2) Definition of Responsibilities and Authority Responsibilities given in some detail. Confusing with duplication.	2) Definition of Responsibilities and Authority Responsibility and authority clearly specified.	2) Definition of Responsibilities and Authority No clear definition of safety role for personnel.	2) Definition of Responsibilities and Authority Specific guidance given in safety booklets.
3) Mechanisms of Accountability and Performance Measurement Foremen and maintenance responsible primarily for system performance. Poorly developed safety accountability.	3) Mechanisms of Accountability and Performance Measurement Safety accountability for robot system not formally specified. Disciplinary action for contravention of protective clothing rules.	3) Mechanisms of Accountability and Performance Measurement No clear means of measuring safety performance.	3) Mechanisms of Accountability and Performance Measurement No means of measuring safety performance.	3) Mechanisms of Accountability and Performance Measurement Disciplinary action for contravention of certain decisions of safety committees.	3) Mechanisms of Accountability and Performance Measurement No means of measuring safety performance.

Figure 6.10 Summary of Motivational Controls

The Overall Climate

In Factory A, little encouragement was felt by maintenance workers for safe behaviour on the robot systems. Their superiors seemed to be concerned mainly with the production difficulties. The Safety Engineer compounded this by visiting the robot system area infrequently. Production and engineering staff did not make significant attempts to create a safety conscious atmosphere. What is more, conditions in the factory were generally poor, with dirty and oily floors and few safety signs or posters. Conditions around the robot system area were slightly better than in the rest of the factory.

Factory B had a clearer way of generating a safety conscious environment. The promotion of health and safety was stated in the company Safety Policy Document as an essential function of good management. To assist in this activity, there was a Safety Department at Headquarters as well as at each factory. General conditions in the factory and around the robot system concurred with this view of a safety conscious company, with clean conditions and well marked roadways and passages. Safety signs were prominent in a number of parts of the factory.

In Factory C the Safety Policy Document stated that health and safety was the mutual objective of management and employees. Factory C was the only factory in this small company to have a Safety Officer and frequent visits to the shop-floor were undertaken by the Production and Factory Managers. However a high level of complacency towards safety from management was found and the factory was generally very dirty and cramped, with a high level of noise and fumes in the air. The conditions around the robot systems matched the rest of the factory.

In contrast to the above, Factory D's Safety Policy Document stated that it was management's duty to do everything possible to prevent personal injuries, with a duty on everyone in the company to prevent injury to themselves. Safety was given equal importance to production sales and costs. The general conditions in the factory were reasonable with a high level of oil and dirt on the floor as the only sign of a low priority for a clean and safe environment.

In Factory F a low priority was placed on safety, with no Safety Officer on-site. The Personnel Manager of the company took some of the duties of a Safety Officer but he was not permanently present. The

Safety Policy Document was also no longer relevant to the company's technology and operating practices. The workforce safety representatives considered that safety had been given a low priority at the outset, with work commencing at the factory without such basic requirements as proper ventilation. The Factory Director was seen to tour the factory frequently, although the purpose of these tours were not necessarily a concern for safety. The general conditions of the factory were poor, with a high level of metallic dust and oil.

In Factory H, a number of matters suggested a high level of safety consciousness in the factory. There were Group Safety Meetings for the whole company, to discuss issues of common interest, for example new technology. The company's Annual Report also showed a concern for safety. Resources were available for safety measures throughout the factory but particularly on the robot systems. The development of special Safety Booklets on particular issues also supports the view of a factory which takes safety seriously and gives it a high priority. The factory environment reflected this, being clean and airy with well marked floor areas and good housekeeping.

Thus the overall climate for safety was poor in half the factories studied. These were also the factories with the most problems in the safety strategies (A, C and F).

The Responsibilities and Authority for Safety

The major source of statements on responsibilities and authority for safety in each factory is the Safety Policy Document. It has been shown above that in each factory, overall responsibility for safety was given to factory management, with such functions as safety and personnel having an advisory role. However, in most of the factories unclear statements of responsibilities were given.

In Factories A and F the means by which the responsibilities for safety were to be achieved were not given because the responsibilities

responsibilities of different workers were not specified clearly. In Factory B the safety responsibilites of personnel and the means to achieve these were expressed in broad terms.

In Factory C, the policy document gave detailed responsibilities but was unclear on the means of achieving these. To some extent the statement of responsibilities in C is confusing since the same responsibilities were given to a number of people. In Factory D the responsibilities and the means of achieving them were set out in some detail, along with the authority given to people and the procedures for safety grievances and inspections. In Factory H, the policy document acted as a general statement of responsibilities. The more specific guidance given in safety booklets was not directed at responsibilities or the means of achieving these, but rather at the specific requirements of the subject of the particular safety booklet.

Thus safety responsibilities and the means to achieve them were given clearly in only two factories (B and D). Factory H's statements on responsibility and authority for safety were deficient because specific guidance did not expand on these subjects. The other factories did not provide a coherent set of responsibilities for safety.

The Mechanisms of Accountability and Performance Measurement

Accountability for production was usually well specified, as was the performance measurement on production parameters. However, accountability for safety and its measurement was not formally expressed or developed in any factory.

Two factories had disciplinary proceedings which could be used for contraventions of decisions but they were not found to be put into practice. In Factory B, the contravention of safe systems and the failure to use prescribed protective clothing bore the threat of disciplinary actions. In Factory F, disciplinary action could result from contravening certain safety committee decisions. Both these disciplinary procedures were directed at production workers. Other workers involved in safety strategy development, implementation and maintenance were not covered.

Workers were therefore not accountable directly for actions which lowered the overall level of safety. Without the wider accountability and measurement of safety performance the success of safety strategies is to some extent fortuitous and not wholly under management control.

The Role of Motivational Controls in the Success of Safety Strategies

The motivational controls available in a factory influence the success of a safety strategy by affecting the conditions under which a strategy is introduced. Thus a good general climate of safety is likely to improve the way in which people work by encouraging an acceptance for the constraints imposed. An example of the failure to create a conducive safety climate occurred in Factory A, where the general lax attitude towards safety was translated into systematic contraventions of the means of containing hazards. However no direct link between motivational controls and the success of strategies can be shown, since contraventions also occurred in Factory H, which had a good generally climate.

The motivational controls in Factories B and D assisted the success of the safety strategies, in that clear responsibilities were given to personnel, who then carried through these responsibilities in developing strategies and ensuring their correct implementation. The lack of clear responsibilities for safety in the other factories led to circumstances where strategic options were not fully implemented even where they were properly developed. Thus the benefits of motivational controls for safety affect the adoption of safety strategies in a diffuse manner and good motivational controls can assist in the implementation and maintenance of safety strategies are still necessary even with good general conditions for safety.

SUMMARY AND CONCLUSIONS

This chapter has analysed the safety strategies in each factory, using the framework for analysis developed by Dawson et al and presented in Chapter 2. It has shown that the effectiveness of measures to control hazards varied considerably. Significant shortcomings have been shown for each stage of the safety strategies in at least one factory.

Shortcomings at one stage has been shown to have an effect on the performance of the subsequent stages. For example, poor hazard identification is correlated with poor development of safety strategies.

The safety strategy elements which were developed match the guidance reviewed in Chapter 3. The emphasis upon containment strategies and in particular on physical safeguards in the guidance was maintained. However some factories were also successful in developing strategies in some of the other categories.

Factories B and D were the most successful in controlling the hazards. Effective measures were adopted at each stage, first to develop the strategies, to implement them and then to maintain them. Fewer problem areas were found in these two factories than elsewhere. The availability of scarce resources and their use for safety measures on the robot systems contributed to their success. Technical specialists in these two factories were also involved on a continuous basis.

In the factories with a well developed safety strategy, failure to control the hazards effectively was the result of the failure to direct resources at strategy implementation and adaptation. This failure was illustrated most clearly in Factory H, where resources were available but implementation was not followed through with a high level of commitment.

This chapter has shown how actions at each stage of the sequence of elements are required to make a successful safety strategy. It has also shown that a combination of all three focusses has a greater potential for success. The presence of each focus can be seen to enhance the behaviour of workers towards the others. Conversely, the failure to develop or implement fully one focus causes problems in the others. For example, the strategy in D was quite effective but problems were encountered with the maintenance of safe working practices. The laxity of control over robot programming also created problems for the complex sequencing in these systems. Thus, well developed and implemented strategies with all three focusses lead to fewer problems in the maintenance of each strategic option.

Motivational controls for safety have been shown to be diffuse in their influence upon people. It has therefore been more difficult to assess the direct impact of motivational controls on the success of safety strategies than of technical controls. However, it is notable that the overall climate and the specification of responsibility and authority for safety were relatively well developed in Factories B and D.

The preliminary hazard assessment in Chapter 5 concluded that the robot systems in Factories C and F exposed workers to higher levels of hazards than in the other systems. This chapter has shown that the safety strategies in these two factories were not successful in controlling these hazards. Furthermore, hazards in Factories A and H were compounded by ineffective safety measures. Thus, significant deficiencies are recognised in the safety strategies of four factories.

The system designs in Factory B have been shown in this chapter to have had a beneficial effect upon safety. In the previous chapter, the design was shown to have contributed to the ease with which problems were solved and to the relatively high system availability. Thus, this thesis has provided evidence of the possibility of achieving safety and production objectives concurrently.

CHAPTER 7

RISK ANALYSIS AND SAFETY ASSESSMENT OF ROBOT SYSTEMS

INTRODUCTION

This chapter begins with a brief consideration of four of the main techniques available for risk analysis, including a more general critique of the use of risk analysis techniques for safety assessment. After this introduction to risk analysis, one technique (Event Tree Analysis) is selected as being the most promising for application to robot systems. The analysis using Event Tree Analysis highlights a number of problem areas with the safety strategies described in preceding chapters.

RISK ANALYSIS TECHNIQUES

Prominent amongst the available techniques are Hazard and Operability (HAZOP) studies, Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Each of these has been applied in numerous studies of industrial equipment to assess risk and by implication the problems associated with the equipment. The techniques are all well established but differ in their approach and assumptions. Hence their applicability to the assessment of robot systems differs. Below is a brief outline of the four risk analysis techniques.

1. HAZOP Studies:- This is a very thorough technique, which involves scrutiny of a large number of possible deviations from normal operating conditions. Guide words, such as 'more', 'less', or 'reverse', are applied to each of the parameters describing conditions for each component of a system. It is normal for a study team made up of a number of disciplines to be present during the study. HAZOP studies are common in process industry safety analysis but have rarely been applied to other industries, such as manufacturing or production (Cox, 1982).
2. FMEA:- This technique identifies all the possible failure conditions of a system and evaluates their effects. In this respect it is similar to the previous technique, but it differs in approach. Each component is considered separately and the effects and consequences

of each failure mode on other components and the overall system are identified. It is essentially a descriptive form of analysis, which can indicate the level of hazard associated with any single component failure. One difficulty with this technique is the lack of a formal method for finding all the failure modes or their effects. An intimate knowledge of the system and its operation is required before a satisfactory analysis is possible. This technique is also poor at identifying hazards resulting from complex failure conditions, where several components fail at once, or from the interaction of different parts of a system in the event of a failure.

3. FTA:- This is a powerful technique that can consider the events which lead to a particular failure. A failure can be traced to all the events or combination of events that could produce it. The technique has a well defined methodology and standardised symbolism. Before the analysis can begin, all failures and failure modes need to be identified, for example by FMEA. The analysis takes the form a tree consisting of the failure at the top, branching out downwards to all the events that could cause it. It is possible to consider complex failure conditions and to include human errors. However, human error in response to an initial component failure is easier to consider than the more numerous and varied human actions that can initiate component or system failures.
4. ETA:- This technique operates in the opposite direction to FTA, beginning with the initiating event and following through a series of subsequent events to a set of outcomes. With the consideration of a subsequent event, the tree branches to produce a number of paths that will lead to different outcomes. This technique is of particular use in identifying outcomes that rely on the interaction of failures and other events (such as human actions) and can even include a time sequence. The main drawbacks of ETA relates to the choice of subsequent events. The selection of these events requires full knowledge of system operation and design. The real skill is then in the choice of events worthy of consideration. Problem areas can be highlighted or obscured by this choice. Knowledge of the system is also useful in reducing the number of branches by eliminating inappropriate states.

THE USE OF RISK ANALYSIS TECHNIQUES IN SAFETY ASSESSMENT

Each of the above techniques suffers from some limitations to their use for safety assessment. These are discussed below.

(1) Emphasis on Machine Failure

Each technique is concerned primarily with failure conditions and particularly those of machinery, or hardware. However, safety research has shown that accidents often involve far more than equipment failure and may occur without any single component becoming inoperative (see Chapter 2). The operations of robot systems have been shown to require a great deal of interactions between humans and machinery. The safety problems were also shown to be linked strongly to these periods of interaction. A technique which is incapable of including the effects of such interactions will not be very useful in assessing the safety of systems, in particular robot systems.

(2) The Quantifications of Parameters

Each analysis technique provides the facility to generate overall hazard probabilities. For this, the frequency of occurrence of each constituent event is required. Some events, such as component failure, can be gathered from past experience or from a series of tests. Other events, such as human actions, will be far harder to quantify. Slovic and Fischhoff note that human error is often omitted from even the most thorough analyses (Slovic and Fischhoff, 1980). This has led to an underestimation of failures, they claim.

Problems arise even when the analysis is limited to parameters which are quantifiable. There is a degree of uncertainty, or error band, for all data on failure rates. Statistical confidence limits are required for all failure rate data. For this reason, Otway and Pahner refer to "formal" instead of objective risk estimation (Otway and Pahner, 1980). They contend that to some extent the interpretation of raw data on risks is always subjective. The use of formal risk analysis techniques merely reduces this subjectivity to a minimum.

(3) The Propagation of Risks

Rowe considers that an adequate model for the propagation of risks should consider causative events, their outcomes, exposure pathways and the consequences of exposure (Rowe, 1977). Each of these steps involves a probability figure. Thus the overall probability is a function of the probability of all four steps. It is rarely the case that risk analysis techniques follow such a model. The first two steps are the usual concerns of any risk analysis. The subsequent steps involving exposure pathways requires a great deal of information which is almost of an unquantifiable nature or is at best highly dependent on individual practices. However, any safety assessment would need to consider how risks are propagated to the potential accident and so would need to take the exposure pathways into account.

(4) Conditions for FTA and ETA

Critchley specifies a number of requirements that need satisfying by these two quantitative techniques:-

(a) Performance requirements of the system and subsystems need to be clearly and fully specified.
(b) The manufacture and construction of parts and materials to a certain standard needs to be verified.
(c) Failure rate data must be drawn from verifiable sources established by user experiences and/or tests which are realistic and reproducible.
(d) Confidence limits or uncertainty factors need to be stated for all data.
(e) An independent analyst would compute similar figures from the same data (a check for 'objectivity').
(f) Enough user experience needs to have been gained so that all credible faults and failures have occurred or sequences leading to them identified.
(Critchley, 1976).

Without these conditions being satisfied, the results would be unreliable. From the preceding discussion, it should be clear that certain events which would be involved in an analysis of industrial robot system safety could not satisfy all 6 conditions stated by Critchley.

(5) Particular Criticisms of FTA

As the most complex and powerful technique available to risk analysts, it is not surprising that FTA has received the greatest share of criticisms. One can see that some of these criticisms could also be applied to other techniques.

Slovic and Fischhoff point out that such analysis tools for communication (Slovic and Fischhoff, 1980). An important part of the analysis is the presentation of risk in the form of a tree. Fischhoff et al (1978) state that analysts have to make three 'arbitrary' decisions as a necessity to carry out their analysis:-

(a) the decision to select some risks specifically and hence some outcomes;
(b) the decision of the level of detail on each fault tree branch;
(c) the decision to group various systems into branches.

The act of formulating a fault tree introduces important communicational and presentational biases. There is little the analyst can do about this, since the powerful technique used will otherwise lead to a very large number of failure pathways.

One other major drawback of FTA is the difficulty in dealing with 'common mode failures'. Whereas the fault tree could represent two failures as independent, in reality the occurrence of one could be concurrent with the occurrence of the other. Perrow identifies this drawback but accepts that all such occurrences cannot be identified, if only because of restrictions of time and resources (Perrow, 1979). Critchley also criticises FTA for this and similar reasons, but makes a point of identifying the advantages of FTA - "it presents a way of making a thorough, consistent and wide-ranging safety appreciation of highly complex, major hazard plant" (Critchley, 1976, p. 19). He considers that it is an efficient and effective way of disclosing design weaknesses and subtle failure modes. Clearly he would prefer to have this advantage without the limitations and problems of attempting a full quantitative study.

PRELIMINARY CONCLUSIONS ON RISK ANALYSIS TECHNIQUES

This discussion has identified some of the limitations on risk analysis techniques, particularly when applied to the safety assessment of an industrial robot system. Major problems concern the interactions of elements of a system and the part played by human intervention. This is particularly so when a quantitative analysis is attempted. It follows from this discussion that a qualitative assessment would be possible, but with a technique that could handle interactions and sequences of events. If this were done, exposure pathways and their consequences could be considered as well as the occurrence of risks. The technique most suited to this would be ETA. From the brief descriptions of analysis techniques and their drawbacks, it would appear that ETA can consider a sequence of actions and suffers least from the emphasis on machine operation and failure. In the following sections, the safety strategies in each of the case studies is considered in the light of an Event Tree Analysis of a typical robot system.

EVENT TREE ANALYSIS OF ROBOT SYSTEMS

ETA has been applied elsewhere in detail to a typical robot system performing arc-welding operations (Jones, Khodabandahloo, Dawson and Husband, forthcoming publication). This analysis considers three types of safeguarding options and assesses their success in controlling hazards identified in 3 event trees. Particular attention is given in this publication to the role of physical safeguards in preventing hazardous outcomes, but implications for equipment design, working practices and training are also given.

A typical robot system consists of a robot, arc-welding equipment, a turntable onto which parts are loaded and the necessary control interlocking facilities. The basic safeguards are fencing and an electro-sensitive safety device (e.s.s.s.). The fencing goes all around the system except for the access area for loading and unloading the turntable which has the e.s.s.s. across it. The e.s.s.s. is interlocked to the equipment, such that if it detects someone when active it stops all actions in the system. There is also an access gate which can be interlocked to the action of the robot and turntable via a junction box. The controls for the turntable and the robot are outside the fencing, and access to these is not restricted. This system is shown in Figure 7.1.

Three initiating events are considered, each of which requires workers to come into close proximity with the robot system. The first, 'weld equipment failure during operation', produces the event tree shown in Figure 7.2. A person may enter the working area to perform some adjustment or cleaning action to restore the welding action to operation. Unless any safeguarding steps are taken, all equipment within the system is on a control halt awaiting a start signal from the operator. The second initiating event, 'person enters working area', produces the event tree shown in Figure 7.3. This is more general than the first event tree, since other actions such as reprogramming are possible. The robot may be required to move and thus could present greater hazards than with the recovery from weld equipment failure. The third initiating event, 'emergency stop activation', produces the event tree shown in Figure 7.4. This event tree does not consider machine failure but analyses the consequences of working practices. In some respects it can be generalised to any controlled shutdown of the process and the subsequent recovery. The equipment must be reset before normal automatic operation can be recommenced.

Each event tree produces a range of outcomes, shown by the branches at the right-hand side of each tree. These outcomes have been categorised according to the hazards present. The majority of outcomes have more than one possible hazard. A minority of outcomes are safe - outcome 1 in Figure 7.2, outcomes 1 and 4 in Figure 7.3 and outcome 3 in Figure 7.4. Other outcomes lead to states which are referred to as "lucky escapes". When a hazard is present and no means of preventing it have been implemented, the fact that the hazard is not realised is merely fortuitous. Although no actual accident occurs, there is effectively nothing preventing it on such occasions.

The analysis of system operation by the 3 event trees does not include the action of any safeguards. It is assumed that the access gate allows access without affecting the operational state of equipment. However, additional options for physical safeguards are considered and

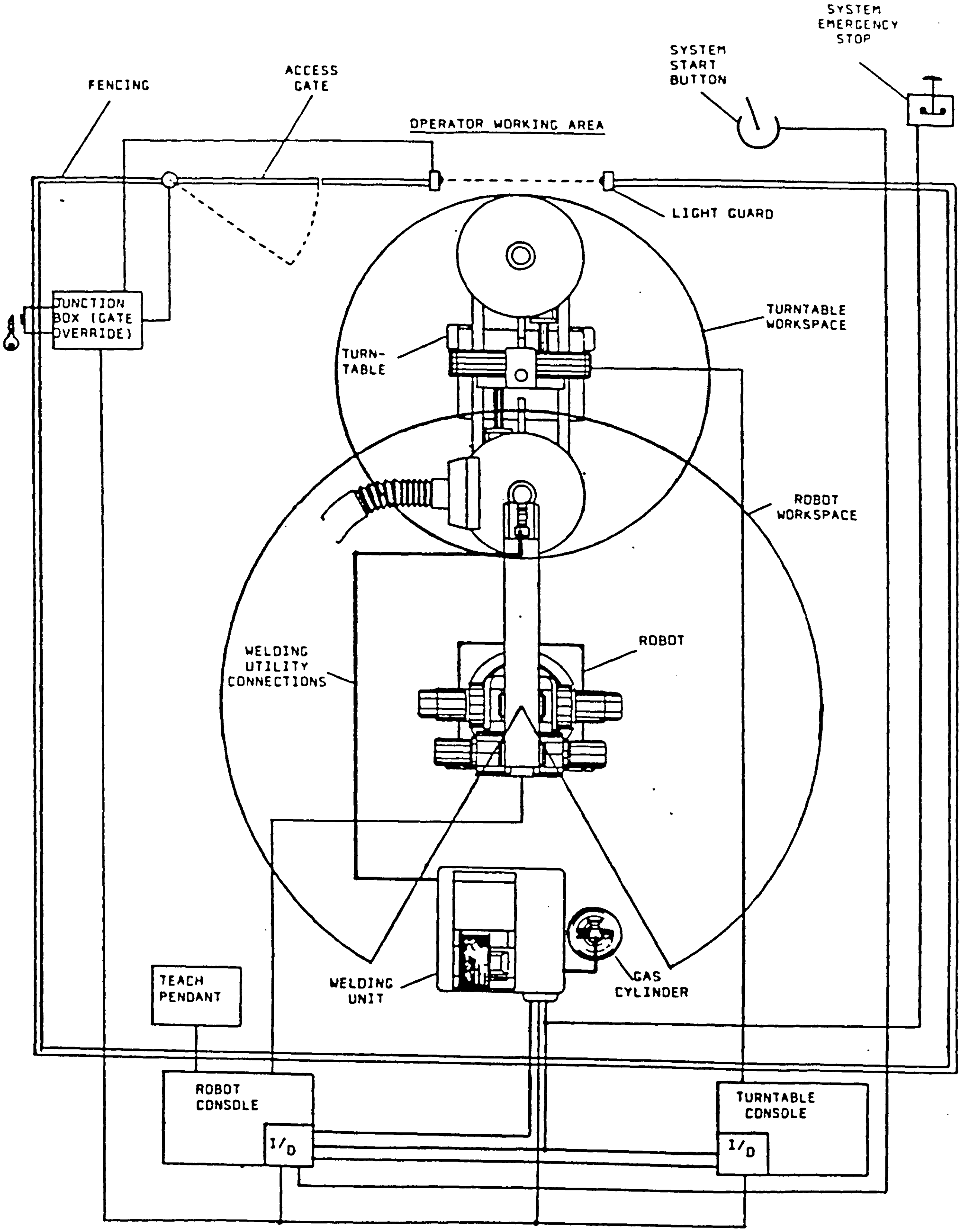
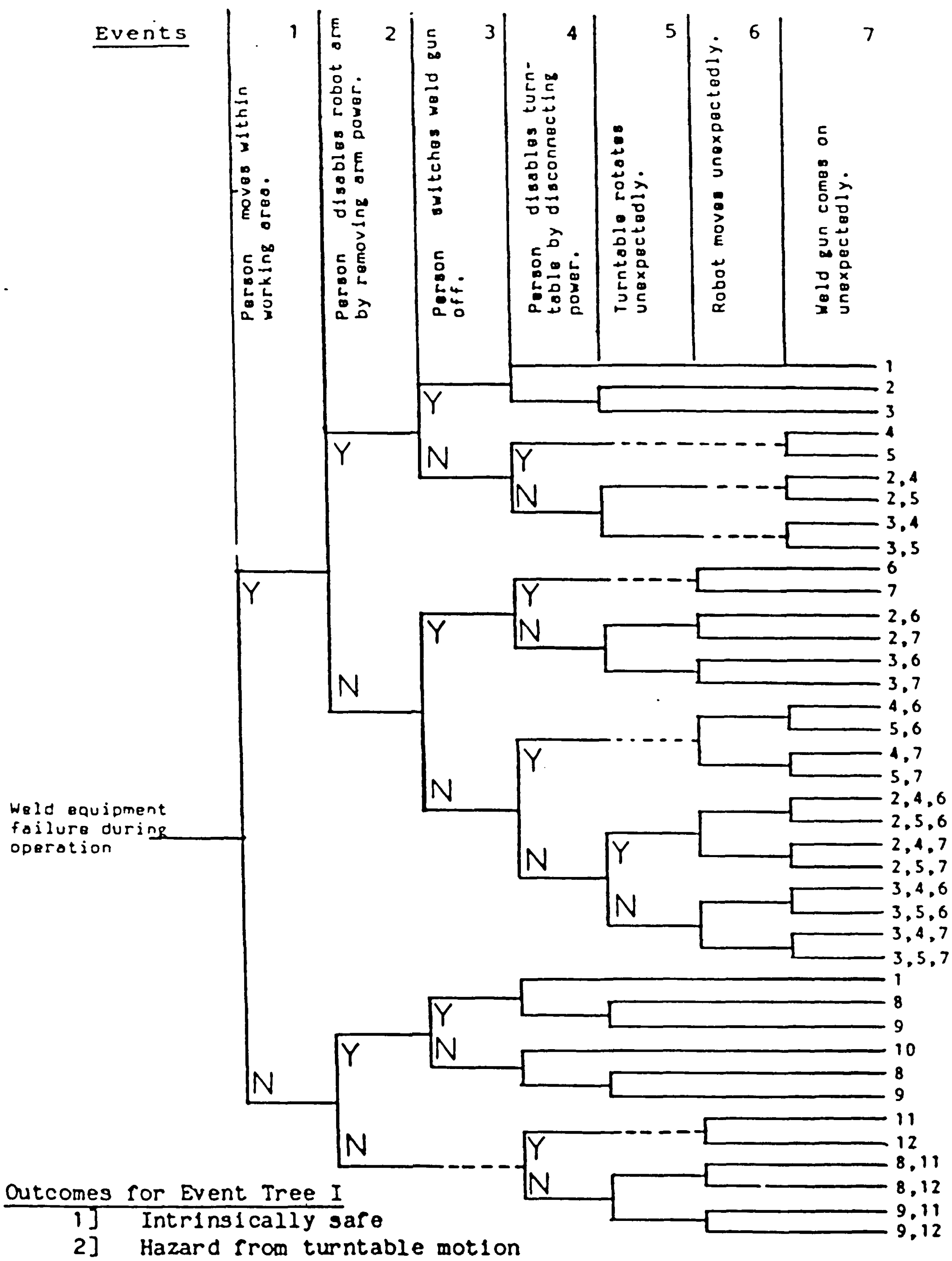


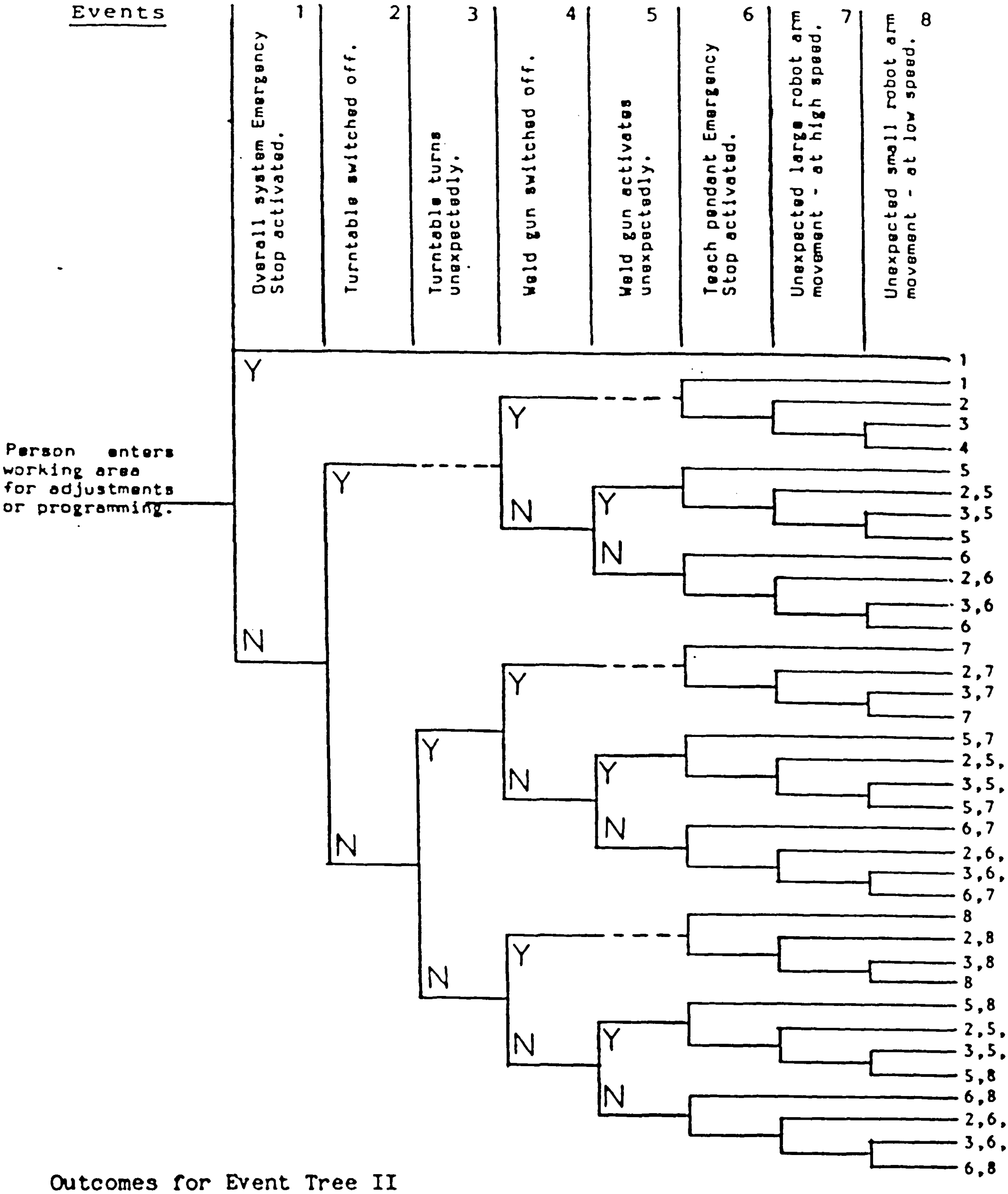
Figure 7.1 Robot Welding System Layout: Including Safeguards (from Jones et al, forthcoming publication)



Outcomes for Event Tree I

1] Intrinsically safe
2] Hazard from turntable motion
3] Hazard from turntable motion not realised - 'lucky escape'.
4] Hazard from weld gun (e.g. weld flash, high voltage).
5] Hazard from weld gun not realised - 'lucky escape'.
6] Hazard from robot motion.
7] Hazard from robot motion not realised.
8] Potential damage due to turntable motion.
9] Potential damage due to turntable motion not realised.
10] No hazard likely to occur for equipment.
11] Potential damage due to robot motion - collision.
12] Potential damage due to robot motion not realised.

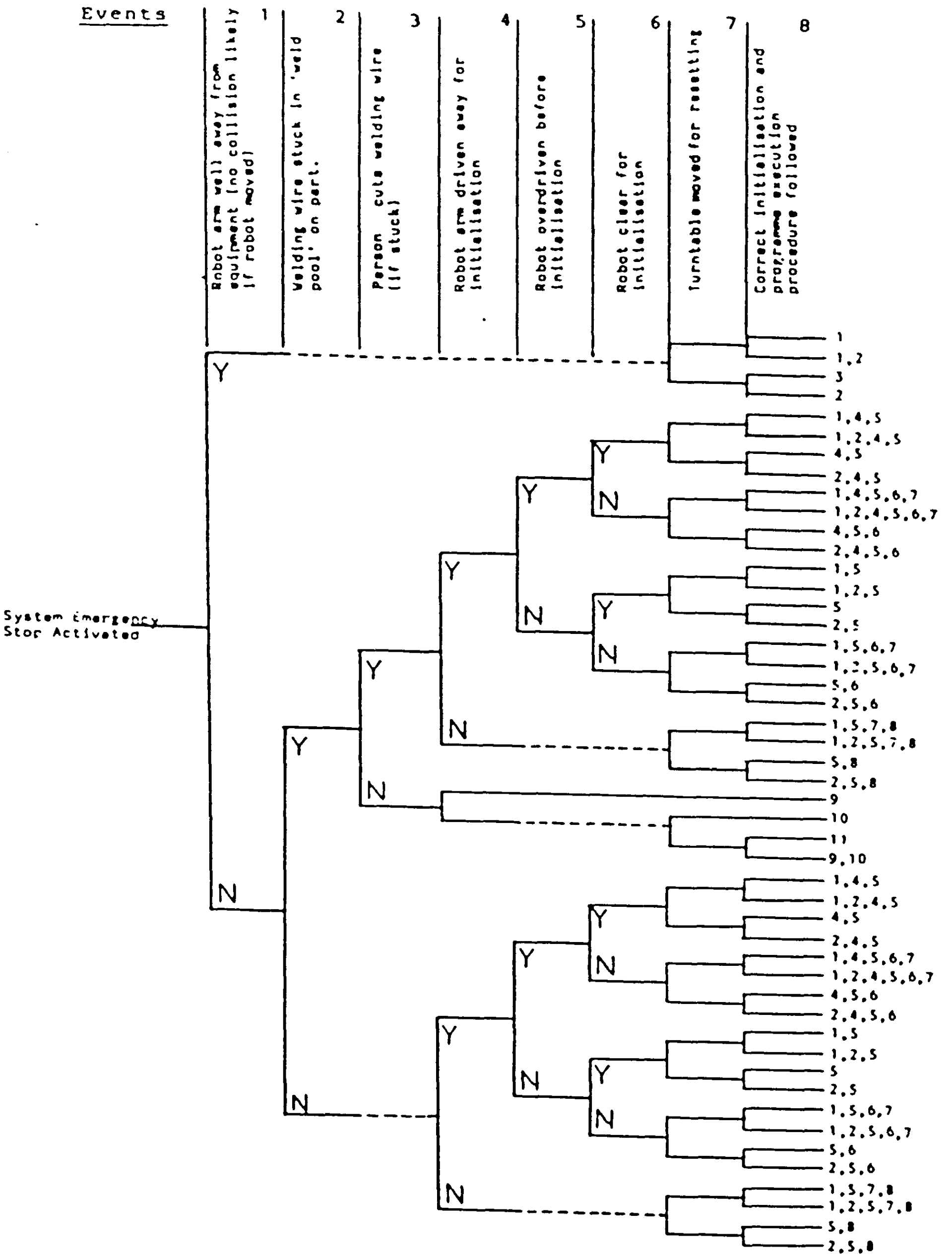
Figure 7.2 Event Tree I: Weld Equipment Failure (from Jones et al, forthcoming publication)



Outcomes for Event Tree II

1] System inactive/put into a safe mode.
2] High level of hazard due to robot collision with equipment or person.
3] Hazard due to robot causing equipment damage and possible harm to person.
4] Task performed satisfactorily.
5] Hazard from weld gun (e.g. weld flash, high voltage).
6] Potential hazard from weld gun - 'lucky escape'.
7] Hazard from turntable motion.
8] Potential hazard from turntable motion - 'lucky escape'.

Figure 7.3 Event Tree II: Person Enters Working Area (from Jones et al, forthcoming publication)



Outcomes for Event Tree III

1] Turntable presents minor hazard to person if correct procedures are not followed.
2] Severe system damage likely from incorrect robot motion (collisions) -during playback mode.
3] No hazard present -safe.
4] Damage to robot due to overdriving the robot prior to initialisation.
5] Hazard for person of unexpected robot motion.
6] Robot collision likely to occur during initialisation.
7] Turntable-robot collision likely (from turntable movement).
8] Robot-other equipment collision likely (from robot movement).
9] Severe damage to weld gun and workpiece occur. Robot may also be damaged. Operation halts at this stage and further problems not likely to occur until this is sorted out).
10] Workpiece and weld gun will be damaged. Turntable and robot arm may also be damaged. (Operation halts.)
11] Correct procedures require the weld wire to be cut: return to event 3.

Figure 7.4 Event Tree III: System Emergency Stop Activated (from Jones et al, Forthcoming Publication) the outcomes of the event trees are re-appraised in the light of the ways each safeguards affect equipment operation. Three safeguarding options for the operation of the access gate are considered:-

(a) Opening the access gate is prevented by a locking device and a key operated override mechanism. Once the key is used the access to the equipment workspaces can be gained with power to the equipment either enabled or disabled. When the override key has been used and the gate is opened to allow access, the case is identical to that of the system without extra safeguards.

(b) Similar to Option (a) the access gate is prevented from opening by a locking device. The override key disables the locking mechanism while only allowing selection of teach mode, (i.e. prevents selection of playback with the gate lock open). The locking mechanism must be such that the override key can only allow selection of playback with the gate locked shut.

(c) The access gate is again prevented from opening by a locking device. The override key in this case not only disables the lock but also produces a routine disabling of the equipment. This means that the equipment is brought to a halt and all machine operation or movement is disabled. In addition only teach mode is selectable on the robot if equipment is enabled once more.

Option (a) has little effect upon the hazards in each event tree. The robot system presents the same hazards to someone who gains access as those presented in Figure 7.2. The only restriction is to authorised personnel, thus removing all hazards from passersby and inexperienced workers. All other means of reducing the hazards, such as removing power from equipment that is not needed, is a matter of personal selection. Thus an emphasis is placed upon training and working practices.

Option (b) hazards are reduced because the override key prevents playback operations and thus reduces the possibility of large, high-speed movements from the robot. It should be noted that large, high-speed motions are still possible under failure conditions. Other hazards still remain, since the person must disable the robot before any repair work is done. In Figure 7.4, recovery from an emergency stop is only slightly affected. The final step of initialisation and restarting the programme would only be possible with the access gate locked.

Option (c) is the most complex of the three options considered. It will halt the operation and automatically disable the robot and other equipment, thus removing the hazards from their unexpected behaviour. In Figure 7.2, this leads to all outcomes except outcome 1 (intrinsically safe) being removed*. In Figure 7.3, the hazards that remain depend on whether or not good practices are adopted. If equipment is only enabled when necessary and disabled when no longer needed, the hazards are well controlled. However, in Figure 7.4, this safeguarding option has little more effect than option (b).

The final event tree, Figure 7.4, is a good illustration of the need for good working practices, even with complex physical safeguarding. For all three options, the robot may need to be moved away from other equipment using the teach pendant and the robot in teach mode. Close contact between machinery and a person is often needed in these procedures. The control sequence of the programme would also need to be checked before execution of the programme takes place. However, it should be clear that option (c) is more effective in controlling hazards. Rather than it being a matter of choice to disable equipment, a positive decision to power up any piece of equipment and increase the hazard level is required. Together with the clear findings of the importance of good working practices, Jones et al also find that training is very important. Variations in robot design makes it necessary for complete training to be undertaken for each type of robot to be used. Correct procedures for all tasks must be established and then taught. Above all, the layout of the robot system and its operation along with failure consequences should be understood by all workers.

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*It should be pointed out that the condition of intrinsic safety in outcome 1 of Figure 7.2 is crucially dependent on the safety integrity of the safeguarding system.

EVENT TREE ANALYSIS APPLIED TO SYSTEMS IN THE EMPIRICAL STUDY

The Generalisation of the Event Tree Analysis

The analysis given above is for a particular robot system, with a given set of operating conditions and controls. This analysis can be used to illustrate some of the features of the robot systems which were studied. The event trees refer to certain actions with an arc-welding robot system. Naturally these actions would be different for a different task. However, it is possible to generalise the terms used in the event trees to make them more widely applicable. Instead of referring to the action of the turntable one could use the term "associated equipment". Instead of the welding gun one could refer to a tool on the end of the robots arm. Instead of having the initiating event of "weld equipment failure during operation" in Figure 7.2, one could have "robot tool failure during operation". Instead of "welding wire stuck in 'weld pool' or part" as an event in Figure 7.4, one could have "robot tool stuck on part or associated equipment".

With these generalisations in mind, one can see that some events in each event tree can be quantified from the production data. Other events involving human actions would be hard to quantify. It should be reiterated that the purpose of considering the robot systems in the light of the Event Tree Analysis of a typical robot welding cell is to illustrate some features of the physical safeguards in each case rather than to quantify the risks posed. It is therefore an incomplete analysis, but one which highlights deficiencies in safety measures.

If the interlocking of physical safeguards in the systems is compared with those in the analysis, one can see that the basic safeguarding options are similar to most of the systems. Only Factory C has robots without some form of fencing around them. Some systems also have electro-sensitive safety devices as barriers across loading areas (Factory A and B - System B5). The interlocking of access gates take a range of options which are similar to some extent to options (a) to (c).

The Application of the Analysis

In Factory A, the interlocking of the access gates ensures all equipment except the robot is made inactive while the keys are used. The robots are prevented from moving by what appears to be a control interruption. Thus the safeguarding has some features that are like option (b) with some of the advantages of (c). However the safety integrity of a control interruption is not as high as if playback was prevented by hardware means.

There are some problems with the safeguard operations. Equipment cannot be powered on when needed with the access gate unlocked. Also, the safeguards in this case were not used as intended. The hazards in Figures 7.2 and 7.3 would be controlled (with exception of robot motion under slow speed in both event trees) so long as correct procedures were followed. However, observation has shown that incorrect procedures occur frequently. Moreover, the hazards in Figure 7.4 would be largely unaffected.

In B, the interlocking of access gates allows easy access but disables equipment nearby completely. The safeguards are therefore very similar to option (c). Teach mode motion has to be positively selected. Some safeguards are not engaged automatically (the physical steps on the lifter tables and the shuttles). The hazards in Figure 7.2 and 7.3 are therefore controlled quite well. There still remains the possibility of lifter or shuttle motion if not prevented and unexpected motion of robot arm at low speed under teach control when this is selected. The hazards in Figure 7.4 are affected in so much as the person carrying out the recovery from an emergency stop could do so from outside the fencing.

In C, the only robot system with fencing (No. 7) does not have a key interlocked access gate. There is the possibility of access through a side panel, as well as through the loading and unloading station. The only safety interlocks within the robots is programme software. Therefore, the hazards in all three events are virtually unaffected.

In D, the safeguards are very complex and also similar to option (c). Opening the access gate causes power to be removed from all equipment. Teach mode can be selected subsequently, but playback mode cannot occur whilst a person is within the system. The main difference between option

(c) and the safeguards in D is that the interlocking is achieved by pressure sensitive mats and limit switches, rather than an override key. Therefore, the hazards in Figures 7.2 and 7.3 are well controlled. There only remains the hazard of robot motion under teach control. The hazards of Figure 7.4 are reduced since the recovery from an emergency stop can be undertaken from outside the system fencing.

In F, neither robot system has much above the basic safeguards in Figure 7.1. In System I, access is possible at all times without affecting operation. In System II, there is a locked access gate, which like option (a) merely restricts access to authorised persons. Observation of System II showed that access occurred nearly always through the loading and unloading stations. Thus, the hazards in all three event trees are hardly affected.

In H, the completed systems would have physical safeguards similar to option (b). The robots would have to be in teach mode before the keys to the inner gates were used. The main difficulty in this case is the failure to implement the completed systems in the period of study. Thus, during the duration of the case study, the physical safeguards did not control hazard in the manner intended and were at best the same as the basic safeguards in the robot welding system (see Figure 7.1).

SUMMARY AND CONCLUSIONS

This chapter has considered the use of risk analysis techniques and has applied the most suitable one (Event Tree Analysis) to the analysis of the robot systems in the empirical study. The findings of a previous study of the risk analysis of a typical robot system are used in this analysis.

The Event Tree Analysis of the system has shown that the design in only two factories (B and D) are really effective at reducing the hazards, thus reinforcing the findings of Chapter 6. The failure to implement physical safeguards correctly was identified as the reason for the failure to control the hazards in Factories A and H. The importance of good working practices with even the best designed systems has been emphasised.

Chapter 6 showed safe working practices are poorly implemented and maintained in nearly all the factories where they are of greater importance due to deficiencies in physical safeguards. In fact, the two cases with well developed and implemented physical safeguards are also those with successful safety strategies focussing on people and their interactions with equipment (i.e. training alone in D and also working practices in B). Chapter 6 concluded that strategies with all 3 focusses were more unsuccessful because of the way in which strategies with one focus were assisted by strategies with another. This chapter has shown how good working practices are required with even the best designed systems. The Event Tree Analysis has thus reinforced the findings of Chapter 6. A decision to control hazards from robot systems with one or more focus of the strategy excluded is likely to be unsuccessful. The effectiveness of the strategy in D owes a lot to the numerous layers of protection from physical safeguards, yet as noted in Chapter 6, the sole problem in D concerned working practices.

This chapter has shown that it is possible to categorise the physical safeguards used with each system in terms of their function and their effectiveness in controlling certain hazards. Thus one can identify the applicability of the physical safeguards in each system to maintaining protection against hazards whilst allowing the necessary actions within the systems. This chapter has shown how this was achieved or in what manner physical safeguards failed.

CHAPTER 8

CONCLUSIONS

INTRODUCTION

This thesis has reported on research on industrial robots and their production systems, concentrating on the safety and production problems and their solutions. The overall aims of the thesis have been:-

(1) to identify problem areas with industrial robot use - their hazards, problems with production difficulties in the development and implementation and safety strategies.

(2) to distinguish safety strategies for different contexts in terms of their effectiveness and to suggest appropriate means for their adoptation.

An initial literature survey set the scene for the thesis with a description of the technology of industrial robots, the context of health and safety at work, the hazards of industrial robots and guidance on their safe use. The empirical study, which forms the major part of the research for this thesis, considered industrial robot production systems with six different robot users. It will be recalled that a set of propositions provided a focus for the data collection and analysis in the empirical study. The summary and conclusions which appear at the end of each chapter have provided a commentary on the findings of this thesis. In this chapter, the propositions are reconsidered in the light of the findings of the study. The propositions are restated below and are followed by a brief discussion on the findings relevant to each set of propositions.

It should be noted that the empirical study from which these findings on the propositions are drawn is limited by a small sample base. The propositions of the study are thus issues to be explored, rather than hypotheses which need to be tested by the empirical research. Although the systems are typical in many respects of industrial robot systems in the U.K., generalisations of the results to all industrial robot systems is problematical. Nonetheless, having reviewed the findings in the light of the propositions, the second part of these conclusions provides a practical guide for robot system users. The conclusions end with recommendations for future research.

THE PROPOSITIONS OF THE STUDY

Proposition Set 1: The Current Use of Robots and the Understanding of Hazards

1.1 The diffusion of robots through industry, particularly the rapid rate of increase in their adoption and spread, creates problems in terms of the general level of understanding of hazards associated with their use. Although knowledge of the means of ensuring safety with robots is developed to some extent, it is expected that this knowledge is poorly distributed amongst user companies.

1.2 The introduction of robots will result in the potential for greatly improved safety, but poor perceptions of the risks and inadequate means of ensuring safety could prevent this potential being realised.

1.3 Exceptions to the generally poor level of understanding of robot safety are expected where substantial experience of robot use has accumulated within the factory.

The systems studied in the empirical study were the first to be based on industrial robots in all the factories except one. Knowledge of robot hazards was poorly developed in each of the five factories before robot introduction and steps were taken in most to improve on this lack of knowledge. The use of commissioning companies to implement the systems in Factories A and F assisted in some respects in increasing hazard awareness. However, the lack of a continual presence of these experienced consultants meant that hazard awareness decreased after system implementation. However, attempts to improve knowledge were not undertaken systematically in all the factories. For example, a lack of a clear process of identification was found in Factories C and F (see Chapter 6).

Poor hazard identification in these factories (C and F) was found to be associated with incomplete safety strategy development. The benefits of robot use, of separating workers from direct contact with hazardous processes, were not gained because of the detrimental effect of poor perceptions of the risks. However, it would not be correct to conclude that the factories with a clear or formal process of hazard identification encountered only the benefits of robot use. For example, Factor A and H identified hazards and developed measures for them, but then ran into significant problems in the implementation and maintenance of these measures. Thus poor hazard identification was found to have an adverse effect upon the development of strategies but other inadequate means of ensuring safety were also found in the subsequent stages of safety strategies.

Factory B had extensive previous experience of industrial robot use. The hazard identification and awareness was found to be well developed and the safety strategies adopted were also amongst the most effective in the study. It was clear that in this case, experience of robot use improved the understanding of the hazards and how they could be controlled.

Proposition Set 2: The Design of Robots

> Each design of an industrial robot is likely to have different failure and problem characteristics from other robot designsand as a result, the impact on safety of robots will not be constant. The problems and failures to which each design is susceptible will influence the hazards posed by the different designs.

Four robot designs were covered by the data on production problems (see Chapter 5), of which one was hydraulically powered. The robot designs were found to have different frequencies of problems and of lengths of downtime. In particular, the hydraulic robots were found to be more prone to lengthy downtime from problems or failures. However, the influence of robot design could not be isolated from the features of system design and work organisation. Thus, the influence of robot design on hazards could not be stated explicitly although some influence was clear. For example, the possibility of the collapse of the robot arm when a power supply fault occurred and the frequency of erratic robot motion with Type 2 robots (a large hydraulic robot) suggested a relatively high level of hazard from incorrect robot arm movements. The numerous incidents in Factory B of robot collision also suggested some problem with the control of the robot arm motion for Types 3 (a large electric robot) and 4 (a medium-sized gantry mounted electric robot), although there was a strong influence from system design in these events.

Proposition Set 3: The Interactions of Equipment in Robot Production Systems

Different applications of robots involve different processes and hence can be expected to involve different hazards. The robot production systems present different hazard levels due to the interactions of the robots with the process and other equipment in the systems. As a corollary, major safety and production problems arise from the interaction of equipment in the robot production systems and not solely from each machine in solation.

The analysis of production problems in Chapter 5 showed that the interactions of equipment were the major cause of problems and that system design, task and work organisation were major influences on the problems. For example, the analysis of the underlying reasons for production interruptions showed how system design, task and work organisation could lead in some companies to a marked increase in the occurrence of some underlying reasons which account for a small percentage of incidents elsewhere. The influence of these factors was particularly noticeable in Factories A, B and F. The frequent occurrence of weld failures in Factory A could be traced to the difficult arc-welding task in this system. The frequency of the interruptions through control emergency stops in Factory B were related to both the requirements of the tasks and the practice of correcting the problem by increasing the limit of power to the electric motors on the robots. The high frequency of component failures in the other equipment in Factory F (System I) signified the problems associated with the dedicated equipment provided by the commissioning company.

Proposition Set 4: The Exposure of Personnel to Hazards

The shift in levels of exposure to hazards is expected to be from relatively lower skilled workers to maintenance and other skilled grades.

The types of personnel involved in problems with the robot systems were found to be dependent largely on the work organisation in each system. Skilled workers were allocated to the systems for nearly all tasks. The production problem analysis in Chapter 5 also found a shift towards experienced and well trained personnel for problem solution in some systems. However, in three systems (in C, F and H) there were clear indications of poorly trained personnel involved in problem solution. In Factory C, the operators received minimal training and were required to carry out some simple problem correction. In Factory F, the chargehands responsible for problem solution had not all received appropriate training. In Factory H, operators went beyond their training in trying to solve problems.

Proposition Set 5: Physical Safeguards

5.1 It is expected that physical safeguarding forms a major part of the safety strategies adopted for each robot production system.
5.2 It is expected that physical safeguards remove hazards mainly from the passive observer and inexperienced or unauthorised employees.

The analysis of the safety strategy in Chapter 6 showed that physical safeguards were a major part of the strategies in each system, including those in Factory C where little beyond a few basic physical safeguards were developed and implemented. The physical safeguards had a role in hazard elimination (especially fencing) but acted mainly to contain the hazards within the systems. Workers in the same area of the factory as the systems were not exposed to the hazards of robots to any great extent. However, once access within a system was gained, most forms of physical safeguards were not effective. Thus, workers within some systems (notably in A, C and F) were not protected from hazards by physical safeguards. It was also possible for these safeguards to contribute to the hazards to which a worker within a system was exposed. For example, the cloudy plastic screens in Factory F (System II) reduced visibility and thereby could obscure the presence of a worker within a system. The system could be started without the presence of this worker within the system being revealed.

Proposition Set 6: Working Practices

The working practices of personnel in contact with equipment in robot production systems has an important influence on the overall safety, notwithstanding the effects of other safeguarding means. Workers' actions during periods of interaction with robot systems will determine the uncontrolled hazards and could also act to prevent the remaining hazards (such as robot motion) from being realised.

The Event Tree Analysis in Chapter 7 has explained the role of good working practices even with a well developed and implemented safety strategy. Close proximity to an operable industrial robot cannot be prevented, since certain mechanical actions are required for programming or recovery from problems. For a safety system similar to the best in the empirical study, working practices still have an important influence on the hazard level during such actions. What is more, the analysis of safety strategies in Chapter 6 has shown how poor working practices encourage the improper use of physical safeguards. For example, the poor working practices in Factory A led to widespread circumvention of the constraints of the physical safeguards.

Proposition Set 7: Training

7.1 Training of personnel is expected to focus on the needs of production. Elements concerned with safety are likely to be introduced as personnel learn of the equipments' operations. Training will be assisted by considerations of equipment interactions.

7.2 On-site training is more likely to give a good understanding of the problems of the robot production systems than training at the suppliers site.

The analysis of the safety strategies showed that safety formed a small part of most training provisions. However, in the most effective strategies, far more safety related training was undertaken. Those workers in direct contact with the systems were trained according to the tasks they were meant to perform.

Two factories adapted their training provisions to include some on-site element and a third carried out all the training within the factory. These three Factories (B, D and H) also had the more successful strategies directed at safety training. Thus, there was some evidence of on-site training providing a more effective means of providing training on the problems of robot production systems.

Proposition Set 8: The Role of Management and Organising for Safety

8.1 Management strategies towards the introduction and safeguarding of robot production systems are likely to be critical in deciding the effectiveness of the measures to be adopted.

8.2 It is expected that the importance placed on safety will be reflected in the influence of and resources available to the safety function. The overall climate towards safety in the factory is expected to have an influence on the steps taken with the robot production systems.

8.3 The power, responsibilities and authority of those involved in ensuring safety and the mechanisms for ensuring accountability are expected to influence the implementation of the safety strategies and hence influence the safety of the systems.

8.4 The means of monitoring and evaluating the safety performance of the system design and personnel are also expected to be particularly influential in maintaining and adapting system design or working practices.

The analysis of the safety strategy in Chapter 6 showed that decisions made by management at each stage of a strategy were important to its success. Thus, management strategies towards safeguarding robot production systems were critical to the effectiveness of the measures taken.

The role of motivational controls in the safety strategies, in terms of the overall climate, the power, responsibility and authority of those involved in ensuring safety and the mechanisms for accountability (propositions 8.2 to 8.4) were diffuse in their influence. Thus it was difficult to assess the direct impact of motivational controls on the success of safety strategies. However, it was notable that the overall climate and the specification of responsibility and authority for safety were well developed in Factories B and D, which also had the most complete safety strategies.

A GUIDE FOR ROBOT SYSTEM USERS

This thesis had considered safety strategies for robot systems in six factories and has drawn some general findings on how such strategies can be effective. A prospective user of industrial robots can benefit from these findings since they identify the areas which should be considered in order to ensure effective strategy adoption. This section brings together the findings on safety strategies by presenting a checklist of questions which should be addressed in the process of deciding upon and implementing a safety strategy

This checklist follows the categorisation of technical and motivational controls used in the analysis of the safety strategies in Chapter 6.

1. Hazard Identification

1.1 What hazards are presented by the process for which the robots are to be used?

1.2 In what way do the particular hazards of industrial robots augment the hazards of the process and of the other equipment? (see Chapter 2 for discussion of hazards of robots).

1.3 What hazardous interactions (during normal operations, maintenance and under failure conditions) are possible within the system?

1.4 Are those responsible for system design fully aware of the hazards?

1.5 Have other robot users identified other hazards which may be relevant to your application?

1.6 Has a formal hazard assessment been undertaken?

2. The Development of Strategies

2.1 Have similar robot systems been visited to ascertain the safety strategies adopted in these cases and has an assessment of their relevance to your application been made?

2.2 Has consideration been given to a range of physical safeguards and an assessment made of the specific hazards which they act against (for example by Event Tree Analysis)?

2.3 Has safe access through physical safeguards been considered so that those within the system are not exposed to hazards because of these safeguards and not left unprotected from the hazards of the system?

2.4 Has consideration been given to the means of circumvention of physical safeguards and measures to reduce this possibility (such as ease of correct use of safeguards)?

2.5 Has training and information been provided for all personnel involved?

2.6 Have personnel been provided with sufficient training on the possible hazardous interaction of equipment in the whole system (for example by on-site training)?

2.7 Has consideration been given to working practices for all activities involving close proximity to equipment? Have formal systems of work for these activities been developed?

2.8 Have the hazards of working practices been included in the assessment of the need for physical safeguards?

2.9 Has consideration been given to the ways in which the three focusses of safety strategies can enhance one another and have steps been taken to ensure their compatibility?

2.10 Have means of reacting to hazard realisation allowed for safe and efficient rescue of personnel from danger (for example by the provision of break-glass bolts on access doors) been included in the system design?

2.11 Has documentation been undertaken on the technical measures and the hazards which are meant to be controlled?

3. The Implementation of Strategies

3.1 Have all the options decided upon for development been implemented?

3.2 Are new personnel provided with training and information on the robot systems to the same standard as those trained initially?

4. Monitoring of Strategies and Identification of Problems and Unanticipated Consequences and Strategy Maintenance

4.1 Are the strategic options which have been developed and implemented operating as intended?

4.2 Is the monitoring performed by personnel not directly involved in a work activity with the system and have they received adequate training and information on the systems' operations and hazards?

4.3 Are accidents and unsafe incidents identified and investigated? Is an assessment of the means by which these events can be prevented undertaken?

4.4 Are strategic options (particularly working practices) periodically reviewed and have those reviews been undertaken by those not directly involved in the activity?

5. Adaptation of Safety Strategies

5.1 Are there means by which resources are made available for strategy adaptation?

5.2 Are adaptations monitored so that the extent of implementation and their effects are known?

6. Motivational Controls

6.1 Is a safe working environment and a safety conscious environment maintained in the factory and around the robot system(s)?

6.2 Are there formal statements on the responsibility and authority of personnel for ensuring safety? Do these statements also specify the means by which these responsibilities are to be enacted?

6.3 Are measures of safety performance and specific accountability for ensuring safety in existence and are they used?

6.4 Are disciplinary proceedings provided for breaches of safety requirements?

RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis has provided substantial new information about the operation of and safeguarding practices with industrial robot systems. It has found that the hazards of industrial robot use are not always adequately guarded and that suitable safeguarding measures become ineffective after their introduction because they are not fully implemented or maintained. Production problems cause a large number of interruptions and result in close interactions between machinery and people. Such interactions pose hazards which cannot be eliminated but can be controlled by the practices adopted by workers. The Event Tree Analysis has shown how good working practices are a critical feature of a safety strategy. Furthermore, this technique has been demonstrated as a means of identifying hazards for which specific measures are designed.

However, these findings are restricted by the small sample base on which they are made. Particular questions need to be asked of a larger sample which is representative to a wide range of robot tasks, to see whether the research can be said to have wider applicability:-

1) The researcher's findings on the availability of robot systems indicate a large amount of production time is lost through problems with automatic production. Comparable studies of the production scheduling in a larger and more varied sample is necessary to establish if this finding applies equally to other systems and other robot tasks.
2) Although the research has found some significant hazards which are not controlled, the number of accidents associated with robots was low. The number of workers exposed to hazards in the small sample base was not sufficient for a large enough base of hours exposed to the hazards. More extensive data collection on accidents with robot systems would be necessary before an accurate picture of the relative accident rate could be established.
3) Different problem and downtime distributions have been identified for the four robot designs covered in the data on production problems. These differences need to be re-assessed for a larger number of robot designs. The reasons for the differences between different robot designs would need to be explained and for this purpose an in-depth mechanical and electrical design analysis would be necessary.

4) The frequency with which physical safeguards were circumvented was high in the Empirical Study. A connection between the need or desire to circumvent physical safeguards and the difficulties of correctly using them was tentatively provided. This area needs further research as it points to one of the major problems of maintaining a safety strategy. The extent of this problem needs to be explored through a larger sample which will be able to identify factors which influence such behaviour more fully.
5) The analysis of the safety strategies has shown that the three focusses of anticipation strategies enhance and complement one another if fully developed and implemented. The extent to which this feature holds true for other robot systems (and even beyond the robot systems to the manufacturing process) needs to be investigated. If it is generally true, it provides a strong argument for developing broadly based safety strategies for all occasions.

Other future research arising from this thesis revolves around a more in depth study of a few systems. This thesis did not attempt to assess fully and quantify the hazards in each system. However, such an assessment is necessary before the benefits to be gained by certain actions or further control measures can be fully ascertained. Thus a study would be necessary involving detailed analysis of system and individual equipment design and the operational capabilities of the overall system. Fault and Event Tree Analysis would be utilised to quantify the possibility of hazardous occurrences and these would be linked to the observed working practices with the systems. Such an analysis would identify the possibility of a hazardous event and also the possibility of this hazardous event becoming an accident. Event Tree Analysis would prove useful in identifying the control measures which would prove effective against each identified hazard.

REFERENCES

AKEEL, H.A. "Intrinsic Robot Safety", Professional Safety, December 1983, Vol. 28, No. 12, pp. 27-31.

ALTAMURO, V.M. "Working Safely with the Ironcollar Worker", National Safety News, July 1983, pp. 38-40.

ATHERLEY, G.R.C. "Strategies in Health and Safety at Work", 1974 E.W. Hancock Paper, Institution of Production Engineers, 1974.

ATHERLEY, G.R.C. "Occupational Health and Safety Concepts - Chemical and Processing Hazards", Applied Science Publishers Ltd., London, 1978.

ASTROP, A. "Robot Applications: A Trio of Successes", Machinery and Production Engineering, 3rd February, 1982, pp. 24-29.

BACKSTROM, T. and HARMS-RINGDAHL, L. "A Statistical Study of Control Systems and Accidents at Work", (Occupational Accident Research Unit, Stockholm), 1984, Journal of Occupational Accidents, Elsevier Science Publishers 6(1984), pp. 201-210.

BARRETT, R.J. "Robot Safety and the Law", Robot Safety, Bonney and Yong (eds.), IFS (Publications) Ltd., 1985, pp. 3-15.

BARRETT, R.J., BELL, R. and HODSON, P.H. "Planning for Robot Installation and Maintenance: A Safety Framework", Proc. 4th British Robot Association Conference, 1981.

BELL, R. "Safety Implications of Programmable Equipment", Electrical Review, 4th June 1982, Vol. 210, No. 22, pp. 20-25.

BELL, R., DANIELS, B.K. and WRIGHT, R.I. "Assessment of Industrial Programmable Electronic Systems with Particular Reference to Robotics Safety", 4th National Reliability Conference, July 1983.

BENNETT, D.J. "Objective Approaches to the Improvement of Machine Tool Reliability", Ph.D. Thesis, University of Birmingham, April 1978.

BOMPAS-SMITH, J.H. "Mechanical Survival - The Use of Reliability Data", McGraw Hill, 1973.

BONNEY, M.C. and YONG, Y.F. (ed.) "Robot Safety", (International Trends in Manufacturing Technology),(IFS Publications) Ltd., 1985.

BRITISH ROBOT ASSOCIATION (BRA) "U.K. Application Analysis", December 1982, (Press Release) BRA.

BRITISH ROBOT ASSOCIATION (BRA) "U.K. Application Analysis", December 1983, (Press Release) BRA.

BRITISH PLASTICS FEDERATION Code of Practice for the Safeguarding of Horizontal Injection Moulding Machines, 1978, (Updated 1984).

BS 2771: 1974 "Specification for Electrical Equipment of Machine Tools. General Purpose and Mass Production Machines and Their Electronic Equipment", British Standards Institution, London, 1974.

BS 5304: 1975 "Code of Practice: Safeguarding of Machinery", British Standards Institution, London, 1975.

BS 6491 Part 1: 1984 "Electro-Sensitive Safety Systems for Industrial Machines. Part 1. Specification for General Requirements", British Standards Institution, London, 1984.

CARLSSON, J. "Robot Accidents in Sweden" in Robot Safety, Bonney and Yong (eds.) IFS (Publications) Ltd., 1985, pp. 49-64.

CARLSSON, J. ET AL "Industrial Robots and Accidents at Work" Trita AOG-0004, Kungl., Tekniska Liogskolan (Royal Institute of Technology), Arbetarskyddsstyrelen (Occupational Accident Research Unit), 1979 (English Translation, 1980).

CARRICO, L.R. "Training and Design for Safe Implementation of Industrial Robots" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 169-177.

COX, R.A. "Uses and Limitations of Analytical Methods in Hazard Assessment and Loss Prevention", I. Chem. E. Jubilee Series Symposium, 1982.

CRITCHLEY, O.H. "Risk Prediction, Safety Analysis and Quantitative Probability Methods - A Caveat", J. Br. Nuclear Energy Society, 1976, Vol. 15, No. 1, pp. 18-20.

DANIELS, B.K., BELL, R. and WRIGHT, R.I. "Safety Integrity Assessment of Programmable Electronic Systems", SAFECOMP, 1983.

DAWSON, S.J.N., POYNTER, P. and STEVENS, D. "Strategies for Controlling Hazards at Work", Journal of Safety Research, Vol. 13, 1982, pp. 95-112.

DAWSON, S.J.N., POYNTER, P. and STEVENS, D. "How to Secure an Effective Health and Safety Programme at Work", OMEGA, 1983, Vol. 11, No. 5, pp. 433-446.

DAWSON, S.J.N., WILLMAN, P., BAMFORD, M. and CLINTON, A. "Health and Safety at Work - Ten Years After", forthcoming publication.

DEPARTMENT OF EMPLOYMENT "Accidents in Factories, HMSO,London, 1974.

DERBY, S., GRAHAM, J. and MEAGHER, J. "A Robot Safety and Collision Avoidance Controller" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 237-246.

EDWARDS, M. "A Study of the Feasibility of the Development and Use of a Systematic Analysis Technique for the Investigation of Industrial Accidents", Birmingham University, Feburary 1981.

ENGELBERGER, J.F. "Robotics in Practice: Management and Applications of Industrial Robots", Kogan Page, 1980.

THE ENGINEER "Nine Reasons Why Robots Should Do the Arc-Welding for Us" September, 1978, p. 35.

EVA, D. and OSWALD, D. "Health and Safety at Work", Pan Trade Union Studies, 1981, Pan Publications.

FISCHHOFF, B., SLOVIC, P. and LICHTENSTEIN, S. "Fault-Trees: Sensitivity of Estimated Failure Probabilities to Problem Representation", Journal of Experimental Psychology, 1978, 4, pp. 330-344.

FLECK, J. "The Diffusion of Robots in British Manufacturing Industry", Final Report on Research Project, The Technology Policy Unit, The University of Aston in Birmingham, June, 1982.

FORD "Photoelectric Guarding", Manufacturing Safety Coordination, (Ford of Europe, U.K.) in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., 1985.

GRAHAM, M.E.K. "Safety Mats" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 205-216.

GREEN, A.E. (ed.) "High Risk Safety Technology", John Wiley & Sons Ltd., 1982.

GREEN, A.E. and BOURNE, A.J. "Reliability Technology", J. Wiley & Sons Ltd., 1972.

GRIFFIN, K. "Safety for Industrial Robot Applications", Professional Safety, December, 1983, Vol. 28, No. 12, pp. 22-26.

HARTLEY, J. "Robots at Work: A Practical Guide for Engineers and Managers", 1983, IFS (Publications) Ltd.

HASEGAWA, Y. and SUGIMOTO, N. "Industrial Safety and Robots", Proceedings of the 12th International Symposium on Industrial Robots, 1982, pp. 9-20.

HSE Guidance Note GS5, "Entry into Confined Spaces", 1977.

HSE "A Guide to the HSW Act", Health and Safety Series Booklet, HS(R)6, 1980.

HSE "Microprocessors in Industry - Safety Implications of the Uses of Programmable Electronic Systems in Factories", HSE Occasional Paper: OP2, 1981.

HSE "Guidance on the Safe Use of Programmable Electronic Systems" (Draft Document for Consultation), Part 1: General Requirements, Part 2: Safety Integrity Assessment, Part 3: Safety Integrity Assessment: Case Study, 1984a.

HSE Guidance Note PM41,"The Application of Photo-Electric Safety Systems to Machinery", 1984b.

HEINRICH, H.W. "Industrial Accident Prevention", McGraw Hill, New York, 1931.

HMSO "The Operations at Unfenced Machinery Regulations" SI 1938, No. 641, (Amended SI 1976, No. 955), HMSO, London.

HMSO "Factories Act 1961", HMSO, London.

HMSO "The Health and Safety at Work etc. Act", 1974, HMSO, London.

HMSO "Safety Representatives and Safety Committees Regulations", SI 1977, No. 500, HMSO, London.

HMSO "Health and Safety Statistics, 1977", HMSO, 1980, London.

HEROUX, N.M. and MUNSON, G. (Snr) "Robots Reduce Exposure to Some Industrial Hazards", From W. Tanner (ed.) Industrial Robots, Soc. Manuf. Engineers, Dearborn Michigan, 1979.

HUNTER, J. "Collision Hazards with Industrial Robots", National Engineering Laboratory, East Kilbride, 11th February, 1981.

I.E.E. News "BRA Figures Better Than Expected", March 1984, No. 99, p. 1.

I.MECH.E/I.PROD.E. "Safety Guarding in Programmable Automation and Robotic Installations" (a jointly organised seminar), Preston 23rd October, 1984.

INBUCON "Industrial Robots in Japan, U.S.A. and U.K.", INBUCON Management Consultants Ltd., 1982.

INDUSTRIAL ENGINEERING "Robotics for the I.E.: Terminology, Types of Robots", Ottinger, L.V., November 1981, p. 30.

THE INDUSTRIAL ROBOT "Robotics in the U.K.", March 1981 Vol. 1, No. 1.

THE INDUSTRIAL ROBOT "Steady Growth for Robots in 1984", March 1985, pp. 30-35.

INDUSTRIAL ROBOT SPECIFICATIONS, Complied by Andre Gugy and Kogan Page, Consultant Editor, Adrian Ioannou, Kogan Page, 1984.

ISSA 2nd Colloquium of the Section of Research of the ISSA. Safety at Work with Automation and New Technologies, "Criteria and Methods for Safety Analysis", Held in Bonn, 8-10 May, 1985.

JAPAN "Japanese Industrial Standards - General Code for Safety of Industrial Robots", JIS B8433, 1983.

JONES, R., KHODABANDEHLOO, K., DAWSON, S.J.N. and HUSBAND, T.M. "Robot System Hazard Assessment Using Event Trees" in Modelling and Design of Flexible Manufacturing Systems, ed. Prof. A. Kusiak, Elservier Science Publishers (forthcoming).

KAY, H. "Accidents: Some Facts and Theories", Psychology at Work, P.B. Warr, ed., Penguin 1971, pp. 97-117.

KELLER, A.Z., KAMATH, A.R.R. and PERERA, U.D. "Reliability Analysis of CNC Machine Tools",Third National Reliability Conference 1981, Vol. 1.

KELLY, M. "Robots in the Automobile Industry", Proceedings of the 4th British Robot Association Annual Conference, 1981.

KILMER, R.D. "Safety Sensor Systems" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 223-235.

KOCHHAR, A.K. and BURNS, N.D. "Microprocessors and their Manufacturing Processes", Edward Arnold, 1983, London.

LABOUR RESEARCH "The Robots Are Coming", April 1984, p. 84.

LINGER, M. "Design of Safety Systems for Human Protection" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publication) Ltd., pp. 117-125.

MTTA "Safe Guarding Industrial Robots Part 1: Basic Principles", The Machine Tool Trades Association, 1982.

MACHINERY AND PRODUCTION ENGINEERING "Robot Revolution Gains Momentum", A. Astrop, 3rd February 1982, pp. 14-19.

MACHINERY AND PRODUCTION ENGINEERING "Welding: Moving in the Right Direction" 17th July, 1985, pp. 34-39.

MEAGHER, J., DERBY, S. and GRAHAM, J. "Robot Safety/Collision Avoidance" Professional Safety, December 1983, Vol. 28, No. 12, pp. 14-16.

MINISTRY OF LABOUR "A Study on Accidents Involving Industrial Robots" Robotics Report No. 5, February 1983, Tokyo, Japan. Translated by U.S. Dept of Commerce, Nat. Tech. Inf. Service, August 1983, PB 83 239822.

NEW SCIENTIST "Britain Grapples with Robots", 24th August, 1980, pp. 183-187.

NEW TECHNOLOGY "Advance or Collapse for British Robotics", 18th February, 1985, p. 9.

NICOLAISEN, P. "Occupational Safety and Industrial Robots" in Robot Safety, (Bonney and Yong eds.), 1985, IFS (Publications) Ltd., pp. 33-48.

OTTO, D. "Planning and Installation of Industrial Robots for the Elimination of Work which is Heavy, Dangerous to Health and Monotonous in Nature", Die Technik, February 1979, Vol. 34, No. 2, pp. 63-68 (translated from the Germany by the HSE).

OTWAY, H. and PAHNER, P. "Risk Assessment in Risk and Chance", J. Dowe, P le Frere (eds.), O.U. Press, 1980, pp. 148-160.

PERCIVAL, N. "The Role of Standards in Flexible Automation Systems", International Conference on the Development of Flexible Automation Systems, 10th-12th July, 1984.

PERCIVAL, N. "Safety Standards in Robotics" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 17-21.

PERROW, C. "T.M.I., A Normal Accident", Draft Paper, November 1979.

PERROW, C. "Normal Accidents: Living with High-Risk Technologies" Basic Books, New York, 1984.

POTTER, R.D. "Safety for Robotics", Professional Safety, December 1983, Vol. 28, No. 12, pp. 18-21.

THE PRODUCTION ENGINEER "Three Robot Users Admit Their Mistakes", July/August 1985, pp. 23-24.

RASMUSSEN, J. "Notes on Human Error Analysis and Prediction" in:- G. Apostolakis and G. Volta (eds.) "Synthesis and Analysis Methods for Safety and Reliability Studies", Plenum Press, 1978, London.

ROBENS, LORD "Safety and Health at Work, Report of the Committee" (1970-72), (Chairman, Lord Robens), Cmnd. 5034, HMSO, 1972, London.

ROBOTICS TODAY "Robot Safety: A Shared Responsibility" Rita R. Schreiber, (Staff Editor), October 1983, p. 61-65.

ROBOTICS TODAY "Practical Robot Safety" (E.J. Kehoe, Asst. Editor), April 1985, pp. 38-41.

ROBINSON, O.F. "Robot Guarding - The Neglected Zones" in Robot Safety Bonney and Yong (eds.) 1985, IFS (Publications) Ltd., pp. 181-188.

ROWE, W.D. "An Anatomy of Risk", Wiley, 1977, New York, London.

RUSSELL, J.W. "Robot Safety Considerations - A Checklist" Professional Safety, December 1983, Vol. 28, No. 12, pp. 36-37.

THE SAFETY PRACTITIONER "The Safety Committee - A Trade Union View" A. Greaves, December 1984, pp. 36-38.

SATO, K. "Case Study of Maintenance of Spotwelding Robots" Plant Maintenance 1982, 14(3): 28.

SELWYN, N.M. "Law on Health and Safety at Work" Butterworths 1982, London.

SIEGEL, S. "Non-Parametric Statistics for the Behavioural Sciences", McGraw Hill, 1956.

SLOVIC, P. and FISCHHOFF, B. "How Safe is Safe Enough" in Risk and Chance", J. Dowie, P. le Frere (ed.), pp. 121-147, 1980, O.U. Press.

SMITH, C.O. "Introduction to Reliability in Design", (International Student Edition), McGraw Hill, 1976.

SPSS "Statistical Package for the Social Sciences - Reference Manual" - N.H. Nie, C.H. Hull, J.G. Jenkins, K. Steinbrenner, D.H. Bent, 2nd Edition, McGraw Hill, 1970, 75.

SPUR, G. and DUELEN, G. "Personnel and Handling Instrument Safety", VDI-Berichte, No. 421, 1981, pp. 95-100, translated by the HSE, 1982, HSE Translation No. 9992.

STEWART, E. "The Reliability of Machine Tools", National Conference on Reliability, 21-23 September, 1977.

STOWE, W.W. "Robots - Safe or Hazardous?", Professional Safety, December 1983, Vol. 28, No. 12, pp. 32-35.

SUGIMOTO, N. "Safety Engineering on Industrial Robots and Their Draft Standards for Safety Requirements", Proceedings of the 7th International Symposium on Industrial Robots, Tokyo, 1977, pp. 461-470.

SUGIMOTO, N. "Systematic Robot-Related Accidents and Standardisation of Safety Measures", in Robot Safety, Bonney and Yong (eds.), 1985 IFS (Publications) Ltd., pp. 23-29.

SUGIMOTO, N. and KAWAGUCHI, K. "Fault-Tree Analysis of Hazards Created by Robots" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 83-98.

TECHNOLOGY (including Engineering Today) "Focus on Health and Safety New Hazards at Work", M. Armstrong, 12th December, 1983, pp. 26-27.

TECHNOLOGY "Robot Firm Massacre Due", 27th February 1984, p. 12.

THOMPSON, C. "Safety Interlock Systems" in Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 189-198.

T.U.C. Handbook on "Safety and Health at Work", 1975, Macdermott and Chant Ltd.

TURNER, B.A. "Organisational and Interorganisational Development of Disasters" ASQ, 1976, Vol. 21, pp. 378-396.

TURNER, B.A. "Man-Made Diasters", Wykeham Ltd., 1978.

U.K. COMMLINE Robots Report, Vol. 8, No. 2, April/June 1983, p. 27.

UNIVERSITY OF NOTTINGHAM, "Robot Safety", A Two Day Seminar held at Crick, Northamptonshire, 10th and 11th November, 1982.

VAN DEEST, R. "Robotic Safety, a Potential Crisis", Professional Safety, January 1984, vol. 29, No. 1, pp. 40-42.

VON GIZYIKI, R. "Social Conditions for and Consequences of the Use of Industrial Robots in Five Factories", Proceedings of the 10th International Symposium on Industrial Robots, 1980.

WARNECKE, H.J. and SCHRAFT, R.D. "Industrial Robots: Application Experience", IFS (Publications) Ltd., 1982.

W. GERMANY VDI Guideline 2853 "Safety Requirements relating to the Construction and Equipment for Handling Appliances and Operation of Industrial Robots and Associated Devices",1984.

WOBBE-OHLENBURG, W. "The Influence of Robots on Qualification and Strain" Soziologisches Forschungsinstitut Gottingen, (SOFI), Germany, 1982.

YONG, Y.F., TAYLOR, N.K. and BONNEY, M.C. "CAD - An Aid to Robot Safety System Design" Robot Safety, Bonney and Yong (eds.), 1985, IFS (Publications) Ltd., pp. 133-40.

ZERMENO-GONZALEZ, R. "The Development and Diffusion of Industrial Robots" University of Aston in Birmingham, Ph.D. Thesis, 1980.

APPENDIX A

Form Letters Sent to Companies

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

Department of Mechanical Engineering
Exhibition Road, London SW7 2BX
Telephone: 01-589 5111 Telex: 261503 Telegrams: IMPCOL London SW7

Dear

I have been given your name by Professor Husband, Director of the Robotics Centre here at Imperial College. I understand your company uses a number of industrial robots and I am writing to seek your cooperation with a research programme I am undertaking.

I am a research student jointly with the Department of Mechanical Engineering and the Department of Social and Economic Studies at Imperial College undertaking research on the safety and reliability of industrial robot systems. At present there is a lack of data available on the reliability and safety problems being faced by robot users, and this research project together with other work in the Robotics Centre is attempting to fill this gap. I enclose a copy of the Postgraduate Courses booklet to show the work being done.

As an initial piece of field research, we wish to cooperate with users in gathering information on their robots, especially the problems that arise in their application. Naturally this information will be treated as confidential between ourselves and each company with no information on applications being passed from one company to another. It is not the purpose of this research to comment on the effectiveness of individual installations but more to draw general conclusions on the safety problems and hazards presented and removed by robot use and to assess how reliability of robot systems can best be achieved.

I hope your company will find this research interesting and will give it your cooperation. I would be grateful if this matter could be brought to the attention of the relevant persons in your company so that contact could be established between such people and myself. I look forward to hearing from you in the near future.

Yours sincerely,

R.H. Jones

Enc.

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

Department of Mechanical Engineering
Exhibition Road, London SW7 2BX
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Yours faithfully,

R.H. Jones

Enc.

APPENDIX B

Explanatory Notes Provided for Diary Completion

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF SOCIAL AND ECONOMIC STUDIES
53 Prince's Gate, Exhibition Road,
London SW7 2PG
Telephone 01-589 5111 Telex 261503

A Study of the Safety and Reliability of Robot Installations

I am a research student at Imperial College, London, working for a PhD on the problems found with robot installations. This work should improve the level of understanding of the risks associated with robots and help towards making robot installations safer and more reliable. To do this, I need to collect information on what problems occur with robots and to assess the consequences of these problems.

This diary is the first step in collecting information on how robot installations behave and what problems are encountered with them. It will also collect information about the potential to cause harm, as well as about accidents and faults.

The diary asks you to record any human-machine interactions and all machine problems which occur. You should record them by putting a tick in the appropriate box and filling out the brief details of the incidentwhich are requested.

The space for comments is designed to get more information on the incidents and to give you the opportunity of giving your personal views on the problem.

I hope most events will be covered in the categories given, but if any other cases occur, please add them (in the boxes marked OTHER). I expect that filling out one record will take no more than five minutes.

I'd like to thank you for your co-operation and help in this work. If there are any problems with it, or any queries, please don't hesitate to contact me (Tel. No. 01-589-5111 ext 1019, or leave a message on the ANSAphone on ext. 2487).

I shall be returning regularly to collect the diary sheets, so I can handle most of the queries then, especially the less urgent ones.

Richard Jones

Research Student

Note to those filling in Diary Forms.

This note is an additional explanation of the study to the one headed "A Study of the Safety and Reliability of Robot Installations". Please make sure you read both of these.The diary is designed to record all human interventions to the system and all machine problems. The whole installation is of interest,not just the robot itself.

One diary form should be filled in for each incident,that is, when human intervention is necessary and the automatic operation is halted. Please try to ensure that the forms are kept accurately with as much information given as possible. The greater the detail of the information, the better this study will be. I have enclosed copies of three test cases,to give you an idea of the sort of return I am looking for. I hope you will find these fairly self-explantory. Note that the present diary forms differ from these examples by having an extra box for the hours of robot use for the week in which the form is filled in.

Thankyou for your assistance. I hope you will contact me as soon as any difficulties arise.

Richard Jones.

(Tel no. 01-589 5111 extn 1019
or 2487)

Note to those filling in Diary Forms.

This note is an additional explanation of the study to the one headed "A Study of the Safety and Reliability of Robot Installations".Please make sure you read both of these. The diary is designed to record all human interventions to the system and all machine problems. The whole installation is of interest, not just the robot itself.
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Thankyou for your assistance and I hope you will contact me as soon as any difficulties arise.

Richard Jones

TEST CASES OF DIARY FORM.

TEST CASE No.1

PUMA robot moves without being commanded to do so during programming, EMERGENCY STOP is pressed, with subsequent fault diagnosis undertaken. Total Downtime caused is 30 minutes.

INCIDENT TIME & DATE: ?
ROBOT TYPE: PUMA
ROBOT TASK:ASSEMBLY
column 1 ACTION TAKEN: FAULT DIAGNOSIS
column 2 REASON FOR ACTION: ERRATIC ROBOT BEHAVIOUR (STARRED)
& PROGRAMMING PROBLEM
& THREATENED DAMAGE TO ROBOT
column 3 MEANS OF INTERRUPTION: PERSONAL ACTION - EMERGENCY STOP
column 4 CLASSIFICATION OF INCIDENT: HAZARD ANTICIPATED/PREVENTATIVE ACTION

DOWNTIME:- 30 mins
UNDERLYING REASON:- CONTROL FAILURE PRODUCED FAULTY SIGNAL TO THE ARMS MOTOR (MAIN SHOULDER AXIS) CAUSING IT TO DRIVE ARM DOWNWARDS.
ANY FURTHER COMMENTS:- POSSIBILITY OF ACCIDENT ALTERS ATTITUDE TO WORKING CLOSE TO ROBOT WHEN POWERED ON.

TEST CASE No.2

PUMA robot fails to move when powered on.This was due to some fault in the control console.

DOWNTIME= 3 hours.
INCIDENT TIME & DATE:?
ROBOT TYPE: PUMA
ROBOT TASK:?
column 1 ACTION TAKEN: REPLACEMENT OF FAULTY EQUIPMENT
column 2 REASON FOR ACTION: MECHANICAL/ELECTRICAL PROBLEM IN ROBOT
(don't star if it is not known which)
column 3 MEANS OF INTERRUPTION: AUTOMATIC - CONTROLLED STOP
column 4 CLASSIFICATION OF INCIDENT: NO DANGER OR HARM LIKELY
DOWNTIME: 3 HRS
UNDERLYING REASON: CONTACT ON CIRCUIT BOARD(x) WAS LOOSE & RIBBON CABLE WAS PARED TO THE WIRE, CAUSING POWER TO EARTH THROUGH THE CONSOLE.

TEST CASE No. 3

ASEA robot clashes with other equipment & smashes it - as a result of erratic behaviour. EMERGENCY STOP brings it to a halt. it is out of action for one shift.

INCIDENT TIME & DATE: ?

ROBOT TYPE: ASEA

ROBOT TASK: ARC WELDING

column 1 ACTION TAKEN: UNPLANNED MAINTENANCE(FOLLOWING AN INCIDENT)

column 2 REASON FOR ACTION: ERRATIC ROBOT BEHAVIOUR (STARRED)
& ELECTRICAL PROBLEMS(ROBOT)

column 3 MEANS OF INTERRUPTION: PERSONAL ACTION - EMERGENCY STOP

column 4 CLASSIFICATION OF INCIDENT: ACCIDENT - DAMAGE TO MACHINE

DOWNTIME:- 8 HRS

UNDERLYING REASON: FAULT IN SUPPLY LINE CAUSED CONTROL ERROR

FURTHER COMMENTS: (INFORMATION ON PARTS REPLACED/REPAIRED)& WORK LAYOUT REORGANISED AND FILTER PLACED ON ELECTRICAL SUPPLY LINE.

IN EACH CASE, THE JOB CATEGORIES OF THE PEOPLE INVOLVED IN IDENTIFYING AND SORTING OUT THE INCIDENT NEED TO BE WRITTEN IN.

TEST CASE No. 1 : PROGRAMMER & MAINTENANCE ELECTRICIAN

TEST CASE No. 2 : OPERATOR & ELECTRICIAN & SERVICE ENGINEER FROM SUPPLIER

TEST CASE No. 3 : OPERATOR & MAINTENANCE TEAM.

PLEASE NOTE THAT THE BOX MARKED WEEKLY ROBOT USE HAS BEEN LEFT BLANK. THIS BOX SHOULD CONTAIN THE HOURS OF USE FOR THE PARTICULAR ROBOT THAT REQUIRES THE ACTION TO BE TAKEN.

APPENDIX C

Check List for Data Collection

CHECK LIST FOR DATA COLLECTION

Accident Statistics (Etc.)

(1) Total hours of operation

(2) Diary returns

(3) Notifiable accidents/Absenteeism before and after robot introduction.

Organisational Structure

(1) Safety Officer
  - Duties (reporting, etc.)
  - Meetings to attend
  - Communications (formal and informal)

(2) Company Promotion and Safety
  - Standardisation on safety
  - Size and influence of safety personnel function
  - Amount of communication with safety functions at factory level
  - Advice given, reporting duties of safety personnel.

Company Safety Policy

(1) Official Statement on Safety

(2) Comparison with Reality
  - Amount of 'lip-service' (particularly by safety personnel).

Safety Representatives

(1) Amount of participation in committee meetings.

(2) Understanding of problems with robots

(3) Amount of consultation with Management (on what issues)

(4) Information given by Management.

Safety Committees

(1) Amount of influence on decision of installation
(2) Issues raised at meetings
(3) Attendance
(4) Membership

Monitoring Functions

(1) Information gathered for evaluation:-
    (a) on accidents
    (b) on incidents
    (c) on robot/system failures
    (d) on maintenance work (log kept?)
        (P.T.W. system?)
    (e) on working practices
    (f) on production and productivity (overall downtime?)
(2) Systematic collection?
    - by whom
    - purposes of analysis of data
(3) Reconsider the basis of training?
    - changes in working practices as a result?
      (who decides?)
(4) Is inspection carried out to supplement statistics?

Training

For various work groups:-
(1) Operators
(2) Maintenance crews
(3) Production engineers/programmers
(4) Safety officers/representatives
(5) Supervisors
(6) Designers
(7) In particular; are they informed of hazards?
(8) Origin of training in each case
(9) Any feedback → passed on to other workers
(10) Psychological evaluation - comparisons between training and working practices actually adopted.

Accountability

(1) Amount of responsibility expected from work groups (monitoring of this commitment?)

(2) Are working practices maintained by supervision, Safety officers/representatives or by workers themselves?

System Design

(1) Scale layout

(2) Types of equipment in installation

(3) Expected performance and limitations

Physical Environment

(1) Description of working conditions

(2) Robots' tasks

Safeguards and Safety Features

(1) Details on types and number

(2) Mode of operation/interlocking

(3) Possibility of circumvention

Working Practices

(1) What should be done (in all modes of operation)

(2) What is actually done

(3) Effectiveness of both sets of practices (comparison with effects of known problems and failures)

Reason for Robot Introduction

Supplementary Questions

(1) Length of time of use of the robots

(2) Length of service of key robot personnel - chargehand, maintenance, operator

(3) Number of people employed in direct contact with robots - operators, supervision and maintenance.

APPENDIX D

The Overall Frequency Results for the Six Robot Systems

COMPANY 'A'

DATA COLLECTED FROM 5/7/83 TO 15/12/83 PRODUCTION HOURS COVERED: 629

	ROBOT NUMBER														
	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
NUMBER OF INCIDENTS	743	237	43	36	52	95	39	40	29	23	16	22	23	24	52
DOWNTIME:															
MINUTES	4065	2129	181	215	341	572	173	---	19	45	50	18	20	18	97
HOURS	94	49	11	9	2	11	4	---	---	---	---	---	---	---	---
DAYS	5	3	2	---	---	---	---	---	---	---	---	---	---	---	---
TOTAL - IN MINUTES	11745	6509	841	755	461	1232	413	---	19	45	50	18	20	18	97
MEAN DOWNTIME	30.7	42.3	64.7	29.0	10.0	18.7	16.5	---	4.8	5.6	8.3	3.0	4.0	4.5	5.4
NO. OF INCIDENTS WITH NO TIME GIVEN	357	83	30	10	10	29	14	40	25	15	10	16	18	20	34

ACTIONS TAKEN (% of incidents)

REPLACEMENT OF FAULTY EQUIP'T	3.6	5.5	---	8.3	1.9	4.2	---	5.0	---	4.3	6.3	---	---	---	1.9
ADJUSTMENT/ CLEANING	7.1	20.3	---	---	---	1.1	---	---	---	4.3	---	---	---	---	1.9
RESETTING	72.5	49.8	53.9	77.8	88.5	81.1	82.1	90.0	100	87.0	87.5	100	87.0	95.8	96.2
REPROGRAMMING	7.8	0.8	35.9	11.1	3.8	12.6	12.8	7.5	---	13.0	12.5	---	4.3	---	1.9
ROUTINE MAINTENANCE	2.0	3.4	2.6	2.8	---	1.1	2.6	---	---	---	---	---	---	---	1.9
UNPLANNED MAINTENANCE	67.4	39.7	51.3	88.9	84.6	75.8	79.5	85.0	96.6	91.3	93.8	81.8	91.3	87.5	92.3
FAULT DIAGNOSIS	5.9	8.9	5.1	2.8	---	6.3	---	5.0	3.4	8.7	6.3	13.6	4.3	4.2	---
ANY OTHER ACTION	6.6	13.5	7.7	2.8	5.8	5.3	2.6	---	---	---	---	---	---	---	---

REASONS GIVEN (% of incidents)

MECHANICAL PROBLEM WITH ROBOT	55.2	---	43.6	83.3	76.9	81.1	79.5	92.5	96.6	91.3	87.5	18.2	78.3	95.8	92.3
MECHANICAL PROBLEM WITH OTHER EQUIP'T	26.2	65.8	7.7	5.6	15.4	6.3	7.7	2.5	3.4	8.7	12.5	---	17.4	4.2	7.7

		ROBOT NUMBER													
	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
ELECTRICAL PROBLEM WITH ROBOT	3.2	---	---	5.6	1.9	7.4	---	7.5	---	---	6.3	18.2	13.0	8.3	---
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	8.3	24.5	---	---	---	2.1	---	2.5	---	---	---	---	---	4.2	---
ELECTRICAL PROBLEM WITH INTERFACE	4.7	11.0	7.7	---	1.9	2.1	2.6	2.5	---	---	---	---	---	---	---
INSPECTION	59.0	16.5	48.8	80.6	80.8	81.1	76.9	82.5	100	78.3	87.5	81.8	73.9	87.5	88.5
PROGRAMME PROBLEM	3.2	0.4	15.4	2.8	3.8	3.2	7.7	5.0	---	13.0	---	---	---	---	---
QUALITY PROBLEMS	7.5	8.0	38.5	2.8	5.8	6.3	7.7	2.5	3.4	4.3	---	---	---	---	1.9
ERRATIC ROBOT	0.5	---	2.6	2.8	---	1.1	---	2.5	---	---	---	---	---	---	---
DROPPED PART	0.5	1.7	---	---	---	---	---	---	---	---	---	---	---	---	---
THREAT OF DAMAGE TO:															
ROBOT	1.2	1.3	---	---	5.8	2.1	---	---	---	---	---	---	4.3	---	---
PERSONS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
MACHINERY	1.6	4.6	---	---	---	---	---	---	---	---	---	---	---	---	---
ANY OTHER REASON	1.3	3.0	---	2.8	---	1.1	2.6	---	---	---	---	---	---	---	---

MEANS OF INTERRUPTION (% of incidents)

E-STOP PRESSED	0.4	1.3	---	---	---	---	---	---	---	---	---	---	---	---	---
OTHER HUMAN ACTION	21.7	36.7	41.0	13.9	11.5	16.8	15.4	7.5	---	13.0	12.5	---	4.3	---	5.8
AUTOMATIC STOP	10.9	14.3	10.3	11.1	13.5	11.6	2.6	---	6.9	4.3	---	18.2	26.1	16.7	3.8
SENSOR STOP	66.9	47.3	48.7	75.0	75.0	71.6	82.1	92.5	93.1	82.6	87.5	81.8	69.6	83.3	90.4

CLASSIFICATION OF INCIDENT (% of incidents)

ACCIDENT TO PERSON	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ACCIDENT TO MACHINE	1.3	3.8	---	---	---	1.1	---	---	---	---	---	---	---	---	---
ACCIDENT TO BOTH	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ACCIDENT - NO DAMAGE	0.7	1.3	---	---	1.9	---	---	---	---	---	---	---	---	---	---
NEAR MISS	0.1	0.4	---	---	---	---	---	---	---	---	---	---	---	---	---
INCIDENT - NO DAMAGE	74.6	51.5	59.0	86.1	86.5	82.1	82.1	92.5	100	91.3	93.8	100	95.7	100	92.3
HAZARD ANTICIPATED	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
NO DAMAGE LIKELY	23.3	43.0	41.0	13.9	11.5	16.8	17.9	7.5	---	8.7	6.3	---	4.3	---	7.7

ROBOT NUMBER

PERSONS IDENTIFYING THE PROBLEM (% of incidents)

	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
FITTER	97.7	94.5	97.4	97.2	100	100	100	95.0	100	100	100	100	100	100	100
ELECTRICIAN	97.8	94.5	97.4	100	100	100	100	95.0	100	100	100	100	100	100	100
PROD. ENGINEER	0.1	0.4	---	---	---	---	---	---	---	---	---	---	---	---	---
OPERATOR	0.4	0.8	---	2.8	---	---	---	---	---	---	---	---	---	---	---
FOREMAN	75.3	74.3	79.5	80.6	78.8	69.5	76.9	77.5	65.5	56.5	87.5	86.4	82.6	79.2	75.0
CHARGEHAND	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
SERVICE ENGINEER	0.1	0.4	---	---	---	---	---	---	---	---	---	---	---	---	---
OTHER	0.8	2.5	---	---	---	---	---	---	---	---	---	---	---	---	---

PERSONS SORTING OUT THE PROBLEM (% of incidents)

	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
FITTER	99.1	97.0	100	100	100	100	100	100	100	100	100	100	100	100	100
ELECTRICIAN	99.1	97.5	100	100	100	100	100	100	100	100	100	100	100	100	100
PROD. ENGINEER	0.1	0.4	---	---	---	---	---	---	---	---	---	---	---	---	---
OPERATOR	0.1	0.4	---	---	---	---	---	---	---	---	---	---	---	---	---
FOREMAN	76.1	75.5	79.5	86.1	78.0	69.5	76.9	82.5	65.5	56.5	87.5	86.4	82.6	79.2	75.0
CHARGEHAND	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
SERVICE ENGINEER	0.7	0.8	---	---	---	---	---	---	---	---	---	---	---	---	---
OTHER	1.3	4.2	---	---	---	---	---	---	---	---	---	---	---	---	---

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
ROBOT - NO DETAIL	0.7	---	2.6	---	---	1.1	---	---	---	---	---	13.6	---	---	---
ROBOT OUT OF SYNCH'	0.4	---	---	---	---	1.1	---	---	---	---	---	---	---	---	---
STIFFNESS IN ROBOT ARM	0.3	---	---	---	1.9	---	---	---	---	4.3	---	---	---	---	---
CABLE PROBLEM	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
COMP'NT FAILURE IN ROBOT ARM	0.1	---	---	---	---	1.1	---	---	---	---	---	---	---	---	---
BLOWN FUSES	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ROBOT IN E-STOP	1.1	---	---	---	---	2.1	---	---	---	---	---	4.5	8.7	12.5	---
FAULT IN CABINET	0.1	---	---	2.8	---	---	---	---	---	---	---	---	---	---	---
ERRATIC ROBOT	0.9	---	---	---	1.9	---	2.6	10.0	---	---	6.3	---	---	---	---
FAULT IN TEACH PENDANT	0.3	---	---	2.8	---	1.1	---	---	---	---	---	---	---	---	---
POWER SUPPLY FAULT	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

	ALL CASES	NONE	NOT GIVEN	ROBOT NUMBER 1	2	3	4	5	6	7	8	9	10	11	12
PROBLEM IN TOOLS	2.2	---	---	5.6	1.9	3.2	5.1	---	---	4.3	6.3	---	8.7	---	3.8
ROBOT WON'T MOVE	0.3	---	2.6	---	---	1.1	---	---	---	---	---	---	---	---	---
ROBOT COLLISION	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
OVERHEATING HYDRAULICS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
OTHER COMPONENT FAILURE	0.8	1.3	2.6	---	1.9	1.1	---	---	---	---	---	---	---	---	---
SYSTEM FAILURE	2.3	7.2	---	---	---	---	---	---	---	---	---	---	---	---	---
SYSTEM CHECKS	2.3	5.1	2.6	---	---	3.2	---	---	---	---	---	---	---	---	---
CHECK ON PARTS	3.2	8.9	2.6	---	---	1.1	2.6	---	---	---	---	---	---	---	---
PART VARIATION	3.2	6.8	2.6	2.8	5.8	1.1	---	---	---	---	---	---	---	---	---
QUALITY PROBLEM	5.5	3.4	2.6	8.3	5.8	5.3	7.7	2.5	---	4.3	---	---	4.3	---	1.9
PROCESS PROBLEM	1.6	2.5	2.6	---	---	1.1	---	---	---	---	---	---	---	---	---
SERVICES PROBLEM	1.6	4.6	---	---	1.9	---	---	---	---	---	---	---	---	---	---
OTHER EQUIP'T PROBLEM	12.9	37.1	---	---	1.9	1.1	---	5.0	---	---	---	---	4.3	---	5.8
SAFETY FUNCTION PROBLEM	1.5	4.6	---	---	---	---	---	---	---	---	---	---	---	---	---
HUMAN ERROR	1.3	3.4	---	---	1.9	---	2.6	---	---	---	---	---	---	---	---
WELD FAILURE	51.3	---	43.6	77.8	75.0	72.6	74.4	82.5	100	87.0	87.5	81.8	73.9	87.5	88.5
SEQUENCE FAULT	6.1	15.2	7.7	---	---	3.2	5.1	---	---	---	---	---	---	---	---

TYPE OF ROBOT USED: Electric, 5- axis robot for arc-welding.

COMPANY 'B' - STATION 5

DATA COLLECTED FROM 15/8/83 TO 25/11/83 PRODUCTION HOURS COVERED: 745.5

	ALL CASES	NONE	NOT GIVEN	ROBOT NUMBER 1	2	3	4	5	6	7	8
NUMBER OF INCIDENTS	662	502	46	12	21	11	4	8	32	12	14
DOWNTIME:											
MINUTES	2954	2017	161	69	185	122	14	26	208	73	79
HOURS	45	24	4	---	8	2	---	---	7	---	---
TOTAL - IN MINUTES	5654	3457	401	69	665	242	14	26	628	73	79
MEAN DOWNTIME	15.3	12.8	21.1	8.6	35.0	26.9	3.5	5.2	33.1	10.4	8.8
NO. OF INCIDENTS WITH NO TIME GIVEN	292	230	28	4	2	2	0	3	13	5	5
ACTIONS TAKEN (% of incidents)											
REPLACEMENT OF FAULTY EQUIP'T	7.9	5.8	10.9	---	28.6	9.1	---	---	15.6	25.0	21.4
ADJUSTMENT/ CLEANING	29.3	27.7	47.8	25.0	28.6	9.1	25.0	50.0	13.8	16.7	14.3
RESETTING	42.0	43.6	28.3	58.3	14.3	54.5	75.0	37.5	28.1	58.3	57.1
REPROGRAMMING	4.2	---	13.0	16.7	23.8	18.2	25.0	12.5	18.8	25.0	14.3
ROUTINE MAINTENANCE	2.7	2.8	6.5	---	---	---	---	---	---	8.3	---
UNPLANNED MAINTENANCE	19.2	18.5	10.9	8.3	33.3	36.4	---	12.5	28.1	33.3	21.4
FAULT DIAGNOSIS	2.9	2.2	4.3	8.3	19.0	---	---	---	3.1	---	---
ANY OTHER ACTION	20.8	26.5	4.3	8.3	4.8	---	---	---	3.1	---	---
REASONS GIVEN (% of incidents)											
MECHANICAL PROBLEM WITH ROBOT	16.8	---	58.7	75.0	61.9	100	100	50.0	65.6	83.3	85.7
MECHANICAL PROBLEM WITH OTHER EQUIP'T	51.2	66.1	4.3	8.3	4.8	---	---	---	3.1	16.7	---
ELECTRICAL PROBLEM WITH ROBOT	10.4	---	30.4	66.7	28.6	90.9	75.0	37.5	28.1	41.7	71.4

				ROBOT NUMBER							
	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	36.3	47.2	---	8.3	4.8	---	---	---	---	8.3	---
ELECTRICAL PROBLEM WITH INTERFACE	4.5	5.6	2.2	---	---	9.1	---	---	---	---	---
INSPECTION	1.5	1.2	4.3	---	4.8	---	---	---	3.1	---	---
PROGRAMME PROBLEM	1.4	---	4.3	8.3	14.3	---	---	---	6.3	---	7.1
QUALITY PROBLEMS	12.5	4.2	58.7	16.7	33.3	9.1	25.0	50.0	46.9	8.3	28.6
ERRATIC ROBOT	---	---	---	---	---	---	---	---	---	---	---
DROPPED PART	0.2	0.2	---	---	---	---	---	---	---	---	---
THREAT OF DAMAGE TO:											
ROBOT	0.2	---	---	---	---	---	---	---	---	8.3	---
PERSONS	---	---	---	---	---	---	---	---	---	---	---
MACHINERY	0.8	0.8	---	---	---	---	---	---	3.1	---	---
ANY OTHER REASON	19.9	26.3	---	---	---	---	---	---	---	---	---

MEANS OF INTERRUPTION (% of incidents)

E-STOP PRESSED	---	---	---	---	---	---	---	---	---	---	---
OTHER HUMAN ACTION	15.3	10.2	54.3	16.7	33.3	18.2	50.0	---	28.1	8.3	14.3
AUTOMATIC STOP	9.7	2.0	19.6	66.7	19.0	72.7	50.0	37.5	21.9	41.7	57.1
SENSOR STOP	74.5	87.1	26.1	16.7	47.6	9.1	---	62.5	50.0	50.0	28.6

CLASSIFICATION OF INCIDENT (% of incidents)

ACCIDENT TO PERSON	---	---	---	---	---	---	---	---	---	---	---
ACCIDENT TO MACHINE	1.1	0.6	---	---	4.8	---	---	---	9.4	---	---
ACCIDENT TO BOTH	---	---	---	---	---	---	---	---	---	---	---
ACCIDENT - NO DAMAGE	0.5	0.6	---	---	---	---	---	---	---	---	---
NEAR MISS	---	---	---	---	---	---	---	---	---	---	---
INCIDENT - NO DAMAGE	63.0	62.0	45.7	83.3	57.1	81.8	50.0	100	62.5	91.7	92.9
HAZARD ANTICIPATED	0.6	0.4	---	---	4.8	---	---	---	3.1	---	---
NO DAMAGE LIKELY	34.4	35.9	54.3	16.7	33.3	18.2	50.0	---	25.0	8.3	7.1

	ALL CASES	NONE	NOT GIVEN	ROBOT NUMBER 1	2	3	4	5	6	7	8
PERSONS IDENTIFYING THE PROBLEM (% of incidents)											
FITTER	2.6	2.2	4.3	---	---	---	---	---	9.4	8.3	---
ELECTRICIAN	89.4	91.4	60.9	100	90.5	90.9	100	100	87.5	91.7	92.9
PROD. ENGINEER	2.6	3.4	---	---	---	---	---	---	---	---	---
OPERATOR	0.2	0.2	---	---	---	---	---	---	---	---	---
FOREMAN	1.2	1.0	4.3	---	---	---	---	---	3.1	---	---
CHARGEHAND	---	---	---	---	---	---	---	---	---	---	---
SERVICE ENGINEER	---	---	---	---	---	---	---	---	---	---	---
OTHER	3.9	0.8	26.1	---	14.3	9.1	25.0	---	9.4	---	7.1
PERSONS SORTING OUT THE PROBLEM (% of incidents)											
FITTER	40.6	41.2	32.6	16.7	57.1	36.4	25.0	12.5	50.0	50.0	35.7
ELECTRICIAN	93.5	93.4	95.7	100	95.2	100	75.0	87.5	87.5	100	92.9
PROD. ENGINEER	0.3	0.4	---	---	---	---	---	---	---	---	---
OPERATOR	---	---	---	---	---	---	---	---	---	---	---
FOREMAN	---	---	---	---	---	---	---	---	---	---	---
CHARGEHAND	---	---	---	---	---	---	---	---	---	---	---
SERVICE ENGINEER	---	---	---	---	---	---	---	---	---	---	---
OTHER	2.3	2.2	2.2	---	---	9.1	---	---	---	8.3	7.1
UNDERLYING REASON FOR INCIDENT (% of incidents)											
ROBOT - NO DETAIL	2.0	---	8.7	16.7	14.3	18.2	---	---	3.1	8.3	---
ROBOT OUT OF SYNCH'	0.2	---	---	---	---	---	---	---	3.1	---	---
STIFFNESS IN ROBOT ARM	---	---	---	---	---	---	---	---	---	---	---
CABLE PROBLEM	0.9	---	---	---	---	18.2	---	---	---	8.3	21.4
COMP'NT FAILURE IN ROBOT ARM	0.5	---	---	---	9.5	9.1	---	---	---	---	---
BLOWN FUSES	---	---	---	---	---	---	---	---	---	---	---
ROBOT IN E-STOP	5.3	---	8.7	50.0	4.8	45.5	50.0	37.5	18.8	25.0	35.7
FAULT IN CABINET	0.2	---	---	8.3	---	---	---	---	---	---	---
ERRATIC ROBOT	0.9	---	4.3	---	9.5	---	---	---	6.3	---	---
FAULT IN TEACH PENDANT	---	---	---	---	---	---	---	---	---	---	---

				ROBOT NUMBER							
	ALL CASES	NONE	NOT GIVEN	1	2	3	4	5	6	7	8
POWER SUPPLY FAULT	---	---	---	---	---	---	---	---	---	---	---
PROBLEM IN TOOLS	4.1	---	15.2	---	28.6	---	25.0	12.5	25.0	25.0	7.1
ROBOT WON'T MOVE	0.3	---	---	---	---	---	---	---	---	8.3	7.1
ROBOT COLLISION	---	---	---	---	---	---	---	---	---	---	---
OVERHEATING HYDRAULICS	---	---	---	---	---	---	---	---	---	---	---
OTHER COMPONENT FAILURE	2.1	2.8	---	---	---	---	---	---	---	---	---
SYSTEM FAILURE	1.5	2.0	---	---	---	---	---	---	---	---	---
SYSTEM CHECKS	---	---	---	---	---	---	---	---	---	---	---
CHECK ON PARTS	---	---	---	---	---	---	---	---	---	---	---
PART VARIATION	6.2	8.0	---	---	---	---	---	---	---	8.3	---
QUALITY PROBLEM	6.5	4.0	30.4	8.3	14.3	9.1	---	---	9.4	---	7.1
PROCESS PROBLEM	20.7	26.7	2.2	---	4.8	---	25.0	---	---	---	---
SERVICES PROBLEM	0.6	0.8	---	---	---	---	---	---	---	---	---
OTHER EQUIP'T PROBLEM	39.4	50.2	8.7	8.3	4.8	---	---	---	6.3	8.3	---
SAFETY FUNCTION PROBLEM	---	---	---	---	---	---	---	---	---	---	---
HUMAN ERROR	0.8	0.8	2.2	---	---	---	---	---	---	---	---
WELD FAILURE	4.4	---	19.6	8.3	9.5	---	---	50.0	28.1	8.3	21.4
SEQUENCE FAULT	3.0	4.0	---	---	---	---	---	---	---	---	---

TYPE OF ROBOT USED: Electric, floor mounted, 5-axes robot for spot-welding

COMPANY 'B' STATION 6

DATA COLLECTED FROM 15/8/83 TO 25/11/83.

Production hours covered: 1077

ROBOT NUMBERS 171 - 261

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
NUMBER OF INCIDENTS	1553	734	30	20	29	70	89	30	14	25	17	64	43
DOWNTIME:													
MINUTES	8390	3217	329	73	316	326	322	109	97	256	80	597	506
HOURS	59	30	1	----	7	2	1	----	----	----	----	4	7
TOTAL - IN MINUTES	11930	5017	389	73	736	446	382	109	97	256	80	837	926
MEAN DOWNTIME	8.8	7.9	16.2	3.7	29.4	7.0	4.3	4.0	8.1	12.8	5.3	15.0	24.4
NO. OF INCIDENTS WITH NO TIME GIVEN	203	101	6	----	4	6	1	3	2	5	2	8	5
ACTIONS TAKEN (% of incidents)													
REPLACEMENT OF FAULTY EQUIP'T	17.0	12.5	33.3	----	20.7	21.4	7.9	16.7	----	20.0	29.4	28.1	46.5
ADJUSTMENT/ CLEANING	19.3	18.0	23.3	10.0	27.6	22.9	2.2	10.0	7.1	16.0	11.8	26.6	18.6
RESETTING	56.7	59.3	26.7	85.0	48.3	61.4	93.3	73.3	71.4	52.0	52.9	39.1	32.6
REPROGRAMMING	6.0	0.1	13.3	5.0	27.6	4.3	12.4	6.7	28.6	8.0	5.9	20.3	9.3
ROUTINE MAINTENANCE	4.8	7.6	16.7	----	----	2.9	----	3.3	----	4.0	----	1.6	----
UNPLANNED MAINTENANCE	29.2	29.7	26.7	25.0	20.7	25.7	5.6	16.7	7.1	72.0	52.9	26.6	39.5
FAULT DIAGNOSIS	1.4	0.8	----	----	6.9	----	1.1	----	----	----	5.9	3.1	9.3
ANY OTHER ACTION	1.5	2.3	----	5.0	----	----	----	----	----	----	----	1.6	2.3
REASONS GIVEN (% of incidents)													
MECHANICAL PROBLEM WITH ROBOT	44.4	----	73.3	95.0	79.3	84.3	97.8	93.3	71.4	84.0	82.4	65.6	93.0
MECHANICAL PROBLEM WITH OTHER EQUIP'T	43.3	87.2	20.0	10.0	3.4	----	2.2	----	----	8.0	5.9	4.7	4.7
ELECTRICAL PROBLEM WITH ROBOT	29.6	----	40.0	85.0	55.2	58.6	95.5	76.7	71.4	52.0	58.8	50.0	58.1

ROBOT NUMBERS 171 - 261

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	31.3	65.3	3.3	----	----	----	----	----	----	----	----	3.1	----
ELECTRICAL PROBLEM WITH INTERFACE	2.5	4.1	3.3	----	----	----	3.4	----	----	----	----	1.6	----
INSPECTION	1.0	1.6	----	----	----	1.4	----	----	7.1	----	----	----	----
PROGRAMME PROBLEM	0.5	----	----	----	----	----	----	----	14.3	----	----	3.1	----
QUALITY PROBLEMS	10.3	7.5	26.7	----	31.0	12.9	1.1	6.7	----	----	11.8	26.6	14.0
ERRATIC ROBOT	3.0	----	10.0	----	3.4	1.4	----	----	----	8.0	5.9	4.7	7.0
DROPPED PART	0.1	0.1	----	----	----	----	----	----	----	----	----	----	----
THREAT OF DAMAGE TO:													
ROBOT	0.4	0.1	3.3	----	----	----	----	----	----	----	----	----	2.3
PERSONS	----	----	----	----	----	----	----	----	----	----	----	----	----
MACHINERY	0.9	0.7	3.3	----	----	1.4	----	----	----	4.0	----	1.6	----
ANY OTHER REASON	0.7	1.4	----	----	----	----	----	----	----	4.0	----	----	----
MEANS OF INTERRUPTION (% of incidents)													
E-STOP PRESSED	0.1	----	----	----	----	----	----	----	----	----	----	----	2.3
OTHER HUMAN ACTION	14.7	13.6	40.0	----	31.0	20.0	1.1	10.0	7.1	8.0	5.9	20.3	14.0
AUTOMATIC STOP	32.5	2.9	36.7	95.0	58.6	57.1	94.4	76.7	78.6	80.0	64.7	48.4	55.8
SENSOR STOP	52.5	83.4	20.0	5.0	10.3	22.9	4.5	13.3	7.1	12.0	29.4	31.3	27.9
CLASSIFICATION OF INCIDENT (% of incidents)													
ACCIDENT TO PERSON	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT TO MACHINE	6.1	6.3	13.3	5.0	10.3	1.4	1.1	----	7.1	32.0	11.8	7.8	7.0
ACCIDENT TO BOTH	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	1.5	----	6.7	5.0	----	----	----	3.3	----	4.0	----	----	----
NEAR MISS	0.2	----	----	----	----	----	----	----	----	----	----	1.6	----
INCIDENT - NO DAMAGE	72.1	72.3	33.3	85.0	55.2	80.0	95.5	83.3	57.1	56.0	76.8	62.5	62.8
HAZARD ANTICIPATED	0.3	0.1	----	----	3.4	1.4	----	----	----	----	5.9	----	2.3
NO DAMAGE LIKELY	19.6	21.1	43.3	5.0	31.0	17.1	3.4	13.3	28.6	8.0	5.9	28.1	27.9

ROBOT NUMBERS 171 - 261

PERSONS IDENTIFYING THE PROBLEM (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
FITTER	1.3	1.4	6.7	----	3.4	1.4	----	3.3	----	4.0	----	1.6	----
ELECTRICIAN	92.2	90.7	63.3	100	86.2	95.7	100	96.7	85.7	96.0	100	95.3	93.0
PROD. ENGINEER	0.3	0.1	----	----	----	----	----	----	----	4.0	----	1.6	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	1.7	1.5	10.0	----	10.3	1.4	----	6.7	----	4.0	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	4.2	3.3	20.0	----	10.3	4.3	----	3.3	----	----	----	6.3	7.0

PERSONS SORTING OUT THE PROBLEM (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
FITTER	51.3	54.2	63.3	35.0	48.3	47.1	12.4	33.3	21.4	72.0	82.4	46.9	69.8
ELECTRICIAN	95.8	94.1	90.0	100	96.6	95.7	100	96.7	85.7	100	100	93.8	95.3
PROD. ENGINEER	0.3	0.3	----	----	----	1.4	----	----	7.1	----	----	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	----	----	----	----	----	----	----	----	----	----	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	0.1	0.3	----	----	----	----	----	----	----	----	----	----	----
OTHER	11.9	12.0	13.3	5.0	24.1	7.1	2.2	3.3	----	36.0	5.9	12.8	18.6

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
ROBOT - NO DETAIL	1.5	----	----	5.0	3.4	5.7	5.6	3.3	21.4	----	----	3.1	----
ROBOT OUT OF SYNCH'	4.4	----	----	5.0	13.8	1.4	13.5	6.7	7.1	20.0	11.8	1.6	11.6
STIFFNESS IN ROBOT ARM	0.5	----	----	----	----	----	----	----	----	8.0	----	----	2.3
CABLE PROBLEM	0.8	----	3.4	----	----	----	----	----	----	8.0	----	1.6	7.0
COMP'NT FAILURE IN ROBOT ARM	1.2	----	----	----	3.4	2.9	3.4	3.3	----	4.0	5.9	1.6	4.7
BLOWN FUSES	0.7	----	----	----	----	----	----	10.0	----	----	----	6.3	----
ROBOT IN E-STOP	14.5	----	10.0	70.0	27.6	42.9	70.8	43.3	14.3	12.0	17.6	21.9	11.6
FAULT IN CABINET	0.8	----	----	----	3.4	1.4	1.1	3.3	----	----	11.8	1.6	4.7
ERRATIC ROBOT	2.3	----	13.3	----	3.4	1.4	----	----	----	----	----	14.1	9.3
FAULT IN TEACH PENDANT	0.1	----	----	----	----	----	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----

	ROBOT NUMBERS 171 - 261												
	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
PROBLEM IN TOOLS	10.6	----	13.3	10.0	13.8	15.7	1.1	16.7	----	36.0	23.5	20.3	25.6
ROBOT WON'T MOVE	0.6	----	----	----	----	----	1.1	----	42.9	----	----	1.6	2.3
ROBOT COLLISION	2.7	----	13.3	5.0	3.4	1.4	----	----	----	8.0	5.9	----	2.3
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER COMPONENT FAILURE	2.6	5.3	3.3	----	----	----	----	----	----	----	----	----	2.3
SYSTEM FAILURE	1.2	2.5	3.3	----	----	----	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----	----	----	----	----	----	----
PART VARIATION	9.0	14.9	----	5.0	3.4	1.4	1.1	3.3	7.1	4.0	17.6	4.7	----
QUALITY PROBLEM	6.2	6.4	20.0	----	17.2	8.6	----	3.3	----	----	----	9.4	4.7
PROCESS PROBLEM	1.4	2.5	3.3	----	----	----	----	----	----	----	----	3.1	----
SERVICES PROBLEM	1.0	1.4	3.3	----	----	----	----	----	----	----	----	----	----
OTHER EQUIP'T PROBLEM	30.5	63.4	----	----	6.9	----	2.2	----	----	----	5.9	1.6	----
SAFETY FUNCTION PROBLEM	0.2	0.4	----	----	----	----	----	----	----	----	----	----	----
HUMAN ERROR	0.6	0.8	3.3	----	----	1.4	----	----	7.1	----	----	----	----
WELD FAILURE	4.8	----	6.7	----	----	15.7	----	6.7	----	----	----	1.6	11.6
SEQUENCE FAULT	1.1	1.8	----	----	----	----	----	----	----	----	----	6.3	----

TYPE OF ROBOT USED: All numbers ending with __3 - electric, floor-mounted, 5 axes robot for spot-welding;
Number 211 - electric, floor-mounted 5 axes robot for adhesive bonding;
All other numbers - electric, gantry-mounted, 6 axes robot for spot-welding.

COMPANY 'B' STATION 6

DATA COLLECTED FROM 15/8/83 TO 25/11/83.

Production hours covered: 1077

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
NUMBER OF INCIDENTS	26	45	20	31	30	14	20	24	19	42	41	29	47
DOWNTIME:													
MINUTES	179	228	65	134	154	66	81	108	193	285	275	78	316
HOURS	1	----	----	----	----	----	----	----	----	4	1	----	1
TOTAL - IN MINUTES	239	228	65	134	154	66	81	108	193	525	335	78	376
MEAN DOWNTIME	10.9	6.5	4.3	5.0	5.7	5.5	4.8	5.1	11.4	14.2	10.8	3.1	9.0
NO. OF INCIDENTS WITH NO TIME GIVEN	4	10	5	4	3	2	3	3	2	5	10	4	5
ACTIONS TAKEN (% of incidents)													
REPLACEMENT OF FAULTY EQUIP'T	19.2	26.7	10.0	16.1	13.3	----	50.0	12.5	36.8	26.2	29.3	6.9	17.0
ADJUSTMENT/ CLEANING	38.5	26.7	45.0	16.1	23.3	42.9	35.0	50.0	5.3	26.2	12.2	10.3	21.3
RESETTING	30.8	33.3	60.0	67.7	66.7	50.0	25.0	58.3	26.3	38.1	36.6	86.2	53.2
REPROGRAMMING	7.7	4.4	5.0	19.4	6.7	21.4	----	4.2	10.5	14.3	----	13.8	21.3
ROUTINE MAINTENANCE	3.8	4.4	----	3.2	----	----	----	4.2	----	4.8	4.9	----	----
UNPLANNED MAINTENANCE	53.8	35.6	20.0	22.6	13.3	14.3	45.0	25.0	63.2	33.3	61.0	13.8	21.3
FAULT DIAGNOSIS	----	----	----	6.5	----	----	----	----	----	----	4.9	3.4	2.1
ANY OTHER ACTION	3.8	----	----	----	----	----	----	4.2	5.3	----	----	----	----
REASONS GIVEN (% of incidents)													
MECHANICAL PROBLEM WITH ROBOT	84.6	86.7	85.0	83.9	83.3	85.7	85.0	87.5	89.5	83.3	80.5	86.2	74.5
MECHANICAL PROBLEM WITH OTHER EQUIP'T	3.8	6.7	----	----	----	----	----	----	5.3	----	19.5	3.4	----

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
ELECTRICAL PROBLEM WITH ROBOT	61.5	42.2	65.0	64.5	66.7	50.0	30.0	41.7	26.3	47.6	26.8	51.7	29.8
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	----	2.2	----	----	----	----	----	----	5.3	----	2.4	3.4	----
ELECTRICAL PROBLEM WITH INTERFACE	----	----	5.0	3.2	3.3	----	----	----	----	----	2.4	----	----
INSPECTION	3.8	----	----	----	----	----	----	----	----	----	----	----	----
PROGRAMME PROBLEM	----	----	----	----	----	----	----	----	----	----	----	----	6.4
QUALITY PROBLEMS	15.4	11.1	15.0	12.9	13.3	14.3	25.0	8.3	5.3	23.8	7.3	----	17.0
ERRATIC ROBOT	----	----	----	----	3.3	----	----	8.3	15.8	2.4	----	37.9	29.8
DROPPED PART	----	----	----	----	----	----	----	----	----	----	----	----	----
THREAT OF DAMAGE TO:													
ROBOT	3.8	----	----	6.5	----	----	----	----	----	----	----	----	----
PERSONS	----	----	----	----	----	----	----	----	----	----	----	----	----
MACHINERY	11.5	----	----	----	----	----	----	----	5.3	----	----	----	2.1
ANY OTHER REASON	----	----	----	----	----	----	----	----	----	----	----	----	----

<u>MEANS OF INTERRUPTION</u> (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
E-STOP PRESSED	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER HUMAN ACTION	26.9	11.1	5.0	19.4	26.7	21.4	20.0	8.3	15.8	23.8	14.6	----	25.5
AUTOMATIC STOP	34.6	44.4	40.0	58.1	63.3	42.9	30.0	45.8	42.1	40.5	41.5	93.1	55.5
SENSOR STOP	38.5	44.4	55.0	22.6	10.0	35.7	50.0	45.8	42.1	35.7	43.9	6.9	19.1

<u>CLASSIFICATION OF INCIDENT</u> (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
ACCIDENT TO PERSON	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT TO MACHINE	23.1	----	----	3.2	----	----	----	----	26.3	7.1	2.4	3.4	6.4
ACCIDENT TO BOTH	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	----	----	----	----	----	----	----	8.3	10.5	4.8	----	20.7	12.8
NEAR MISS	----	----	----	3.2	3.3	----	----	----	----	----	----	----	----
INCIDENT - NO DAMAGE	53.8	84.4	75.0	71.0	80.0	71.4	70.0	83.3	52.6	64.3	87.8	72.4	57.4
HAZARD ANTICIPATED	----	----	----	----	----	----	----	----	----	----	----	----	----
NO DAMAGE LIKELY	23.1	15.6	25.0	22.6	16.7	28.6	30.0	8.3	10.5	23.8	9.8	3.4	23.4

ROBOT NUMBERS 262 - 332

PERSONS IDENTIFYING THE PROBLEM (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
FITTER	----	----	----	3.2	----	----	----	----	5.3	----	2.4	----	2.1
ELECTRICIAN	96.2	93.3	100	93.5	93.3	92.9	90.0	91.7	94.7	88.1	92.7	100	93.6
PROD. ENGINEER	3.8	----	----	----	----	----	----	----	----	----	4.9	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	3.8	2.2	----	----	----	----	----	4.2	----	----	2.4	----	2.1
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	3.8	6.7	----	6.5	6.7	7.1	10.0	4.2	----	11.9	2.4	----	4.3

PERSONS SORTING OUT THE PROBLEM (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
FITTER	80.8	60.0	50.0	48.4	23.3	35.7	75.0	79.2	78.9	52.4	73.2	24.1	38.3
ELECTRICIAN	100	100	95.0	100	100	100	85.0	100	100	97.6	95.1	100	97.9
PROD. ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	----	----	----	----	----	----	----	----	----	----	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	11.5	17.8	20.0	12.9	----	7.1	15.0	12.5	36.8	7.1	31.7	----	4.3

UNDERLYING REASON FOR INCIDENT (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
ROBOT - NO DETAIL	3.8	2.2	5.0	----	----	----	----	----	----	----	2.4	3.4	4.3
ROBOT OUT OF SYNCH'	7.7	2.2	10.0	16.1	3.3	7.1	5.0	8.3	----	16.7	4.9	24.1	8.3
STIFFNESS IN ROBOT ARM	15.4	----	----	----	----	----	----	----	----	----	----	----	2.1
CABLE PROBLEM	----	2.2	----	3.2	----	----	----	4.2	5.3	----	4.9	----	----
COMP'NT FAILURE IN ROBOT ARM	3.8	2.2	5.0	----	----	----	----	----	5.3	2.4	2.4	3.4	----
BLOWN FUSES	----	----	----	----	----	----	5.0	----	5.3	2.4	----	----	2.1
ROBOT IN E-STOP	19.2	17.8	25.0	19.4	56.7	35.7	10.0	8.3	5.3	9.5	9.8	20.7	4.3
FAULT IN CABINET	----	----	----	----	3.3	----	----	----	----	----	----	3.4	2.1
ERRATIC ROBOT	7.7	----	----	6.5	3.3	----	----	----	----	9.5	2.4	----	12.8
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----	----	5.3	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
PROBLEM IN TOOLS	34.6	35.6	10.0	35.5	3.3	14.3	40.0	25.0	52.6	21.4	48.8	3.4	12.8
ROBOT WON'T MOVE	----	2.2	----	----	----	----	----	----	----	----	----	----	----
ROBOT COLLISION	----	----	----	----	----	----	----	8.3	15.8	4.8	----	37.9	27.7
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER COMPONENT FAILURE	----	----	----	----	----	----	----	----	----	----	----	----	----
SYSTEM FAILURE	----	----	----	----	----	----	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----	----	----	----	----	----	----
PART VARIATION	7.7	----	5.0	12.9	----	----	10.0	25.0	----	----	4.9	----	2.1
QUALITY PROBLEM	----	6.7	10.0	3.2	20.0	14.3	10.0	----	----	7.1	----	----	10.6
PROCESS PROBLEM	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICES PROBLEM	----	----	----	----	----	7.1	5.0	----	----	----	7.3	----	----
OTHER EQUIP'T PROBLEM	----	2.2	----	----	----	----	----	4.2	----	----	----	----	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----	----	----	----	----	----	----
HUMAN ERROR	----	----	----	----	----	----	----	----	----	----	----	----	----
WELD FAILURE	----	26.7	25.0	----	10.0	21.4	15.0	16.7	5.3	26.2	12.2	3.4	10.6
SEQUENCE FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----

TYPE OF ROBOT USED: All numbers ending with __3 - electric, floor-mounted, 5 axes robot for spot-welding;
Number 211 - electric, floor-mounted 5 axes robot for adhesive bonding;
All other numbers - electric, gantry-mounted, 6 axes robot for spot-welding.

COMPANY 'B' STATION 7

DATA COLLECTED FROM 16/8/83 TO 25/11/83.

Production hours covered: 974.5

ROBOT NUMBERS 171 - 261

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
NUMBER OF INCIDENTS	1820	883	34	34	53	55	18	35	31	7	22	46	24
DOWNTIME:													
MINUTES	8371	3464	176	86	421	260	146	152	211	72	120	400	41
HOURS	43	19	----	----	3	2	2	1	1	----	1	2	----
TOTAL - IN MINUTES	10951	4604	176	86	601	380	266	212	271	72	180	520	41
MEAN DOWNTIME	7.2	6.0	7.3	3.1	14.7	8.3	19.0	7.6	10.4	10.3	10.0	13.7	2.6
NO. OF INCIDENTS WITH NO TIME GIVEN	301	115	6	6	12	9	4	7	5	----	4	8	8

ACTIONS TAKEN (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
REPLACEMENT OF FAULTY EQUIP'T	13.7	9.2	20.6	5.9	22.6	16.4	11.1	11.4	----	42.9	36.4	34.8	16.7
ADJUSTMENT/ CLEANING	25.7	27.3	11.8	17.6	24.5	5.5	22.2	42.9	12.9	14.3	27.3	4.3	54.2
RESETTING	58.6	68.6	44.1	76.5	39.6	69.1	50.0	42.9	54.8	42.9	31.8	23.9	37.5
REPROGRAMMING	4.9	0.2	5.9	2.9	15.1	12.7	11.1	2.9	19.4	----	----	8.7	----
ROUTINE MAINTENANCE	2.5	4.5	14.7	----	----	----	----	----	----	----	----	----	----
UNPLANNED MAINTENANCE	21.4	14.7	26.5	11.8	50.9	20.0	27.8	17.1	12.9	42.9	45.5	67.4	16.7
FAULT DIAGNOSIS	2.0	1.9	----	----	1.9	1.8	----	2.9	----	----	9.1	----	----
ANY OTHER ACTION	1.5	2.3	2.9	----	----	1.8	----	----	6.5	----	----	----	----

REASONS GIVEN (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
MECHANICAL PROBLEM WITH ROBOT	42.6	----	82.4	91.2	79.2	85.5	94.4	74.3	71.0	100	81.8	82.6	70.8
MECHANICAL PROBLEM WITH OTHER EQUIP'T	42.5	84.1	2.9	----	7.5	----	----	2.9	9.7	----	4.5	10.9	8.3
ELECTRICAL PROBLEM WITH ROBOT	27.4	----	38.2	79.4	39.6	70.9	61.1	40.0	54.8	85.7	59.1	26.1	37.5

			ROBOT NUMBERS 171 - 261										
	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	30.9	62.8	2.9	----	----	----	----	----	9.7	----	----	----	4.2
ELECTRICAL PROBLEM WITH INTERFACE	5.2	10.0	4.7	----	----	----	----	----	----	----	----	----	----
INSPECTION	0.5	0.7	----	----	----	3.6	----	----	----	----	----	----	----
PROGRAMME PROBLEM	2.2	----	2.9	----	13.2	7.3	5.6	2.9	9.7	----	4.5	8.7	----
QUALITY PROBLEMS	16.3	6.3	32.4	8.8	18.9	12.7	5.6	45.7	16.1	----	22.7	15.2	54.2
ERRATIC ROBOT	0.7	----	8.8	5.9	1.9	----	----	----	----	----	----	2.2	----
DROPPED PART	----	----	----	----	----	----	----	----	----	----	----	----	----
THREAT OF DAMAGE TO:													
ROBOT	0.5	----	----	----	1.9	3.6	----	----	----	----	4.5	2.2	----
PERSONS	----	----	----	----	----	----	----	----	----	----	----	----	----
MACHINERY	1.0	0.2	2.9	----	1.9	5.5	----	14.3	----	----	4.5	2.2	----
ANY OTHER REASON	0.9	1.4	2.9	----	----	1.8	----	----	----	----	----	----	----

MEANS OF INTERRUPTION (% of incidents)

E-STOP PRESSED	0.2	0.3	----	----	----	----	----	----	----	----	----	----	----
OTHER HUMAN ACTION	10.7	7.7	26.5	2.9	26.4	14.5	16.7	8.6	22.6	----	9.1	15.2	4.2
AUTOMATIC STOP	28.3	7.8	29.4	76.5	39.6	69.1	55.6	34.3	48.4	71.4	54.5	15.2	29.2
SENSOR STOP	60.8	84.1	44.1	20.6	34.0	16.4	27.8	57.1	29.0	28.6	36.4	69.6	66.7

CLASSIFICATION OF INCIDENT (% of incidents)

ACCIDENT TO PERSON	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT TO MACHINE	4.8	6.3	5.9	----	3.8	10.9	----	2.9	----	----	----	8.7	----
ACCIDENT TO BOTH	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	0.7	0.3	2.9	----	1.9	----	----	5.7	----	----	4.5	2.2	----
NEAR MISS	----	----	----	----	----	----	----	----	----	----	----	----	----
INCIDENT - NO DAMAGE	81.5	81.9	64.7	97.1	69.8	78.2	83.3	80.0	67.7	100	86.4	73.9	91.7
HAZARD ANTICIPATED	1.0	0.5	----	----	5.7	----	5.6	----	----	----	----	2.2	----
NO DAMAGE LIKELY	11.9	11.0	26.5	2.9	18.9	10.9	11.1	11.4	32.3	----	9.1	13.0	8.3

PERSONS IDENTIFYING THE PROBLEM (% of incidents)

FITTER	0.8	0.7	----	2.9	----	----	----	2.9	----	----	----	----	----
ELECTRICIAN	95.2	94.1	79.4	100	96.2	96.4	100	97.1	83.9	100	100	93.5	100
PROD. ENGINEER	0.2	0.3	----	----	----	----	----	----	----	----	----	2.2	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----

ROBOT NUMBERS 171 - 261

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
FOREMAN	0.2	----	----	----	1.9	----	----	2.9	3.2	----	----	2.2	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	1.8	1.1	2.9	----	1.9	3.6	----	----	12.9	----	----	2.2	----

PERSONS SORTING OUT THE PROBLEM (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
FITTER	45.0	48.4	52.9	14.7	62.3	27.3	61.1	42.9	25.8	71.4	54.5	69.6	29.2
ELECTRICIAN	98.1	97.1	100	100	100	100	100	100	96.8	100	100	100	100
PROD. ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	----	----	----	----	----	----	----	----	----	----	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	2.3	2.6	2.9	----	1.9	----	----	----	----	----	----	10.9	----

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
ROBOT - NO DETAIL	1.9	----	2.9	----	1.9	10.9	5.6	2.9	38.7	----	----	----	----
ROBOT OUT OF SYNCH'	5.2	----	5.9	44.1	13.2	1.8	27.8	8.6	----	28.6	4.5	----	16.7
STIFFNESS IN ROBOT ARM	0.2	----	----	----	1.9	----	----	----	----	----	----	----	----
CABLE PROBLEM	1.2	----	----	----	3.8	----	5.6	----	----	14.3	18.2	4.3	----
COMP'NT FAILURE IN ROBOT ARM	0.5	----	----	----	----	----	----	2.9	----	----	9.1	----	----
BLOWN FUSES	0.3	----	----	2.9	----	3.6	----	----	----	----	----	----	----
ROBOT IN E-STOP	11.9	----	8.8	26.5	9.4	49.1	5.6	8.6	6.5	14.3	18.2	6.5	8.3
FAULT IN CABINET	0.5	----	----	----	1.9	----	----	----	6.5	14.3	----	----	----
ERRATIC ROBOT	1.5	----	5.9	2.9	3.8	5.5	5.6	----	6.5	----	4.5	8.7	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----
PROBLEM IN TOOLS	13.5	----	32.4	14.7	45.3	14.5	33.3	25.7	22.6	28.6	18.2	67.4	4.2
ROBOT WON'T MOVE	0.5	----	----	----	----	----	5.6	2.9	6.5	----	----	----	4.2
ROBOT COLLISION	1.0	----	5.9	----	----	1.8	----	14.3	----	----	----	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----	----	----	----	----	----	----

ROBOT NUMBERS 171 - 261

	ALL CASES	NONE	NOT GIVEN	171	172	173	181	182	211	251	252	253	261
OTHER COMPONENT FAILURE	2.0	3.5	----	----	----	----	----	----	----	----	----	----	4.2
SYSTEM FAILURE	4.5	9.1	5.9	----	----	----	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----	----	----	----	----	----	----
PART VARIATION	10.2	19.1	----	----	----	----	5.6	2.9	----	----	----	----	4.2
QUALITY PROBLEM	4.4	5.4	11.8	----	3.8	3.6	----	----	9.7	----	----	----	----
PROCESS PROBLEM	1.3	1.1	11.8	----	3.8	1.8	----	2.9	3.2	----	----	----	----
SERVICES PROBLEM	1.1	0.7	5.9	----	----	----	5.6	----	----	----	4.5	8.7	4.2
OTHER EQUIP'T PROBLEM	29.1	58.9	----	----	5.7	----	----	----	----	----	----	----	----
SAFETY FUNCTION PROBLEM	0.1	0.2	----	----	----	----	----	----	----	----	----	----	----
HUMAN ERROR	0.5	1.1	----	----	----	----	----	----	----	----	----	----	----
WELD FAILURE	8.0	----	2.9	8.8	5.7	5.5	----	28.6	----	----	22.7	4.3	54.2
SEQUENCE FAULT	0.1	0.1	----	----	----	----	----	----	----	----	----	----	----

TYPE OF ROBOT USED: All numbers ending with __3 - electric, floor-mounted, 5 axes robot for spot-welding;
Number 211 - electric, floor-mounted 5 axes robot for adhesive bonding;
All other numbers - electric, gantry-mounted, 6 axes robot for spot-welding.

COMPANY 'B' STATION 7

DATA COLLECTED FROM 16/8/83 TO 25/11/83.

Production hours covered: 974.5

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
NUMBER OF INCIDENTS	63	128	60	35	40	15	18	24	66	46	26	25	22
DOWNTIME:													
MINUTES	485	707	156	95	154	65	100	84	411	176	129	88	172
HOURS	----	1	----	----	1	----	1	----	8	1	----	----	----
TOTAL - IN MINUTES	485	767	156	95	214	65	160	84	891	236	129	88	172
MEAN DOWNTIME	9.3	6.8	3.6	2.9	6.3	8.1	13.3	4.7	17.1	6.2	7.2	4.2	7.8
NO. OF INCIDENTS WITH NO TIME GIVEN	11	15	16	2	6	7	6	6	14	8	8	4	10
ACTIONS TAKEN (% of incidents)													
REPLACEMENT OF FAULTY EQUIP'T	28.6	14.8	10.0	5.7	17.5	20.0	33.3	25.0	10.6	23.9	23.1	12.0	25.0
ADJUSTMENT/ CLEANING	22.2	10.2	40.0	8.6	35.0	46.7	66.7	41.7	28.8	23.9	30.8	12.0	53.1
RESETTING	49.2	64.1	53.3	7.7	45.0	33.3	11.1	25.0	37.9	47.8	46.2	76.0	28.1
REPROGRAMMING	7.9	16.4	3.3	11.4	7.5	6.7	11.1	8.3	19.7	4.3	3.8	----	3.1
ROUTINE MAINTENANCE	----	----	----	----	----	----	----	----	1.5	----	----	----	----
UNPLANNED MAINTENANCE	44.4	23.4	13.3	8.6	17.5	20.0	22.2	33.3	30.3	23.9	38.5	8.0	31.3
FAULT DIAGNOSIS	6.3	1.6	----	5.7	5.0	----	----	4.2	1.5	4.3	----	----	----
ANY OTHER ACTION	----	1.6	----	----	----	----	----	----	3.0	----	----	----	----
REASONS GIVEN (% of incidents)													
MECHANICAL PROBLEM WITH ROBOT	88.9	90.6	75.0	94.3	80.0	86.7	50.0	75.0	77.3	80.4	88.5	92.0	84.4
MECHANICAL PROBLEM WITH OTHER EQUIP'T	1.6	1.6	1.7	----	5.0	----	5.6	4.2	4.5	2.2	3.8	----	3.1
ELECTRICAL PROBLEM WITH ROBOT	61.9	68.0	56.7	82.9	57.5	53.3	11.1	25.0	40.9	41.3	53.8	76.0	31.2

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	----	0.8	----	----	----	----	----	----	1.5	----	----	4.0	----
ELECTRICAL PROBLEM WITH INTERFACE	----	----	----	----	----	----	----	----	----	2.2	----	----	----
INSPECTION	----	----	----	----	----	----	----	----	1.5	----	----	----	----
PROGRAMME PROBLEM	3.2	5.5	----	----	5.0	----	11.1	----	7.6	----	----	----	----
QUALITY PROBLEMS	6.3	16.4	40.0	11.4	45.0	46.7	77.8	50.0	21.2	30.4	30.8	12.0	62.5
ERRATIC ROBOT	1.6	0.8	----	----	----	----	----	----	1.5	----	----	4.0	3.1
DROPPED PART	----	----	----	----	----	----	----	----	----	----	----	----	----
THREAT OF DAMAGE TO:													
ROBOT	1.6	----	3.3	----	----	----	----	----	1.5	----	----	----	----
PERSONS	----	----	----	----	----	----	----	----	----	----	----	----	----
MACHINERY	4.8	----	----	----	----	----	----	----	1.5	----	----	----	----
ANY OTHER REASON	----	0.8	----	----	----	----	----	----	3.0	----	----	----	----

MEANS OF INTERRUPTION (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
E-STOP PRESSED	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER HUMAN ACTION	7.9	10.9	1.7	2.9	17.5	20.0	27.8	25.0	22.7	19.6	7.7	4.0	9.4
AUTOMATIC STOP	60.3	62.5	50.0	74.3	45.0	40.0	5.6	20.8	37.9	34.8	50.0	68.0	25.0
SENSOR STOP	31.7	26.6	48.3	22.9	37.5	40.0	66.7	54.2	39.4	45.7	42.3	28.0	65.6

CLASSIFICATION OF INCIDENT (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
ACCIDENT TO PERSON	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT TO MACHINE	6.3	2.3	1.7	----	----	----	11.1	4.2	7.6	----	3.8	----	----
ACCIDENT TO BOTH	----	----	----	----	----	----	----	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	1.6	0.8	1.7	----	----	----	----	----	----	----	----	----	----
NEAR MISS	----	----	----	----	----	----	----	----	----	----	----	----	----
INCIDENT - NO DAMAGE	85.7	82.8	93.3	97.1	77.5	80.0	61.1	70.8	69.7	82.6	88.5	96.0	87.5
HAZARD ANTICIPATED	3.2	2.3	----	----	2.5	----	----	----	1.5	----	3.8	4.0	----
NO DAMAGE LIKELY	3.2	10.9	3.3	2.9	20.0	20.0	27.8	25.0	21.2	17.6	3.8	----	12.5

PERSONS IDENTIFYING THE PROBLEM (% of incidents)

	262	263	291	292	293	301	302	311	312	321	322	331	332
FITTER	----	1.6	----	----	----	----	----	----	1.5	4.3	----	----	3.1
ELECTRICIAN	98.4	97.7	98.3	100	95.0	93.3	100	91.7	92.4	91.3	100	100	100
PROD. ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
FOREMAN	----	----	----	----	----	----	----	----	----	----	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	1.6	1.6	1.7	----	5.0	----	----	4.2	4.5	6.5	----	----	----
PERSONS SORTING OUT THE PROBLEM (% of incidents)													
FITTER	63.5	32.0	20.0	22.9	32.5	33.3	55.6	54.2	47.0	47.8	46.2	20.0	59.4
ELECTRICIAN	98.4	98.4	100	100	100	100	100	100	95.5	100	100	100	96.9
PROD. ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OPERATOR	----	----	----	----	----	----	----	----	----	----	----	----	----
FOREMAN	----	----	----	----	----	----	----	----	----	----	----	----	----
CHARGEHAND	----	----	----	----	----	----	----	----	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----	----	----	----	----	----	----	----
OTHER	4.8	3.9	----	----	----	----	----	----	3.0	2.2	----	4.0	----
UNDERLYING REASON FOR INCIDENT (% of incidents)													
ROBOT - NO DETAIL	4.8	3.9	1.7	----	----	----	----	----	4.5	----	----	----	----
ROBOT OUT OF SYNCH'	14.3	3.1	26.7	8.6	----	----	----	8.3	16.7	----	3.8	32.0	----
STIFFNESS IN ROBOT ARM	----	----	----	2.4	----	----	5.6	----	----	----	3.8	----	----
CABLE PROBLEM	9.5	1.6	1.7	----	----	6.7	----	----	3.0	----	----	----	----
COMP'NT FAILURE IN ROBOT ARM	3.2	----	----	----	2.5	----	----	----	----	----	3.8	8.0	----
BLOWN FUSES	1.6	----	----	----	----	----	----	----	3.0	----	----	----	----
ROBOT IN E-STOP	12.7	51.6	16.7	60.0	27.5	33.3	5.6	4.2	10.6	28.3	34.6	16.0	3.1
FAULT IN CABINET	1.6	1.6	1.7	2.9	----	----	----	----	----	----	----	4.0	----
ERRATIC ROBOT	3.2	3.1	----	----	2.5	----	5.6	----	6.1	----	----	----	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----
PROBLEM IN TOOLS	33.3	16.4	8.3	5.7	27.5	20.0	33.3	45.8	28.8	41.3	23.1	8.0	34.4
ROBOT WON'T MOVE	1.6	----	----	5.7	----	----	----	----	----	2.2	----	----	----
ROBOT COLLISION	6.3	3.1	----	----	----	----	5.6	----	----	----	----	4.0	3.1
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----	----	----	----	----	----	----

ROBOT NUMBERS 262 - 332

	262	263	291	292	293	301	302	311	312	321	322	331	332
OTHER COMPONENT FAILURE	----	0.8	----	----	----	----	----	----	----	----	3.8	8.0	----
SYSTEM FAILURE	----	----	----	----	----	----	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----	----	----	----	----	----	----
PART VARIATION	----	----	5.0	5.7	2.5	----	----	4.2	3.0	4.3	----	4.0	6.3
QUALITY PROBLEM	1.6	3.1	1.7	2.9	7.5	6.7	5.6	8.3	6.1	2.2	----	----	6.3
PROCESS PROBLEM	----	0.8	----	----	----	----	----	----	1.5	2.2	----	----	6.3
SERVICES PROBLEM	1.6	2.3	----	----	----	----	----	----	1.5	----	----	----	----
OTHER EQUIP'T PROBLEM	1.6	----	----	----	2.5	----	----	----	3.0	2.2	----	8.0	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----	----	----	----	----	----	----
HUMAN ERROR	----	----	----	----	----	----	----	----	----	----	----	----	----
WELD FAILURE	3.2	8.6	36.7	5.7	27.5	33.3	38.9	29.2	12.1	17.4	26.9	8.0	40.6
SEQUENCE FAULT	----	----	----	----	----	----	----	----	----	----	----	----	----

TYPE OF ROBOT USED: All numbers ending with __3 - electric, floor-mounted, 5 axes robot for spot-welding;
Number 211 - electric, floor-mounted 5 axes robot for adhesive bonding;
All other numbers - electric, gantry-mounted, 6 axes robot for spot-welding.

COMPANY 'F'

DATA COLLECTED FROM 14/7/83 TO 16/1/84

Production hours covered : 1166.5

	ALL CASES	ROBOT NUMBER NONE	NOT GIVEN	1	2
NUMBER OF INCIDENTS	811	601	17	83	110
DOWNTIME:					
MINUTES	11746	8979	318	1054	1395
HOURS	129	96	1	4	28
TOTAL - IN MINUTES	19486	14739	378	1294	3075
MEAN DOWNTIME	24.2	24.7	22.2	15.8	28.2
NO. OF INCIDENTS WITH NO TIME GIVEN	6	4	----	1	1
ACTIONS TAKEN (% of incidents)					
REPLACEMENT OF FAULTY EQUIP'T	22.8	25.1	17.6	14.5	17.3
ADJUSTMENT/ CLEANING	50.3	58.9	23.5	22.9	28.2
RESETTING	41.2	34.8	35.3	66.3	58.2
REPROGRAMMING	7.6	0.3	17.6	37.3	23.6
ROUTINE MAINTENANCE	22.3	29.8	----	1.2	0.9
UNPLANNED MAINTENANCE	11.1	13.0	5.9	2.4	8.2
FAULT DIAGNOSIS	1.0	1.3	----	----	----
ANY OTHER ACTION	6.3	4.2	47.1	6.0	11.8
REASONS GIVEN (% of incidents)					
MECHANICAL PROBLEM WITH ROBOT	13.9	----	23.5	51.8	60.0
MECHANICAL PROBLEM WITH OTHER EQUIP'T	43.5	55.6	23.5	9.6	6.4
ELECTRICAL PROBLEM WITH ROBOT	16.2	----	17.6	72.3	61.8
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	18.0	23.1	17.6	1.2	2.7
ELECTRICAL PROBLEM WITH INTERFACE	3.1	3.3	5.9	2.4	1.8
INSPECTION	3.2	2.7	5.9	6.0	3.6
PROGRAMME PROBLEM	1.8	0.3	5.9	8.4	4.5
QUALITY PROBLEMS	42.9	47.8	23.5	32.5	27.2
ERRATIC ROBOT	1.6	----	17.6	6.0	4.5
DROPPED PART	0.2	0.3	----	----	----
THREAT OF DAMAGE TO:					
ROBOT	5.4	0.2	----	25.3	20.0
PERSONS	0.2	0.3	----	----	----
MACHINERY	3.0	3.3	----	2.4	1.8
ANY OTHER REASON	3.2	1.8	41.2	6.0	2.7

	ROBOT NUMBER				
	ALL CASES	NONE	NOT GIVEN	1	2
MEANS OF INTERRUPTION (% of incidents)					
E-STOP PRESSED	1.0	1.0	----	1.2	0.9
OTHER HUMAN ACTION	30.0	33.4	58.8	18.1	15.5
AUTOMATIC STOP	25.4	22.1	11.8	37.3	36.4
SENSOR STOP	41.6	41.3	23.5	42.2	45.5
CLASSIFICATION OF INCIDENT (% of incidents)					
ACCIDENT TO PERSON	0.1	0.2	----	----	----
ACCIDENT TO MACHINE	2.1	2.5	----	----	1.8
ACCIDENT TO BOTH	----	----	----	----	----
ACCIDENT - NO DAMAGE	0.4	0.3	----	1.2	----
NEAR MISS	0.2	0.3	----	----	----
INCIDENT - NO DAMAGE	17.1	13.8	5.9	25.3	30.9
HAZARD ANTICIPATED	1.6	1.3	----	3.6	1.8
NO DAMAGE LIKELY	75.1	78.2	88.9	66.3	62.7
PERSONS IDENTIFYING THE PROBLEM (% of incidents)					
FITTER	0.2	0.3	----	----	----
ELECTRICIAN	0.7	0.7	----	2.4	----
PROD. ENGINEER	----	----	----	----	----
OPERATOR	8.5	10.0	----	1.2	7.3
CHARGEHAND	53.1	49.6	41.2	62.6	67.3
LEADING-HAND	14.5	13.8	5.9	20.5	14.4
SERVICE ENGINEER	----	----	----	----	----
OTHER	6.7	3.8	23.5	21.7	8.2
PERSONS SORTING OUT THE PROBLEM (% of incidents)					
FITTER	8.9	10.0	----	2.4	9.1
ELECTRICIAN	12.1	13.3	5.9	7.2	9.9
PROD. ENGINEER	0.1	----	----	1.2	----
OPERATOR	0.2	0.3	----	----	----
CHARGEHAND	75.1	71.5	100	84.3	83.6
LEADING-HAND	45.0	48.6	47.1	39.7	29.1
SERVICE ENGINEER	0.1	----	----	----	0.9
OTHER	2.5	2.7	11.8	----	1.8
UNDERLYING REASON FOR INCIDENT (% of incidents)					
ROBOT - NO DETAIL	0.7	----	----	3.6	2.7
ROBOT OUT OF SYNCH'	0.2	----	----	1.2	0.9
STIFFNESS IN ROBOT ARM	----	----	----	----	----
CABLE PROBLEM	1.0	----	----	4.8	3.6
COMP'NT FAILURE IN ROBOT ARM	0.4	----	----	----	2.7
BLOWN FUSES	----	----	----	----	----

	ALL CASES	ROBOT NUMBER NONE	NOT GIVEN	1	2
ROBOT IN E-STOP	0.9	----	----	3.6	3.6
FAULT IN CABINET	0.4	----	5.9	----	1.8
ERRATIC ROBOT	5.3	----	11.8	22.9	20.0
FAULT IN TEACH PENDANT	----	----	----	----	----
POWER SUPPLY FAULT	6.3	----	----	27.7	25.5
PROBLEM IN TOOLS	2.2	----	5.9	4.8	11.8
ROBOT WON'T MOVE	0.2	----	----	----	1.8
ROBOT COLLISION	----	----	----	----	----
OVERHEATING HYDRAULICS	1.4	----	----	7.2	4.5
OTHER COMPONENT FAILURE	16.8	21.6	5.9	2.4	2.7
SYSTEM FAILURE	----	----	----	----	----
SYSTEM CHECKS	0.1	----	5.9	----	----
CHECK ON PARTS	----	----	----	----	----
PART VARIATION	3.6	3.3	----	----	8.2
QUALITY PROBLEM	23.1	30.3	----	3.6	1.8
PROCESS PROBLEM	1.4	----	41.2	2.4	1.8
SERVICES PROBLEM	2.3	2.5	----	2.4	1.8
OTHER EQUIP'T PROBLEM	31.1	39.3	17.6	9.6	4.5
SAFETY FUNCTION PROBLEM	0.4	0.5	----	----	----
HUMAN ERROR	0.9	1.2	----	----	----
WELD FAILURE	----	----	----	----	----
SEQUENCE FAULT	1.1	0.8	5.9	3.6	----

TYPE OF ROBOT USED: Hydraulic, 6-axis robot for spot welding

COMPANY 'H'

DATA COLLECTED FROM 23/5/83 TO 6/4/84
Production hours covered : 1252

		ROBOT NUMBER			
	ALL CASES	NONE	NOT GIVEN	1	2
NUMBER OF INCIDENTS	13	0	0	7	6
DOWNTIME:					
MINUTES	60	----	----	60	0
HOURS	217	----	----	178	39
TOTAL - IN MINUTES	13080	----	----	10740	2340
MEAN DOWNTIME	1189	----	----	1790	468
NO. OF INCIDENTS WITH NO TIME GIVEN	2	----	----	1	1

ACTIONS TAKEN (% of incidents)

	ALL CASES	NONE	NOT GIVEN	1	2
REPLACEMENT OF FAULTY EQUIP'T	23.1	----	----	28.6	16.7
ADJUSTMENT/ CLEANING	30.8	----	----	----	66.7
RESETTING	7.7	----	----	----	16.7
REPROGRAMMING	38.5	----	----	42.9	33.3
ROUTINE MAINTENANCE	----	----	----	----	----
UNPLANNED MAINTENANCE	38.5	----	----	28.6	50.0
FAULT DIAGNOSIS	23.1	----	----	28.6	16.7
ANY OTHER ACTION	7.7	----	----	14.3	----

REASONS GIVEN (% of incidents)

	ALL CASES	NONE	NOT GIVEN	1	2
MECHANICAL PROBLEM WITH ROBOT	15.4	----	----	----	33.3
MECHANICAL PROBLEM WITH OTHER EQUIP'T	30.8	----	----	28.6	33.3
ELECTRICAL PROBLEM WITH ROBOT	23.1	----	----	----	50.0
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	----	----	----	----	----
ELECTRICAL PROBLEM WITH INTERFACE	----	----	----	----	----
INSPECTION	----	----	----	----	----
PROGRAMME PROBLEM	15.4	----	----	28.6	----
QUALITY PROBLEMS	----	----	----	----	----
ERRATIC ROBOT	7.7	----	----	14.3	----
DROPPED PART	----	----	----	----	----
THREAT OF DAMAGE TO:					
ROBOT	7.7	----	----	14.3	----
PERSONS	----	----	----	----	----
MACHINERY	15.4	----	----	28.6	----
ANY OTHER REASON	7.7	----	----	14.3	----

	ALL CASES	ROBOT NUMBER NONE	NOT GIVEN	1	2
MEANS OF INTERRUPTION (% of incidents)					
E-STOP PRESSED	7.7	----	----	14.3	----
OTHER HUMAN ACTION	53.8	----	----	85.7	16.7
AUTOMATIC STOP	38.5	----	----	----	83.3
SENSOR STOP	----	----	----	----	----
CLASSIFICATION OF INCIDENT (% of incidents)					
ACCIDENT TO PERSON	----	----	----	----	----
ACCIDENT TO MACHINE	23.1	----	----	42.9	----
ACCIDENT TO BOTH	----	----	----	----	----
ACCIDENT - NO DAMAGE	15.4	----	----	28.6	----
NEAR MISS	----	----	----	----	----
INCIDENT - NO DAMAGE	15.4	----	----	----	33.3
HAZARD ANTICIPATED	23.1	----	----	28.6	16.7
NO DAMAGE LIKELY	23.1	----	----	----	50.0
PERSONS IDENTIFYING THE PROBLEM (% of incidents)					
FITTER	----	----	----	----	----
ELECTRICIAN	15.4	----	----	----	33.3
PROD. ENGINEER	----	----	----	----	----
OPERATOR	92.3	----	----	100	83.3
FOREMAN	----	----	----	----	----
CHARGEHAND	----	----	----	----	----
SERVICE ENGINEER	----	----	----	----	----
OTHER	----	----	----	----	----
PERSONS SORTING OUT THE PROBLEM (% of incidents)					
FITTER	23.1	----	----	----	50.0
ELECTRICIAN	30.8	----	----	14.3	50.0
PROD. ENGINEER	----	----	----	----	----
OPERATOR	46.2	----	----	85.7	----
FOREMAN	----	----	----	----	----
CHARGEHAND	----	----	----	----	----
SERVICE ENGINEER	15.4	----	----	14.3	16.7
OTHER	----	----	----	----	----
UNDERLYING REASON FOR INCIDENT (% of incidents)					
ROBOT - NO DETAIL	----	----	----	----	----
ROBOT OUT OF SYNCH'	----	----	----	----	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----
CABLE PROBLEM	7.7	----	----	----	16.7
COMP'NT FAILURE IN ROBOT ARM	7.7	----	----	----	16.7
BLOWN FUSES	----	----	----	----	----

		ROBOT NUMBER			
	ALL CASES	NONE	NOT GIVEN	1	2
ROBOT IN E-STOP	7.7	----	----	----	16.7
FAULT IN CABINET	7.7	----	----	14.3	----
ERRATIC ROBOT	23.1	----	----	28.6	16.7
FAULT IN TEACH PENDANT	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----
PROBLEM IN TOOLS	15.4	----	----	14.3	16.7
ROBOT WON'T MOVE	----	----	----	----	----
ROBOT COLLISION	----	----	----	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----
OTHER COMPONENT FAILURE	7.7	----	----	----	16.7
SYSTEM FAILURE	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----
PART VARIATION	----	----	----	----	----
QUALITY PROBLEM	----	----	----	----	----
PROCESS PROBLEM	----	----	----	----	----
SERVICES PROBLEM	----	----	----	----	----
OTHER EQUIP'T PROBLEM	----	----	----	----	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----
HUMAN ERROR	23.1	----	----	42.9	----
WELD FAILURE	----	----	----	----	----
SEQUENCE FAULT	----	----	----	----	----

TYPE OF ROBOT USED: Hydraulic, 6-axis robot for routing and drilling.

APPENDIX E

Results for the Classification Categories

ACCIDENT CLASSIFICATION
ACCIDENT TO PERSON

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	1	---	---	---	---	1	---
DOWNTIME:							
MINUTES	15	---	---	---	---	15	---
HOURS	---	---	---	---	---	---	---
TOTAL - IN MINUTES	15	---	---	---	---	15	---
MEAN DOWNTIME	15	---	---	---	---	15	---
NO. OF INCIDENTS WITH NO TIME GIVEN	0	---	---	---	---	0	---

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
ROBOT - NO DETAIL	---	---	---	---	---	---	---
ROBOT OUT OF SYNCH'	---	---	---	---	---	---	---
STIFFNESS IN ROBOT ARM	---	---	---	---	---	---	---
CABLE PROBLEM	---	---	---	---	---	---	---
COMP'NT FAILURE IN ROBOT ARM	---	---	---	---	---	---	---
BLOWN FUSES	---	---	---	---	---	---	---
ROBOT IN E-STOP	---	---	---	---	---	---	---
FAULT IN CABINET	---	---	---	---	---	---	---
ERRATIC ROBOT	---	---	---	---	---	---	---
FAULT IN TEACH PENDANT	---	---	---	---	---	---	---
POWER SUPPLY FAULT	---	---	---	---	---	---	---
PROBLEM IN TOOLS	---	---	---	---	---	---	---
ROBOT WON'T MOVE	---	---	---	---	---	---	---
ROBOT COLLISION	---	---	---	---	---	---	---
OVERHEATING HYDRAULICS	---	---	---	---	---	---	---
OTHER COMPONENT FAILURE	---	---	---	---	---	---	---
SYSTEM FAILURE	---	---	---	---	---	---	---
SYSTEM CHECKS	---	---	---	---	---	---	---
CHECK ON PARTS	---	---	---	---	---	---	---
PART VARIATION	---	---	---	---	---	---	---
QUALITY PROBLEM	---	---	---	---	---	---	---
PROCESS PROBLEM	---	---	---	---	---	---	---
SERVICES PROBLEM	---	---	---	---	---	---	---
OTHER EQUIP'T PROBLEM	---	---	---	---	---	---	---
SAFETY FUNCTION PROBLEM	100	---	---	---	---	100	---
HUMAN ERROR	---	---	---	---	---	---	---
WELD FAILURE	---	---	---	---	---	---	---
SEQUENCE FAULT	---	---	---	---	---	---	---

ACCIDENT CLASSIFICATION
ACCIDENT TO MACHINE

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	220	10	7	95	88	17	3
DOWNTIME:							
MINUTES	2839	108	113	1270	903	425	20
HOURS	47	11	2	16	5	11	2
TOTAL - IN MINUTES	5659	768	233	2230	1203	1085	140
MEAN DOWNTIME	29.3	128.0	38.8	25.1	16.3	63.8	70.0
NO. OF INCIDENTS WITH NO TIME GIVEN	27	4	1	6	15	0	1

<u>UNDERLYING REASON FOR INCIDENT</u> (% of incidents)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
ROBOT - NO DETAIL	2.7	----	----	3.2	3.4	----	----
ROBOT OUT OF SYNCH'	1.4	----	----	2.1	1.1	----	----
STIFFNESS IN ROBOT ARM	1.4	----	----	3.2	----	----	----
CABLE PROBLEM	1.4	----	----	2.1	1.1	----	----
COMP'NT FAILURE IN ROBOT ARM	1.4	----	----	3.2	----	----	----
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	0.9	----	----	2.1	----	----	----
FAULT IN CABINET	0.5	----	----	1.1	----	----	----
ERRATIC ROBOT	9.1	----	42.9	9.5	9.1	----	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----
PROBLEM IN TOOLS	11.8	----	----	14.7	12.5	5.9	----
ROBOT WON'T MOVE	----	----	----	----	----	----	----
ROBOT COLLISION	5.9	----	----	7.4	6.8	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(36.4)	(0.0)	(42.9)	(48.4)	(34.1)	(5.9)	(0.0)
OTHER COMPONENT FAILURE	16.4	20.0	----	14.7	9.1	70.6	----
SYSTEM FAILURE	0.5	----	----	1.1	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----
PART VARIATION	15.5	----	----	10.5	26.1	5.9	----
QUALITY PROBLEM	2.3	----	----	1.1	4.5	----	----
PROCESS PROBLEM	3.2	----	----	3.2	4.5	----	----
SERVICES PROBLEM	----	----	----	----	----	----	----
OTHER EQUIP'T PROBLEM	22.7	50.0	57.1	20.0	21.6	17.6	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----
HUMAN ERROR	2.7	20.0	----	1.1	----	----	100
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	0.5	10.0	----	----	----	----	----

ACCIDENT CLASSIFICATION
ACCIDENT - NO DAMAGE

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	48	5	3	23	12	3	2
DOWNTIME:							
MINUTES	324	28	65	69	142	20	----
HOURS	192	10	4	1	----	3	174
TOTAL - IN MINUTES	11844	628	305	129	142	200	10440
MEAN DOWNTIME	236.2	209.3	152.5	5.6	11.8	66.7	5220
NO. OF INCIDENTS WITH NO TIME GIVEN	3	2	1	0	0	0	0

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
ROBOT - NO DETAIL	----	----	----	----	----	----	----
ROBOT OUT OF SYNCH'	2.1	----	----	----	8.3	----	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----	----	----
CABLE PROBLEM	----	----	----	----	----	----	----
COMP'NT FAILURE IN ROBOT ARM	4.2	----	----	4.3	8.3	----	----
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	----	----	----	----	----	----	----
FAULT IN CABINET	2.1	----	----	----	----	----	50.0
ERRATIC ROBOT	2.1	----	----	----	----	----	50.0
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----
PROBLEM IN TOOLS	4.2	----	----	----	16.7	----	----
ROBOT WON'T MOVE	----	----	----	----	----	----	----
ROBOT COLLISION	56.3	----	----	95.7	41.7	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(70.8)	(0)	(0)	(100)	(75.0)	(0)	(100)
OTHER COMPONENT FAILURE	2.1	----	----	----	----	33.3	----
SYSTEM FAILURE	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----
PART VARIATION	8.3	60.0	----	----	8.3	----	----
QUALITY PROBLEM	----	----	----	----	----	----	----
PROCESS PROBLEM	----	----	----	----	----	----	----
SERVICES PROBLEM	----	----	----	----	----	----	----
OTHER EQUIP'T PROBLEM	14.6	20.0	66.7	----	16.7	66.7	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----
HUMAN ERROR	----	----	----	----	----	----	----
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	4.2	20.0	33.3	----	----	----	----

ACCIDENT CLASSIFICATION
NEAR MISS

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	6	1	----	3	----	2	----
DOWNTIME:							
MINUTES	129	49	----	60	----	20	----
HOURS	----	----	----	----	----	----	----
TOTAL - IN MINUTES	129	49	----	60	----	20	----
MEAN DOWNTIME	25.8	49	----	20.0	----	20.0	----
NO. OF INCIDENTS WITH NO TIME GIVEN	1	0	----	0	----	1	----
UNDERLYING REASON FOR INCIDENT (% of incidents)							
ROBOT - NO DETAIL	----	----	----	----	----	----	----
ROBOT OUT OF SYNCH'	----	----	----	----	----	----	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----	----	----
CABLE PROBLEM	16.7	----	----	33.3	----	----	----
COMP'NT FAILURE IN ROBOT ARM	----	----	----	----	----	----	----
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	----	----	----	----	----	----	----
FAULT IN CABINET	----	----	----	----	----	----	----
ERRATIC ROBOT	33.3	----	----	66.7	----	----	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----
PROBLEM IN TOOLS	----	----	----	----	----	----	----
ROBOT WON'T MOVE	----	----	----	----	----	----	----
ROBOT COLLISION	----	----	----	----	----	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(50.0)	(0)	(0)	(100)	(0)	(0)	(0)
OTHER COMPONENT FAILURE	----	----	----	----	----	----	----
SYSTEM FAILURE	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----
PART VARIATION	----	----	----	----	----	----	----
QUALITY PROBLEM	----	----	----	----	----	----	----
PROCESS PROBLEM	----	----	----	----	----	----	----
SERVICES PROBLEM	16.7	----	----	----	----	50.0	----
OTHER EQUIP'T PROBLEM	16.7	----	----	----	----	50.0	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----
HUMAN ERROR	----	----	----	----	----	----	----
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	16.7	100	----	----	----	----	----

ACCIDENT CLASSIFICATION
INCIDENT - NO DAMAGE

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	3716	554	417	1120	1484	139	2
DOWNTIME:							
MINUTES	17438	2338	2012	5258	6116	1714	----
HOURS	147	45	24	28	19	23	8
TOTAL - IN MINUTES	26258	5038	3452	6938	7256	3094	480
MEAN DOWNTIME	8.8	17.9	15.2	6.7	5.6	22.3	240.0
NO. OF INCIDENTS WITH NO TIME GIVEN	723	272	190	83	178	----	----
	UNDERLYING REASON FOR INCIDENT (% of incidents)						
ROBOT - NO DETAIL	1.3	0.9	1.4	1.2	1.5	0.7	----
ROBOT OUT OF SYNCH'	4.3	0.2	0.2	6.0	6.2	----	----
STIFFNESS IN ROBOT ARM	0.2	0.4	----	0.3	0.3	----	----
CABLE PROBLEM	0.9	----	1.0	0.7	1.3	----	50.0
COMP'NT FAILURE IN ROBOT ARM	0.6	----	0.5	1.2	0.4	2.2	----
BLOWN FUSES	0.5	----	----	1.0	0.4	----	----
ROBOT IN E-STOP	13.0	1.4	8.4	19.8	14.6	0.7	50.0
FAULT IN CABINET	0.6	0.2	0.2	0.9	0.6	----	----
ERRATIC ROBOT	0.8	0.5	0.5	1.1	0.3	4.3	----
FAULT IN TEACH PENDANT	0.1	0.2	----	0.1	----	----	----
POWER SUPPLY FAULT	1.0	----	----	----	----	26.6	----
PROBLEM IN TOOLS	7.9	1.1	3.1	8.2	12.0	2.9	----
ROBOT WON'T MOVE	0.5	0.4	0.5	0.4	0.6	----	----
ROBOT COLLISION	0.6	----	----	1.2	0.5	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(32.1)	(5.2)	(15.8)	(42.1)	(38.7)	(37.4)	(100)
OTHER COMPONENT FAILURE	2.0	0.5	2.9	1.4	1.5	15.8	----
SYSTEM FAILURE	3.2	2.5	2.4	1.4	5.3	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	0.03	0.2	----	----	----	----	----
PART VARIATION	8.2	1.8	9.8	8.8	10.3	0.7	----
QUALITY PROBLEM	0.5	----	1.7	0.7	0.2	----	----
PROCESS PROBLEM	0.5	1.1	0.7	0.2	0.5	----	----
SERVICES PROBLEM	1.0	0.5	1.0	1.2	1.1	1.4	----
OTHER EQUIP'T PROBLEM	32.9	10.6	53.2	35.7	32.8	39.6	----
SAFETY FUNCTION PROBLEM	0.2	1.1	----	0.3	----	----	----
HUMAN ERROR	0.5	0.7	1.0	0.4	0.3	2.2	----
WELD FAILURE	16.6	68.8	7.0	6.1	9.2	----	----
SEQUENCE FAULT	2.1	6.9	----	1.5	0.1	2.9	----

ACCIDENT CLASSIFICATION
HAZARD ANTICIPATED

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	43	----	4	5	18	13	3
DOWNTIME:							
MINUTES	494	----	10	58	183	203	40
HOURS	24	----	4	----	7	----	13
TOTAL - IN MINUTES	1934	----	250	58	603	203	820
MEAN DOWNTIME	53.7	----	62.5	14.5	50.3	15.6	273.3
NO. OF INCIDENTS WITH NO TIME GIVEN	7	----	0	1	6	0	0
	UNDERLYING REASON FOR INCIDENT (% of incidents)						
ROBOT - NO DETAIL	4.7	----	----	----	11.1	----	----
ROBOT OUT OF SYNCH'	----	----	----	----	----	----	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----	----	----
CABLE PROBLEM	----	----	----	----	----	----	----
COMP'NT FAILURE IN ROBOT ARM	4.7	----	25.0	----	5.6	----	----
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	----	----	----	----	----	----	----
FAULT IN CABINET	----	----	----	----	----	----	----
ERRATIC ROBOT	18.6	----	----	40.0	22.2	7.7	33.3
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	4.7	----	----	----	----	15.4	----
PROBLEM IN TOOLS	23.3	----	25.0	----	33.3	15.4	33.3
ROBOT WON'T MOVE	----	----	----	----	----	----	----
ROBOT COLLISION	----	----	----	----	----	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(55.8)	(0)	(50.0)	(40.0)	(72.2)	(38.5)	(66.7)
OTHER COMPONENT FAILURE	7.0	----	----	----	----	----	33.3
SYSTEM FAILURE	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----
PART VARIATION	----	----	----	----	----	----	----
QUALITY PROBLEM	----	----	----	----	----	----	----
PROCESS PROBLEM	4.7	----	----	20.0	5.6	----	----
SERVICES PROBLEM	----	----	----	----	----	----	----
OTHER EQUIP'T PROBLEM	27.9	----	50.0	40.0	16.7	38.5	----
SAFETY FUNCTION PROBLEM	2.3	----	----	----	5.6	----	----
HUMAN ERROR	2.3	----	----	----	----	7.7	----
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	----	----	----	----	----	----	----

ACCIDENT CLASSIFICATION
NO DAMAGE LIKELY

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	1534	173	228	304	217	609	3
DOWNTIME:							
MINUTES	13848	1542	697	1673	1027	8909	----
HOURS	210	62	11	14	12	91	20
TOTAL - IN MINUTES	26448	5262	1357	2513	1747	14369	1200
MEAN DOWNTIME	23.3	56.0	10.6	13.1	15.1	23.8	600.0
NO. OF INCIDENTS WITH NO TIME GIVEN	398	79	100	112	101	5	1

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
ROBOT - NO DETAIL	1.6	----	3.1	2.0	2.8	0.8	----
ROBOT OUT OF SYNCH'	0.2	1.2	----	----	----	0.2	----
STIFFNESS IN ROBOT ARM	0.1	----	----	0.7	----	----	----
CABLE PROBLEM	0.9	----	0.9	0.7	0.9	1.3	----
COMP'NT FAILURE IN ROBOT ARM	0.3	0.6	----	0.7	0.5	----	33.3
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	0.5	----	----	0.3	0.5	1.0	----
FAULT IN CABINET	0.3	----	----	0.3	0.5	0.5	----
ERRATIC ROBOT	4.0	2.3	0.4	3.3	5.1	5.6	33.3
FAULT IN TEACH PENDANT	0.1	0.6	----	----	----	----	----
POWER SUPPLY FAULT	0.7	----	----	----	----	1.8	----
PROBLEM IN TOOLS	9.2	5.8	5.7	19.4	22.1	1.6	33.3
ROBOT WON'T MOVE	0.4	----	----	1.6	----	0.2	----
ROBOT COLLISION	----	----	----	----	----	----	----
OVERHEATING HYDRAULICS	0.7	----	----	----	----	1.8	----
	(19.0)	(10.4)	(10.1)	(29.0)	(32.3)	(14.8)	(100)
OTHER COMPONENT FAILURE	7.6	0.6	0.9	3.6	2.8	15.8	----
SYSTEM FAILURE	0.6	1.7	----	0.7	1.8	----	----
SYSTEM CHECKS	1.2	9.8	----	----	----	0.2	----
CHECK ON PARTS	1.5	13.3	----	----	----	----	----
PART VARIATION	5.1	6.4	----	10.2	4.1	4.4	----
QUALITY PROBLEM	27.6	23.7	15.8	28.9	33.6	30.5	----
PROCESS PROBLEM	11.6	3.5	58.8	4.9	5.5	1.8	----
SERVICES PROBLEM	2.0	5.2	----	1.0	1.4	2.6	----
OTHER EQUIP'T PROBLEM	19.8	17.9	13.6	17.1	8.8	28.1	----
SAFETY FUNCTION PROBLEM	0.5	2.9	----	----	0.5	0.3	----
HUMAN ERROR	1.0	2.3	0.4	1.0	2.8	0.3	----
WELD FAILURE	0.9	----	----	2.0	3.7	----	----
SEQUENCE FAULT	0.6	2.3	----	----	----	0.8	----

ACCIDENT CLASSIFICATION
(NO CLASSIFICATION GIVEN)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	34	----	3	3	1	27	----
DOWNTIME:							
MINUTES	499	----	57	2	----	440	----
HOURS	1	----	----	----	----	1	----
TOTAL - IN MINUTES	559	----	57	2	----	500	----
MEAN DOWNTIME	17.5	----	19.0	1.0	----	18.5	----
NO. OF INCIDENTS WITH NO TIME GIVEN	2	----	0	1	1	0	----

UNDERLYING REASON FOR INCIDENT (% of incidents)

ROBOT - NO DETAIL	5.9	----	----	33.3	100	----	----
ROBOT OUT OF SYNCH'	2.9	----	----	----	----	3.7	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----	----	----
CABLE PROBLEM	----	----	----	----	----	----	----
COMP'NT FAILURE IN ROBOT ARM	----	----	----	----	----	----	----
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	----	----	----	----	----	----	----
FAULT IN CABINET	----	----	----	----	----	----	----
ERRATIC ROBOT	5.9	----	----	----	----	7.4	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	2.9	----	----	----	----	3.7	----
PROBLEM IN TOOLS	2.9	----	----	----	----	3.7	----
ROBOT WON'T MOVE	2.9	----	----	----	----	3.7	----
ROBOT COLLISION	----	----	----	----	----	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(23.5)	(0)	(0)	(33.3)	(100)	(22.2)	(0)
OTHER COMPONENT FAILURE	8.8	----	----	----	----	11.1	----
SYSTEM FAILURE	----	----	----	----	----	----	----
SYSTEM CHECKS	----	----	----	----	----	----	----
CHECK ON PARTS	----	----	----	----	----	----	----
PART VARIATION	----	----	----	----	----	----	----
QUALITY PROBLEM	2.9	----	----	----	----	3.7	----
PROCESS PROBLEM	----	----	----	----	----	----	----
SERVICES PROBLEM	----	----	----	----	----	----	----
OTHER EQUIP'T PROBLEM	44.1	----	----	----	----	55.6	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----
HUMAN ERROR	2.9	----	----	----	----	3.7	----
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	----	----	----	----	----	----	----

APPENDIX F

Details of Underlying Reasons and Their Associated Downtime

UNDERLYING REASONS AND THEIR ASSOCIATED DOWNTIME

UNDERLYING REASON		ROBOT SYSTEM			
		'A'	'B5'	'B6'	'B7'
ROBOT - NO DETAIL	DOWNTIME	23	422	197	501
	MEAN DOWNTIME	5.8	38.4	9.9	20.0
	NO. OF INCIDENTS	5	13	24	34
	NO. OF VALID INCIDENTS	4	11	20	25
ROBOT OUT OF SYNCH'	DOWNTIME	13	10	350	336
	MEAN DOWNTIME	13.0	10.0	5.3	4.0
	NO. OF INCIDENTS	3	1	69	94
	NO. OF VALID INCIDENTS	1	1	66	83
STIFFNESS IN ROBOT ARM	DOWNTIME	----	----	123	10
	MEAN DOWNTIME	----	----	15.4	2.5
	NO. OF INCIDENTS	2	----	8	4
	NO. OF VALID INCIDENTS	0	----	8	4
CABLE PROBLEM	DOWNTIME	----	225	205	466
	MEAN DOWNTIME	----	56.3	15.8	22.2
	NO. OF INCIDENTS	----	6	13	22
	NO. OF VALID INCIDENTS	----	4	13	21
COMP'NT FAILURE IN ROBOT ARM	DOWNTIME	180	185	373	210
	MEAN DOWNTIME	180	61.7	23.3	52.5
	NO. OF INCIDENTS	1	3	19	9
	NO. OF VALID INCIDENTS	1	3	16	4
BLOWN FUSES	DOWNTIME	----	----	184	69
	MEAN DOWNTIME	----	----	16.7	11.5
	NO. OF INCIDENTS	----	----	11	6
	NO. OF VALID INCIDENTS	----	----	11	6
ROBOT IN E-STOP	DOWNTIME	8	134	698	713
	MEAN DOWNTIME	2.7	6.1	3.2	3.4
	NO. OF INCIDENTS	8	35	225	217
	NO. OF VALID INCIDENTS	3	22	216	207
FAULT IN CABINET	DOWNTIME	420	28	362	179
	MEAN DOWNTIME	420	28	32.9	19.9
	NO. OF INCIDENTS	1	1	12	10
	NO. OF VALID INCIDENTS	1	1	11	9

UNDERLYING REASON		ROBOT SYSTEM			
		'A'	'B5'	'B6'	'B7'
ERRATIC ROBOT	DOWNTIME	155	250	1166	559
	MEAN DOWNTIME	77.5	50.0	38.9	24.3
	NO. OF INCIDENTS	7	6	35	28
	NO. OF VALID INCIDENTS	2	5	30	23
FAULT IN TEACH PENDANT	DOWNTIME	10	----	----	----
	MEAN DOWNTIME	10	----	----	----
	NO. OF INCIDENTS	2	----	1	----
	NO. OF VALID INCIDENTS	1	----	0	----
POWER SUPPLY FAULT	DOWNTIME	----	----	----	----
	MEAN DOWNTIME	----	----	----	----
	NO. OF INCIDENTS	----	----	----	----
	NO. OF VALID INCIDENTS	----	----	----	----
PROBLEM IN TOOLS	DOWNTIME	88	698	1670	1890
	MEAN DOWNTIME	17.6	36.7	12.6	9.3
	NO. OF INCIDENTS	16	27	165	245
	NO. OF VALID INCIDENTS	5	19	133	204
ROBOT WON'T MOVE	DOWNTIME	52	7	108	55
	MEAN DOWNTIME	26.0	3.5	12.0	6.9
	NO. OF INCIDENTS	2	2	10	9
	NO. OF VALID INCIDENTS	2	2	9	8
ROBOT COLLISION	DOWNTIME	----	----	430	231
	MEAN DOWNTIME	----	----	10.2	13.6
	NO. OF INCIDENTS	----	----	42	19
	NO. OF VALID INCIDENTS	----	----	42	17
OVERHEATING HYDRAULICS	DOWNTIME	----	----	----	----
	MEAN DOWNTIME	----	----	----	----
	NO. OF INCIDENTS	----	----	----	----
	NO. OF VALID INCIDENTS	----	----	----	----
OTHER COMPONENT FAILURE	DOWNTIME	12	520	998	966
	MEAN DOWNTIME	4.0	52.0	31.2	33.3
	NO. OF INCIDENTS	6	14	41	36
	NO. OF VALID INCIDENTS	3	10	32	29
SYSTEM FAILURE	DOWNTIME	660	69	142	223
	MEAN DOWNTIME	47.1	13.8	7.5	2.8
	NO. OF INCIDENTS	17	10	19	82
	NO. OF VALID INCIDENTS	14	5	19	81

UNDERLYING REASON		ROBOT SYSTEM			
		'A'	'B5'	'B6'	'B7'
SYSTEM CHECKS	DOWNTIME	244	----	----	----
	MEAN DOWNTIME	22.2	----	----	----
	NO. OF INCIDENTS	17	----	----	----
	NO. OF VALID INCIDENTS	11	----	----	----
CHECK ON PARTS	DOWNTIME	375	----	----	----
	MEAN DOWNTIME	20.8	----	----	----
	NO. OF INCIDENTS	24	----	----	----
	NO. OF VALID INCIDENTS	18	----	----	----
PART VARIATION	DOWNTIME	248	52	1058	1175
	MEAN DOWNTIME	17.7	6.5	8.3	6.9
	NO. OF INCIDENTS	24	41	140	186
	NO. OF VALID INCIDENTS	14	8	127	171
QUALITY PROBLEM	DOWNTIME	1844	235	618	551
	MEAN DOWNTIME	97.1	10.7	14.0	22.0
	NO. OF INCIDENTS	41	43	97	80
	NO. OF VALID INCIDENTS	19	22	44	25
PROCESS PROBLEM	DOWNTIME	588	123	207	220
	MEAN DOWNTIME	84.0	1.5	20.7	14.7
	NO. OF INCIDENTS	12	137	21	24
	NO. OF VALID INCIDENTS	7	84	10	15
SERVICES PROBLEM	DOWNTIME	174	28	215	246
	MEAN DOWNTIME	34.8	9.3	16.5	12.9
	NO. OF INCIDENTS	12	4	16	20
	NO. OF VALID INCIDENTS	5	3	13	19
OTHER EQUIP'T PROBLEM	DOWNTIME	3699	1964	2414	2070
	MEAN DOWNTIME	63.8	14.3	5.4	4.3
	NO. OF INCIDENTS	96	261	473	530
	NO. OF VALID INCIDENTS	58	137	448	481
SAFETY FUNCTION PROBLEM	DOWNTIME	26	----	55	----
	MEAN DOWNTIME	4.3	----	18.3	----
	NO. OF INCIDENTS	11	----	3	2
	NO. OF VALID INCIDENTS	6	----	3	0
HUMAN ERROR	DOWNTIME	169	65	28	27
	MEAN DOWNTIME	21.1	32.5	3.1	2.7
	NO. OF INCIDENTS	10	5	9	10
	NO. OF VALID INCIDENTS	8	2	9	10

UNDERLYING REASON		ROBOT SYSTEM			
		'A'	'B5'	'B6'	'B7'
WELD FAILURE	DOWNTIME	1055	31	218	212
	MEAN DOWNTIME	6.1	3.4	4.7	3.0
	NO. OF INCIDENTS	381	29	74	145
	NO. OF VALID INCIDENTS	172	9	46	70
SEQUENCE FAULT	DOWNTIME	1702	521	96	0
	MEAN DOWNTIME	54.9	28.9	5.6	0
	NO. OF INCIDENTS	45	20	17	1
	NO. OF VALID INCIDENTS	31	18	17	1
MISSING	DOWNTIME	----	87	15	42
	MEAN DOWNTIME	----	21.8	2.1	7.0
	NO. OF INCIDENTS	----	4	9	7
	NO. OF VALID INCIDENTS	----	4	7	6

UNDERLYING REASONS AND THEIR ASSOCIATED DOWNTIME

UNDERLYING REASONS		ROBOT SYSTEMS			
		'F'	'H'		OVERALL
ROBOT - NO DETAIL	DOWNTIME	694	----		1837
	MEAN DOWNTIME	115.7	----		27.8
	NO. OF INCIDENTS	6	----		82
	NO. OF VALID INCIDENTS	6	----		66
ROBOT OUT OF SYNCH'	DOWNTIME	95	----		804
	MEAN DOWNTIME	47.5	----		5.3
	NO. OF INCIDENTS	2	----		169
	NO. OF VALID INCIDENTS	2	----		153
STIFFNESS IN ROBOT ARM	DOWNTIME	----	----		133
	MEAN DOWNTIME	----	----		11.1
	NO. OF INCIDENTS	----	----		14
	NO. OF VALID INCIDENTS	----	----		12
CABLE PROBLEM	DOWNTIME	420	360		1676
	MEAN DOWNTIME	52.5	360		35.7
	NO. OF INCIDENTS	8	1		50
	NO. OF VALID INCIDENTS	8	1		47
COMP'NT FAILURE IN ROBOT ARM	DOWNTIME	650	960		2558
	MEAN DOWNTIME	216.7	960		91.4
	NO. OF INCIDENTS	3	1		36
	NO. OF VALID INCIDENTS	3	1		28
BLOWN FUSES	DOWNTIME	----	----		253
	MEAN DOWNTIME	----	----		14.9
	NO. OF INCIDENTS	----	----		17
	NO. OF VALID INCIDENTS	----	----		17
ROBOT IN E-STOP	DOWNTIME	60	120		1733
	MEAN DOWNTIME	8.6	120		3.8
	NO. OF INCIDENTS	7	1		493
	NO. OF VALID INCIDENTS	7	1		456
FAULT IN CABINET	DOWNTIME	350	10320		11659
	MEAN DOWNTIME	116.7	10320		448.4
	NO. OF INCIDENTS	3	1		28
	NO. OF VALID INCIDENTS	3	1		26

UNDERLYING REASONS		ROBOT SYSTEMS			
		'F'	'H'		OVERALL
ERRATIC ROBOT	DOWNTIME	565	270		2965
	MEAN DOWNTIME	13.1	135.0		28.2
	NO. OF INCIDENTS	43	3		122
	NO. OF VALID INCIDENTS	43	2		105
FAULT IN TEACH PENDANT	DOWNTIME	----	----		10
	MEAN DOWNTIME	----	----		10
	NO. OF INCIDENTS	----	----		3
	NO. OF VALID INCIDENTS	----	----		1
POWER SUPPLY FAULT	DOWNTIME	458	----		458
	MEAN DOWNTIME	9.0	----		9.0
	NO. OF INCIDENTS	51	----		51
	NO. OF VALID INCIDENTS	51	----		51
PROBLEM IN TOOLS	DOWNTIME	285	250		4881
	MEAN DOWNTIME	15.8	125.0		12.8
	NO. OF INCIDENTS	18	2		473
	NO. OF VALID INCIDENTS	18	2		381
ROBOT WON'T MOVE	DOWNTIME	10	----		232
	MEAN DOWNTIME	10	----		10.5
	NO. OF INCIDENTS	2	----		25
	NO. OF VALID INCIDENTS	1	----		22
ROBOT COLLISION	DOWNTIME	----	----		661
	MEAN DOWNTIME	----	----		11.2
	NO. OF INCIDENTS	----	----		61
	NO. OF VALID INCIDENTS	----	----		59
OVERHEATING HYDRAULICS	DOWNTIME	140	----		140
	MEAN DOWNTIME	12.7	----		12.7
	NO. OF INCIDENTS	11	----		11
	NO. OF VALID INCIDENTS	11	----		11
OTHER COMPONENT FAILURE	DOWNTIME	6263	660		9419
	MEAN DOWNTIME	46.1	660		44.6
	NO. OF INCIDENTS	136	1		234
	NO. OF VALID INCIDENTS	136	1		211
SYSTEM FAILURE	DOWNTIME	----	----		1094
	MEAN DOWNTIME	----	----		9.2
	NO. OF INCIDENTS	----	----		128
	NO. OF VALID INCIDENTS	----	----		119

UNDERLYING REASONS		ROBOT SYSTEMS			
		'F'	'H'		OVERALL
SYSTEM CHECKS	DOWNTIME	15	----		259
	MEAN DOWNTIME	15	----		21.6
	NO. OF INCIDENTS	1	----		18
	NO. OF VALID INCIDENTS	1	----		12
CHECK ON PARTS	DOWNTIME	----	----		375
	MEAN DOWNTIME	----	----		20.8
	NO. OF INCIDENTS	----	----		24
	NO. OF VALID INCIDENTS	----	----		18
PART VARIATION	DOWNTIME	475	----		3008
	MEAN DOWNTIME	16.4	----		8.6
	NO. OF INCIDENTS	29	----		420
	NO. OF VALID INCIDENTS	29	----		349
QUALITY PROBLEM	DOWNTIME	2477	----		5725
	MEAN DOWNTIME	13.4	----		19.4
	NO. OF INCIDENTS	187	----		448
	NO. OF VALID INCIDENTS	185	----		295
PROCESS PROBLEM	DOWNTIME	175	----		1313
	MEAN DOWNTIME	15.9	----		10.3
	NO. OF INCIDENTS	11	----		205
	NO. OF VALID INCIDENTS	11	----		127
SERVICES PROBLEM	DOWNTIME	455	----		1118
	MEAN DOWNTIME	23.9	----		18.9
	NO. OF INCIDENTS	19	----		71
	NO. OF VALID INCIDENTS	19	----		59
OTHER EQUIP'T PROBLEM	DOWNTIME	5569	----		15716
	MEAN DOWNTIME	22.4	----		11.4
	NO. OF INCIDENTS	252	----		1612
	NO. OF VALID INCIDENTS	249	----		1373
SAFETY FUNCTION PROBLEM	DOWNTIME	30	----		111
	MEAN DOWNTIME	10.0	----		7.9
	NO. OF INCIDENTS	3	----		19
	NO. OF VALID INCIDENTS	3	----		14
HUMAN ERROR	DOWNTIME	160	140		589
	MEAN DOWNTIME	22.9	70.0		15.5
	NO. OF INCIDENTS	7	3		44
	NO. OF VALID INCIDENTS	7	2		38

UNDERLYING REASONS		ROBOT SYSTEMS			
		'F'	'H'		OVERALL
WELD FAILURE	DOWNTIME	----	----		1516
	MEAN DOWNTIME	----	----		5.1
	NO. OF INCIDENTS	----	----		629
	NO. OF VALID INCIDENTS	----	----		297
SEQUENCE FAULT	DOWNTIME	90	----		2409
	MEAN DOWNTIME	10.0	----		31.7
	NO. OF INCIDENTS	9	----		92
	NO. OF VALID INCIDENTS	9	----		76
MISSING	DOWNTIME	50	----		194
	MEAN DOWNTIME	16.7	----		9.7
	NO. OF INCIDENTS	3	----		23
	NO. OF VALID INCIDENTS	3	----		20

APPENDIX G

Downtime for Robot Related Problems in Each System

ROBOT RELATED PROBLEMS
FOR EACH ROBOT IN EACH SYSTEM

FACTORY A

		ROBOT NUMBERS												
	ALL CASES	NOT GIVEN	1	2	3	4	5	6	7	8	9	10	11	12
TOTAL DOWNTIME (mins)	949	17	470	35	274	123	----	----	----	----	11	4	----	15
INCIDENTS	47	6	4	3	10	3	4	----	2	2	4	4	3	2
VALID INCIDENTS	20	1	3	1	7	2	0	----	0	0	4	1	0	1
MEAN DOWNTIME	47.5	17.0	156.7	35.0	39.1	61.5	----	----	----	----	2.8	4.0	----	15.0

FACTORY B - SYSTEM B5

		ROBOT NUMBERS								
	ALL CASES	NOT GIVEN	1	2	3	4	5	6	7	8
TOTAL DOWNTIME (mins)	1959	303	66	640	240	12	25	539	73	61
INCIDENTS	94	17	9	14	10	3	4	18	9	10
VALID INCIDENTS	68	7	6	14	8	3	4	12	7	7
MEAN DOWNTIME	28.8	43.3	11.0	45.7	30.0	4.0	6.3	44.9	10.4	8.7

FACTORY B - SYSTEM B6

	ROBOT NUMBERS												
	ALL CASES	NOT GIVEN	171	172	173	181	182	211	251	252	253	261	262
TOTAL DOWNTIME (mins)	5866	265	71	596	320	376	96	94	246	66	735	881	237
INCIDENTS	634	16	19	21	51	86	26	12	24	13	47	35	24
VALID INCIDENTS	575	14	19	19	49	86	24	10	19	11	40	34	20
MEAN DOWNTIME	10.2	18.9	3.7	31.4	6.5	4.4	4.0	9.4	12.9	6.0	18.4	25.9	11.9

	ROBOT NUMBERS											
	263	291	292	293	301	302	311	312	321	322	331	332
TOTAL DOWNTIME (mins)	188	46	105	94	17	52	65	193	462	299	78	284
INCIDENTS	29	11	25	21	8	12	13	18	28	31	28	36
VALID INCIDENTS	25	10	22	20	6	11	11	17	26	25	25	32
MEAN DOWNTIME	7.5	4.6	4.8	4.7	2.8	4.7	5.9	11.4	17.8	12.0	3.1	8.9

FACTORY B SYSTEM B7

		ROBOT NUMBERS											
	ALL CASES	NOT GIVEN	171	172	173	181	182	211	251	252	253	261	262
TOTAL DOWNTIME (mins)	5219	119	85	509	330	259	177	220	72	171	496	17	460
INCIDENTS	697	21	31	43	48	16	23	27	7	16	40	8	58
VALID INCIDENTS	611	17	27	35	41	13	21	23	7	16	34	6	49
MEAN DOWNTIME	8.5	7.0	3.1	14.5	8.0	19.9	8.4	9.6	10.3	10.7	14.6	2.8	9.4

		ROBOT NUMBERS										
	263	291	292	293	301	302	311	312	321	322	331	332
TOTAL DOWNTIME (mins)	656	124	88	183	61	159	60	467	210	99	70	127
INCIDENTS	108	34	30	24	9	10	14	48	33	18	18	13
VALID INCIDENTS	99	30	29	21	7	10	12	42	29	17	15	11
MEAN DOWNTIME	6.6	4.1	3.0	8.7	8.7	15.9	5.0	11.1	7.2	5.8	4.7	11.5

FACTORY F

	ROBOT NUMBERS ALL CASES	NOT GIVEN	1	2
TOTAL DOWNTIME (mins)	3727	63	864	2800
INCIDENTS	154	4	63	87
VALID INCIDENTS	153	4	63	86
MEAN DOWNTIME	24.4	15.8	13.7	32.6

FACTORY H

	ROBOT NUMBERS ALL CASES	NOT GIVEN	1	2
TOTAL DOWNTIME (mins)	12280	----	10600	1680
INCIDENTS	9	----	4	5
VALID INCIDENTS	8	----	4	4
MEAN DOWNTIME	1535	----	2650	420

APPENDIX H

Robot Related Problems by Place and by Robot Type

ROBOT RELATED PROBLEMS BY PLACE

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	1635	47	94	634	697	154	9
DOWNTIME:							
MINUTES	11340	229	759	4246	4139	1927	40
HOURS	311	12	20	27	18	30	204
TOTAL - IN MINUTES	30000	949	1959	5866	5219	3727	12280
MEAN DOWNTIME	20.9	47.5	28.8	10.2	8.5	24.4	1535
NO. OF INCIDENTS WITH NO TIME GIVEN	200	27	26	59	86	1	1
ACTIONS TAKEN (% of incidents)							
REPLACEMENT OF FAULTY EQUIP'T	20.9	19.1	22.3	21.8	20.5	17.5	33.3
ADJUSTMENT/ CLEANING	11.8	4.3	11.7	9.8	9.8	20.1	33.3
RESETTING	60.0	42.6	48.9	62.0	60.1	65.6	11.1
REPROGRAMMING	14.1	23.4	21.3	12.0	9.6	34.4	44.4
ROUTINE MAINTENANCE	1.5	8.5	2.1	2.4	0.4	----	----
UNPLANNED MAINTENANCE	28.0	27.7	33.0	28.2	32.0	6.5	22.2
FAULT DIAGNOSIS	3.1	25.5	5.3	2.4	2.3	----	22.2
ANY OTHER ACTION	1.2	4.3	5.3	0.9	0.9	0.6	----
REASONS GIVEN (% of incidents)							
MECHANICAL PROBLEM WITH ROBOT	87.2	59.6	87.2	89.8	93.7	59.1	22.2
MECHANICAL PROBLEM WITH OTHER EQUIP'T	3.0	14.9	1.1	3.0	1.4	6.5	22.2
ELECTRICAL PROBLEM WITH ROBOT	65.7	42.6	59.6	66.4	66.3	73.4	33.3
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	0.6	2.1	1.1	0.8	0.3	0.6	----
ELECTRICAL PROBLEM WITH INTERFACE	0.6	----	1.1	0.9	0.1	0.6	----
INSPECTION	1.0	8.5	4.3	0.2	0.1	3.9	----
PROGRAMME PROBLEM	3.2	4.3	7.4	0.8	3.9	7.1	11.1
QUALITY PROBLEMS	10.3	4.3	13.8	6.5	9.2	31.8	----
ERRATIC ROBOT	4.3	6.4	----	7.3	1.6	5.8	11.1
DROPPED PART	----	----	----	----	----	----	----
THREAT OF DAMAGE TO:							
ROBOT	3.5	4.3	----	0.8	1.1	26.6	11.1
PERSONS	----	----	----	----	----	----	----
MACHINERY	1.7	----	1.1	1.4	2.2	0.6	11.1
ANY OTHER REASON	0.4	6.4	----	0.2	0.3	0.6	----

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
	MEANS OF INTERRUPTION (% of incidents)						
E-STOP PRESSED	0.1	----	----	0.2	----	0.6	----
OTHER HUMAN ACTION	14.4	40.4	28.7	11.2	12.3	17.5	55.6
AUTOMATIC STOP	62.1	42.6	53.2	72.2	61.7	34.4	44.4
SENSOR STOP	23.2	17.0	18.1	16.2	26.0	46.1	----
	CLASSIFICATION OF INCIDENT (% of incidents)						
ACCIDENT TO PERSON	----	----	----	----	----	----	----
ACCIDENT TO MACHINE	4.9	----	3.2	7.3	4.3	0.6	----
ACCIDENT TO BOTH	----	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	2.1	----	----	3.6	1.3	----	22.2
NEAR MISS	0.2	----	----	0.5	----	----	----
INCIDENT - NO DAMAGE	73.0	61.7	70.2	74.3	82.4	33.8	22.2
HAZARD ANTICIPATED	1.5	----	2.1	0.3	1.9	3.2	22.2
NO DAMAGE LIKELY	17.9	38.3	24.5	13.9	10.0	58.4	33.3
	PERSONS IDENTIFYING THE PROBLEM (% of incidents)						
FITTER	3.9	93.6	6.4	1.1	1.0	----	----
ELECTRICIAN	86.5	95.7	90.2	95.7	97.1	0.6	22.2
PROD. ENGINEER	0.3	----	----	0.6	0.1	----	----
OPERATOR	0.6	----	----	----	----	0.6	88.9
FOREMAN/CHARGEHAND	9.4	68.1	1.1	1.4	0.3	70.8	----
LEADING-HAND	1.7	----	----	----	----	18.2	----
SERVICE ENGINEER	----	----	----	----	----	----	----
OTHER	4.2	----	10.6	3.5	1.3	17.5	----
	PERSONS SORTING OUT THE PROBLEM (% of incidents)						
FITTER	41.3	100	42.6	42.7	42.8	6.5	22.2
ELECTRICIAN	89.4	100	91.5	97.8	99.3	8.4	44.4
PROD. ENGINEER	----	----	----	----	----	----	----
OPERATOR	0.2	----	----	----	----	----	33.3
FOREMAN/CHARGEHAND	10.2	74.5	----	----	----	85.7	----
LEADING-HAND	3.2	----	----	----	----	34.4	----
SERVICE ENGINEER	0.2	----	----	----	----	0.6	22.2
OTHER	6.2	----	4.3	12.5	2.4	0.6	----

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
ROBOT - NO DETAIL	5.0	10.6	13.8	3.8	4.9	3.9	----
ROBOT OUT OF SYNCH'	10.3	6.4	1.1	10.9	13.5	1.3	----
STIFFNESS IN ROBOT ARM	0.9	4.3	----	1.3	0.6	----	----
CABLE PROBLEM	3.1	----	6.4	2.1	3.2	5.2	11.1
COMP'NT FAILURE IN ROBOT ARM	2.2	2.1	3.2	3.0	1.3	1.9	11.1
BLOWN FUSES	1.0	----	----	1.7	0.9	----	----
ROBOT IN E-STOP	30.2	17.0	37.2	35.5	31.1	4.5	11.1
FAULT IN CABINET	1.7	2.1	1.1	1.9	1.4	1.9	11.1
ERRATIC ROBOT	7.5	14.9	6.4	5.5	4.0	27.9	33.3
FAULT IN TEACH PENDANT	0.2	4.3	----	0.2	----	----	----
POWER SUPPLY FAULT	3.1	----	----	----	----	33.1	----
PROBLEM IN TOOLS	28.9	34.0	28.7	26.0	35.2	11.7	22.2
ROBOT WON'T MOVE	1.5	4.3	2.1	1.6	1.3	1.3	----
ROBOT COLLISION	3.7	----	----	6.6	2.7	----	----
OVERHEATING HYDRAULICS	0.7	----	----	----	----	7.1	----

ROBOT RELATED PROBLEMS
BY ROBOT TYPE

	ALL CASES	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE NOT GIVEN
NUMBER OF INCIDENTS	1635	86	163	463	911	12
DOWNTIME:						
MINUTES	11340	483	1967	3103	5682	105
HOURS	311	13	234	31	32	1
TOTAL - IN MINUTES	30000	1263	16007	4963	7602	165
MEAN DOWNTIME	20.9	23.8	99.4	12.5	9.4	15.0
NO. OF INCIDENTS WITH NO TIME GIVEN	200	33	2	65	99	1
<u>ACTIONS TAKEN</u> (% of incidents)						
REPLACEMENT OF FAULTY EQUIP'T	20.9	10.5	18.4	20.7	22.3	25.0
ADJUSTMENT/ CLEANING	11.8	7.0	20.9	6.7	11.5	8.3
RESETTING	60.0	52.3	62.6	60.3	60.4	41.7
REPROGRAMMING	14.1	20.1	35.0	14.3	9.9	----
ROUTINE MAINTENANCE	1.5	4.7	----	1.7	1.3	----
UNPLANNED MAINTENANCE	28.0	20.9	7.4	29.2	31.4	58.3
FAULT DIAGNOSIS	3.1	14.0	1.2	2.2	2.9	----
ANY OTHER ACTION	1.2	4.7	0.6	1.7	0.8	----
<u>REASONS GIVEN</u> (% of incidents)						
MECHANICAL PROBLEM WITH ROBOT	87.2	67.4	57.1	90.1	95.1	83.3
MECHANICAL PROBLEM WITH OTHER EQUIP'T	3.0	10.5	7.4	1.9	2.1	----
ELECTRICAL PROBLEM WITH ROBOT	65.7	53.5	71.2	68.7	64.9	33.3
ELECTRICAL PROBLEM WITH OTHER EQUIP'T	0.6	3.5	0.6	0.6	0.3	----
ELECTRICAL PROBLEM WITH INTERFACE	0.6	----	0.6	0.6	0.5	----
INSPECTION	1.0	4.7	3.7	0.9	0.2	----
PROGRAMME PROBLEM	3.2	7.0	7.4	4.3	1.6	----
QUALITY PROBLEMS	10.3	4.7	30.1	9.1	7.9	16.7
ERRATIC ROBOT	4.3	3.5	6.1	1.5	5.3	16.7
DROPPED PART	----	----	----	----	----	----
THREAT OF DAMAGE TO:						
ROBOT	3.5	2.3	25.8	0.4	1.2	----
PERSONS	----	----	----	----	----	----
MACHINERY	1.7	----	1.2	1.5	2.0	----
ANY OTHER REASON	0.4	3.5	0.6	0.2	0.2	----

	ALL CASES	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE NOT GIVEN
MEANS OF INTERRUPTION (% of incidents)						
E-STOP PRESSED	0.1	----	0.6	----	0.1	----
OTHER HUMAN ACTION	14.4	26.7	19.6	14.9	12.1	8.3
AUTOMATIC STOP	62.1	53.5	35.0	65.2	66.3	50.0
SENSOR STOP	23.2	18.6	43.6	19.9	21.5	41.7
CLASSIFICATION OF INCIDENT (% of incidents)						
ACCIDENT TO PERSON	----	----	----	----	----	----
ACCIDENT TO MACHINE	4.9	1.2	0.6	4.5	6.0	16.7
ACCIDENT TO BOTH	----	----	----	----	----	----
ACCIDENT - NO DAMAGE	2.1	----	1.2	0.4	3.2	8.3
NEAR MISS	0.2	----	----	0.4	0.1	----
INCIDENT - NO DAMAGE	73.0	66.3	33.1	78.4	78.2	66.7
HAZARD ANTICIPATED	1.5	----	4.3	1.7	1.0	----
NO DAMAGE LIKELY	17.9	31.4	57.1	14.3	11.5	8.3
PERSONS IDENTIFYING THE PROBLEM (% of incidents)						
FITTER	3.9	51.2	----	2.0	1.2	----
ELECTRICIAN	86.5	94.2	1.8	95.2	96.5	91.7
PROD. ENGINEER	0.3	----	----	0.2	0.4	----
OPERATOR	0.6	----	5.5	----	----	----
FOREMAN/CHARGEHAND	9.4	38.4	66.9	1.1	0.7	----
LEADING-HAND	1.7	----	17.2	----	----	----
SERVICE ENGINEER	----	----	----	----	----	----
OTHER	4.2	1.2	16.6	3.9	2.4	----
PERSONS SORTING OUT THE PROBLEM (% of incidents)						
FITTER	41.3	66.3	7.4	38.0	46.3	66.7
ELECTRICIAN	89.4	97.7	10.4	97.4	98.5	100
PROD. ENGINEER	----	----	----	----	----	----
OPERATOR	0.2	----	1.8	----	----	----
FOREMAN/CHARGEHAND	10.2	40.7	81.0	----	----	----
LEADING-HAND	3.2	----	32.5	----	----	----
SERVICE ENGINEER	0.2	----	1.8	----	----	----
OTHER	6.2	----	0.6	6.7	7.5	8.3

UNDERLYING REASON FOR INCIDENT (% of incidents)

	ALL CASES	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE NOT GIVEN
ROBOT - NO DETAIL	5.0	23.3	3.7	6.9	2.6	----
ROBOT OUT OF SYNCH'	10.3	4.7	1.2	2.2	16.8	----
STIFFNESS IN ROBOT ARM	0.9	2.3	----	----	1.3	----
CABLE PROBLEM	3.1	----	5.5	2.6	3.2	----
COMP'NT FAILURE IN ROBOT ARM	2.2	1.2	2.5	1.7	2.5	----
BLOWN FUSES	1.0	----	----	1.3	1.2	----
ROBOT IN E-STOP	30.2	14.0	4.9	45.8	28.4	16.7
FAULT IN CABINET	1.7	3.5	2.5	1.3	1.6	----
ERRATIC ROBOT	7.5	10.5	28.2	6.3	4.0	16.7
FAULT IN TEACH PENDANT	0.2	2.3	----	----	0.1	----
POWER SUPPLY FAULT	3.1	----	31.3	----	----	----
PROBLEM IN TOOLS	28.9	26.7	12.3	29.8	31.4	50.0
ROBOT WON'T MOVE	1.5	11.6	1.2	0.9	1.0	----
ROBOT COLLISION	3.7	----	----	1.3	5.8	16.7
OVERHEATING HYDRAULICS	0.7	----	6.7	----	----	----

APPENDIX I

Details of Incidents with Short, Medium and Long Duration

INCIDENTS OF SHORT DURATION
(less than or equal to 10 minutes)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	3467	264	281	1150	1333	438	1
DOWNTIME:							
MINUTES	13916	1239	1137	3914	4227	3389	10
HOURS	----	----	----	----	----	----	----
TOTAL - IN MINUTES	13916	1239	1137	3914	4227	3389	10
MEAN DOWNTIME	4.0	4.7	4.0	3.4	3.2	7.7	10.0
NO. OF INCIDENTS WITH NO TIME GIVEN	----	----	----	----	----	----	----
	<u>UNDERLYING REASON FOR INCIDENT</u> (% of incidents)						
ROBOT - NO DETAIL	1.3	1.1	1.8	1.5	1.4	0.2	----
ROBOT OUT OF SYNCH'	4.0	----	0.4	5.1	5.9	----	----
STIFFNESS IN ROBOT ARM	0.2	----	----	0.3	0.3	----	----
CABLE PROBLEM	0.4	----	0.4	0.4	0.6	----	----
COMP'NT FAILURE IN ROBOT ARM	0.2	----	0.4	0.5	----	----	----
BLOWN FUSES	0.2	----	----	0.3	0.3	----	----
ROBOT IN E-STOP	12.7	1.1	7.5	18.2	15.1	1.4	----
FAULT IN CABINET	0.3	----	----	0.5	0.2	----	----
ERRATIC ROBOT	1.5	----	0.4	1.1	0.9	5.7	----
FAULT IN TEACH PENDANT	0.03	0.4	----	----	----	----	----
POWER SUPPLY FAULT	1.2	----	----	----	----	9.8	----
PROBLEM IN TOOLS	8.1	0.8	3.6	8.8	11.9	1.8	100
ROBOT WON'T MOVE	0.4	----	0.7	0.4	0.5	0.2	----
ROBOT COLLISION	1.4	----	----	3.1	0.8	----	----
OVERHEATING HYDRAULICS	0.2	----	----	----	----	1.6	----
	(32.2)	(3.4)	(15.0)	(40.4)	(38.0)	(20.8)	(100)
OTHER COMPONENT FAILURE	2.6	1.1	1.4	1.4	1.1	12.1	----
SYSTEM FAILURE	3.1	4.2	1.1	1.4	5.7	----	----
SYSTEM CHECKS	0.1	1.5	----	----	----	----	----
CHECK ON PARTS	0.3	3.4	----	----	----	----	----
PART VARIATION	9.0	3.0	2.5	10.5	12.2	3.4	----
QUALITY PROBLEM	5.5	1.1	6.0	2.3	1.3	29.5	----
PROCESS PROBLEM	2.9	1.1	29.5	0.3	0.8	0.5	----
SERVICES PROBLEM	0.9	0.4	1.1	0.6	0.9	1.8	----
OTHER EQUIP'T PROBLEM	32.7	12.1	35.2	36.6	33.9	29.5	----
SAFETY FUNCTION PROBLEM	0.3	2.3	----	0.1	----	0.5	----
HUMAN ERROR	0.7	1.9	----	0.8	0.8	0.2	----
WELD FAILURE	7.9	58.0	3.2	3.7	5.1	1.6	----
SEQUENCE FAULT	1.5	6.4	4.6	1.3	0.1	----	----

INCIDENTS OF MEDIUM DURATION
(between 10 minutes and one hour)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	787	87	62	169	161	307	1
DOWNTIME:							
MINUTES	18456	2207	1463	3940	3758	7068	20
HOURS	----	----	----	----	----	----	----
TOTAL - IN MINUTES	18456	2207	1463	3940	3758	7068	20
MEAN DOWNTIME	23.5	25.5	23.6	23.3	23.3	23.0	20.0
NO. OF INCIDENTS WITH NO TIME GIVEN	----	----	----	----	----	----	----
	UNDERLYING REASON FOR INCIDENT (% of incidents)						
ROBOT - NO DETAIL	1.7	1.1	6.5	1.2	1.2	1.3	----
ROBOT OUT OF SYNCH'	1.5	1.1	----	4.1	1.9	0.3	----
STIFFNESS IN ROBOT ARM	0.5	----	----	2.4	----	----	----
CABLE PROBLEM	3.3	----	3.2	4.7	6.8	1.6	----
COMP'NT FAILURE IN ROBOT ARM	1.4	----	----	4.7	1.2	0.3	----
BLOWN FUSES	1.1	----	----	4.1	1.2	----	----
ROBOT IN E-STOP	1.9	----	1.6	4.1	3.7	0.3	----
FAULT IN CABINET	1.5	----	1.6	1.8	3.7	0.7	----
ERRATIC ROBOT	5.2	1.1	3.2	7.1	5.0	5.9	----
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	1.0	----	----	----	----	2.6	----
PROBLEM IN TOOLS	10.7	3.4	8.1	14.8	25.5	3.3	----
ROBOT WON'T MOVE	1.0	2.3	----	2.4	1.2	----	----
ROBOT COLLISION	1.0	----	----	1.8	3.1	----	----
OVERHEATING HYDRAULICS	0.5	----	----	----	----	1.3	----
	(32.4)	(9.2)	(16.1)	(53.3)	(54.7)	(17.6)	(-)
OTHER COMPONENT FAILURE	10.5	----	6.5	7.1	6.8	18.2	----
SYSTEM FAILURE	1.4	1.1	3.2	1.8	3.1	----	----
SYSTEM CHECKS	0.9	6.9	----	----	----	0.3	----
CHECK ON PARTS	0.9	8.0	----	----	----	----	----
PART VARIATION	4.2	5.7	1.6	3.0	5.0	4.6	----
QUALITY PROBLEM	11.7	9.2	8.1	9.5	4.3	18.2	----
PROCESS PROBLEM	2.8	1.1	1.6	4.1	2.5	2.9	----
SERVICES PROBLEM	3.2	3.4	----	3.0	4.3	3.3	----
OTHER EQUIP'T PROBLEM	24.4	20.7	41.9	14.2	17.4	31.3	----
SAFETY FUNCTION PROBLEM	0.4	----	----	1.2	----	0.3	----
HUMAN ERROR	1.4	2.3	3.2	----	----	2.0	100
WELD FAILURE	3.0	21.8	----	1.8	1.2	----	----
SEQUENCE FAULT	2.0	10.3	4.8	1.2	----	0.7	----

INCIDENTS OF LONG DURATION
(greater than or equal to 1 hour)

	ALL CASES	'A'	'B5'	'B6'	'B7'	'F'	'H'
NUMBER OF INCIDENTS	187	35	27	31	25	60	9
DOWNTIME:							
MINUTES	3214	619	354	536	386	1289	30
HOURS	621	128	45	59	43	129	217
TOTAL - IN MINUTES	40474	8299	3054	4076	2966	9029	13050
MEAN DOWNTIME	216.4	237.1	113.1	131.5	118.6	150.5	1450
NO. OF INCIDENTS WITH NO TIME GIVEN	----	----	----	----	----	----	----
	<u>UNDERLYING REASON FOR INCIDENT</u> (% of incidents)						
ROBOT - NO DETAIL	4.3	----	7.4	3.2	16.0	1.7	----
ROBOT OUT OF SYNCH'	1.1	----	----	----	4.0	1.7	----
STIFFNESS IN ROBOT ARM	----	----	----	----	----	----	----
CABLE PROBLEM	3.7	----	3.7	----	8.0	5.0	11.1
COMP'NT FAILURE IN ROBOT ARM	5.3	2.9	7.4	6.5	8.0	3.3	11.1
BLOWN FUSES	----	----	----	----	----	----	----
ROBOT IN E-STOP	0.5	----	----	----	----	----	11.1
FAULT IN CABINET	2.7	2.9	----	6.5	----	1.7	11.1
ERRATIC ROBOT	7.0	2.9	7.4	16.1	12.0	----	22.2
FAULT IN TEACH PENDANT	----	----	----	----	----	----	----
POWER SUPPLY FAULT	----	----	----	----	----	----	----
PROBLEM IN TOOLS	8.6	----	14.8	22.6	16.0	----	11.1
ROBOT WON'T MOVE	----	----	----	----	----	----	----
ROBOT COLLISION	2.1	----	----	9.7	4.0	----	----
OVERHEATING HYDRAULICS	----	----	----	----	----	----	----
	(35.3)	(8.6)	(40.7)	(64.5)	(68.0)	(13.3)	(77.8)
OTHER COMPONENT FAILURE	20.3	----	7.4	12.9	16.0	45.0	11.1
SYSTEM FAILURE	1.1	5.7	----	----	----	----	----
SYSTEM CHECKS	0.5	2.9	----	----	----	----	----
CHECK ON PARTS	1.1	5.7	----	----	----	----	----
PART VARIATION	1.6	2.9	----	3.2	4.0	----	----
QUALITY PROBLEM	5.9	22.9	----	6.5	4.0	----	----
PROCESS PROBLEM	2.1	8.6	----	----	4.0	----	----
SERVICES PROBLEM	1.6	2.9	----	3.2	----	1.7	----
OTHER EQUIP'T PROBLEM	25.7	22.9	44.4	9.7	4.0	40.0	----
SAFETY FUNCTION PROBLEM	----	----	----	----	----	----	----
HUMAN ERROR	1.1	2.9	----	----	----	----	11.1
WELD FAILURE	----	----	----	----	----	----	----
SEQUENCE FAULT	3.7	14.3	7.4	----	----	----	----

APPENDIX J

Statistical Analysis of Production Problem Data

STATISTICAL ANALYSIS OF PRODUCTION PROBLEM DATA

The detailed discussion in Chapter 5 on interruptions to production deals with the pattern of downtime figures in the robot systems. Differences between the systems and between types of robots are identified in this discussion. However, a major problem in the comparison of frequencies (in terms of percentages) is identified, namely the small sample base for some percentages. An analysis of the statistical significance of the differences overcomes this problem and is presented here. The statistical significance tests are presented in sections, similar to the sections in the chapter. However, tests for the significance in the differences between frequencies of occurrence are presented before the tests on the difference between mean downtimes.

THE ANALYSIS OF FREQUENCIES OF OCCURRENCE

Throughout the statistical tests on the frequencies of occurrence the Chi-square test (X^2) is applied (Siegel 1956, pp. 42-47).

The Overall Incidents

Table G.1 gives the number of incidents recorded in each system along with the production hours for each system over which the incidents were recorded. In each column there is a bracketed figure for the expected number of incidents. These are calculated by taking the proportion of the total production hours in each system and obtaining the product of this proportion and the total number of incidents. Thus the expected number of incidents in A is:-

$$\frac{629}{5844.5} \times 5602 = 602.9$$

	A	B5	B6	B7	F	H	Total
Incidents	(602.9) 743	(714.6) 662	(1032.3) 1553	(934.1) 1820	(1118.1) 811	(1200.1) 13	5602
Production Hours	629	745.5	1077	974.5	1166.5	1252	5844.5

Table G.1

χ^2 is given by $\sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$ (Siegel 1956, p. 43)

(where i is the number of categories up to k)

The number of degrees of freedom equal (k-1)
O_i is the observed number of cases in the i^{th} category.
E_i is the expected number of cases in the i^{th} category
under H_0 (the null hypothesis)

The null hypothesis (H_0) in this case is that the number of incidents in each system is proportional to their share of the total production hours. In other words, there is no differentiation between the systems.

The alternative hypothesis (H_1) is that there is a difference between the systems with respect to the number of incidents as a proportional of total production hours.

N = 5620 in the test.

The sampling distribution of χ^2 follows the Chi-square distributions for various degrees of freedom given in the Table C,(Siegel 1956, p. 249). Table C gives the critical Chi-square values at various significance levels. A value for χ^2 calculated as above which is less than the critical value for the degrees of freedom (Chi-square critical) will mean that the null hypothesis is accepted, whereas a value over the critical value will mean that it is rejected. A high significance level ($\alpha = 0.01$) is chosen to reduce the possibility of rejecting H_0 when it is true. The probability of the error of rejecting a correct H_0 (commonly referred to as a Type I error) is the value of the significance level α. With such a value, the chance of accepting H_0 where it is in fact false is higher than if a significance level of, say, $\alpha = 0.05$ was taken but the chance of rejecting H_0 when it is time is smaller.

Thus the tests is erring on the conservative side to make sure that there is a high significance to any identified variation from the null hypothesis.

χ^2 for Table G.1 equals 2397.85
Chi-square (critical) for 5 degrees of freedom equals 15.09 (for $\alpha = 0.01$).
Thus the null hypothesis is rejected.

Therefore there is a significant difference in the number of incidents per production period in each system. The biggest difference from the expected value occurs with H, which has a very small number of incidents. If the test is repeated without the incidents in H, one can test to see if there is any significant difference between the rest. This is shown in Table G.2.

	A	B5	B6	B7	F	Total
Incidents	(765.5) 743	(907.3) 662	(1310.7) 1553	(1186.0) 1820	(1419.6) 811	5589
Production Hours	629	745.5	1077	974.5	1166.5	4592.5

Table G.2

χ^2 for the Table G.2 equals 711.60.
Chi-square (critical) for 4 degrees of freedom equals 13.28
Therefore the null hypothesis is rejected once more.

If only B6 and B7 are considered, Table G.3 is produced. It is of particular interest to check if the difference between these two is significant, since they are identified in Chapter 5 as the most similar.

	B6	B7	Total
Incidents	(1770.8) 1553	(1602.2) 1820	3373
Production Hours	1077	974.5	2051.5

Table G.3

χ^2 for Table G.3 equals 56.37.
Chi-square (critical) for one degree of freedom equals 6.64.

Therefore, even for these two systems, the null hypothesis is rejected. Thus each system's incidents is taken from a separate population, when the number of incidents per production period are tested for a significance level of 0.01.

The classification of the incidents

In the overall frequency tables in Appendix A, incidents have a categorisation according to the classification of the severity of the incident. It has been stated that the proportion of incidents resulting in accidents in each system is low. To show whether this pattern is the same or significantly different in each system, a Chi-square test can be applied to the frequencies of accidents and non-accidents. For this, the categories have to be combined since some have very few incidents in them.

Siegel states that one must ensure that less than 20% of the cells of a table have expected frequencies of less than 5 and no cell has an expected frequency of less than 1 (Siegel, 1956, p. 178). If these conditions are not satisfied, the results of the test cannot be said to be meaningful. The manner of combining categories must follow a logical pattern, and in this case, it is sensible to separate those where no accident or damage occurred or was likely to occur from cases where accidents did occur or could have occurred. Thus the first 5 categories and the hazard anticipated category are combined, leaving Incident - no damage and No damage likely as the other group. In Table G.4 the incidents with no classification (34) are excluded.

	A	B5	B6	B7	F	H	Total
Accidents and Potential Accidents	42.6 16	37.8 14	88.8 126	104.2 119	44.9 36	0.7 8	319
Other Incidents	700.4 727	621.2 645	1461.2 1424	1714.8 1700	739 748	12.3 5	5249
Total	743	659	1550	1819	784	13	5568

The condition of an expected frequency of at least one for each expected frequency is not fulfilled even with this combination of categories. However, it is clear that H has an unusual distribution of incidents with more incidents in the accidents and potential accidents than in the other incident group. If the remaining 5 systems are significantly different on their own, it is a reasonable assumption that the incidents in H would only serve to increase this difference. The same can be said of the act of combination of categories, since any variation within the combined categories in each system would increase the variation and thus lower the possibility of the incidents in each being classed as similar. Both these actions of simplification of the categories make the test a conservative one. Table G.5 is for the remaining five systems.

	A	B5	B6	B7	F	Total
Accidents and Potential Accidents	(41.6) 16	(36.9) 14	(86.8) 126	(101.8) 119	(43.9) 36	311
Other Incidents	(701.4) 727	(622.1) 645	(1463.2) 1424	(1717.2) 1700	(740.1) 748	5244
Total	743	659	1550	1819	784	5555

Table G.5

For this test, the null hypothesis (H_0) is that the incidents in the systems are from the same population, so that they have frequencies for accidents and potential accidents that are proportional to the total number of incidents in each system.

The alternative hypothesis (H_1) is that the incidents in the systems can be differentiated in terms of the proportion of accidents and potential accidents.

In this test, $n = 5555$, and α is the same as for the previous tests, that is equal to 0.01. In this case, the degrees of freedom for the Chi-square distribution are given by $(k-1)(r-1)$, where k is the number of columns in the table and r is the number of rows (excluding Total). Thus there are four degrees of freedom.

χ^2 for Table G.5 equals 55.06

Chi-square (critical) equals 13.28.

The calculated values exceeds the critical value considerably and the null hypothesis is rejected once more. The systems are thus significantly different when the classification of the incidents in each system is considered.

The two most similar systems are B6 and B7. Table G.6 shows the observed and expected frequencies for these two systems.

	B6	B7	Total
Accidents and Potential Accidents	(112.7) 126	(132.3) 119	245
Other Incidents	(1437.3) 1424	(1686.7) 1700	3124
Total	1550	1819	3369

Table G.6

χ^2 for Table G.6 equals 3.13.

Chi-square (critical) equals 6.64.

Therefore, in this case, we accept H_0. Thus, the incidents in B6 and B7 are from the same population when considered in terms of this combination of the classification categories. However, there are enough incidents in each category with these two systems for the categories to be tested separately. Table G.7, shows the full table for B6 and B7, exluding only those categories in which neither have any incidents.

χ^2 for Table G.7 equals 57.98

Chi-square (critical) value equals 15.09.

	B6	B7	Total
Accident to Machine	(84.7) 95	(99.3) 89	184
Accident/No Damage	(16.1) 23	(18.9) 12	35
Near Miss	(1.4) 3	(1.6) -	3
Incident - No Damage	(1197.6) 1120	(1405.4) 1483	2603
Hazard Anticipated	(10.6) 15	(12.4) 18	23
No Damage Likely	(239.7) 304	(281.3) 217	521
Total	1550	1819	3369

Table G.7

Thus the null hypothesis is rejected. This result shows that the close fit between the frequencies for accidents and potential accidents and other incidents is not maintained within each of these groups of categories. Thus the variation between the two systems in terms of individual categories is significantly different, although not when accidents, potential accidents and other incidents are compared as combined groups.

The underlying reasons

The null hypothesis H_0 for this test is similar to those above, that the systems come from the same population, with no difference in the underlying reasons for the incidents. The alternative hypothesis, H_1, is that a difference exists in the frequencies of the underlying reasons as a proportion of the total incidents for each system.

In this test, we have numerous underlying reasons with only a few incidents in some systems. To ensure that the conditions required for X^2 test (that each expected frequency should not be less than one and fewer than 20% should have less than 5) it is possible to consider two groups of underlying reasons and test the significance of the differences. The incidents are separated into robot related incidents and the others. Variations are noted between systems even on this level in Chapter 5. If the variations in the two groups are not significant then it is possible that the variations between systems in each underlying reason are also not significant. However this possibility must be tested subsequently to find if there is a significant difference between each category.

Table G.8 below presents the frequency of robot related reasons and other reasons for each system, along with their expected frequencies. This is not for all the incidents, as incidents with underlying reasons missing are excluded. There are 23 of these and so the total number in Table G.8 is 5579.

	A	B5	B6	B7	F	H	Total
Robot Related	(217.7) 47	(192.8) 94	(452.5) 634	(531.3) 697	(236.8) 154	(3.8) 9	1635
Other Reasons	(525.3) 696	(465.2) 564	(1091.5) 910	(1281.7) 1116	(571.2) 654	(9.2) 4	3944
Total	743	658	1544	1813	808	13	5579

Table G.8

X^2 for Table G.8 equals 488.02

Chi-square (critical) equals 15.09.

Therefore we reject H_0 in favour of H_1. Thus, the systems differ in terms of the frequencies of the underlying reasons as a proportion of the total number of incidents for each system.

As before, some similarity has been found for B6 and B7 in the test. Below is the reduced table for B6 and B7 alone, Table G.9.

	B6	B7	Total
Robot Related	(612.2) 634	(718.8) 697	1331
Other Reasons	(931.8) 910	(1094.2) 1116	2026
Total	1544	1813	3357

Table G.9

χ^2 for Table G.9 equals 2.38
Chi-square (critical) equals 6.64.

Therefore the χ^2 calculated is within the range that is acceptable for H_0. Thus we accept H_0 for the grouped categories, and can say that the two systems come from the same population.

However we need to test further whether the variations in the underlying reasons are significant. Since B6 and B7 both have very large samples, it is possible to calculate χ^2 for the underlying reasons in nearly their basic state. Only two underlying reasons have to be combined - 'Fault in control cabinet' and 'fault in teach pendant'. These two faults are considered to have some common features and thus can be combined. The table of frequencies is presented below in Table G.10.

χ^2 for Table G.10 equals 108.15
Chi-square (critical) equals 40.29.

Therefore, for the variations in categories of underlying reasons between B6 and B7, the null hypothesis is rejected. This is despite the grouped categories being similar enough for the null hypothesis to be accepted at the significance level of 0.01.

	B6	B7	Total
10	(26.7) 24	(31.3) 34	58
11	(75.0) 69	(88.0) 94	163
12	(5.5) 8	(6.5) 4	12
13	(16.1) 13	(18.9) 22	35
14	(12.9) 19	(15.1) 9	28
15	(7.8) 11	(9.2) 6	17
16	(203.3) 225	(238.7) 217	442
17 & 19	(10.6) 13	(12.4) 10	23
18	(29.0) 35	(34.0) 28	63
120	(188.6) 165	(221.4) 245	410
130	(8.7) 10	(10.3) 9	19
140	(28.1) 42	(32.9) 19	61
22	(35.4) 41	(41.6) 36	77
33	(46.5) 19	(54.5) 82	101
42	(149.9) 140	(176.1) 186	326
43	(81.4) 97	(95.6) 80	177
44	(20.7) 21	(24.3) 24	45
55	(16.6) 16	(19.4) 20	36
66	(461.3) 473	(541.7) 530	1003
77	(2.3) 3	(2.7) 2	5
88	(8.7) 9	(10.3) 10	19
200	(100.7) 74	(118.3) 145	219
210	(8.3) 17	(9.7) 1	18
	1544	1813	3357

10 - Robot reason - no detail
11 - Robot out of synchronisation
12 - Stiffness in robot arm
13 - Cable problem
14 - Component failure in robot arm
15 - Blown fuses
22 - Other component failures
33 - System failure
42 - Part variation
44 - Process problem
55 - Services problem
16 - Robot in Emergency Stop
17 - Fault in cabinet
18 - Erratic robot
19 - Fault in teach pendant
120 - Problem in tools
130 - Robot won't move
140 - Robot collision
66 - Other equipment problem
77 - Safety function problem
88 - Human error
200 - Weld failure
210 - Sequence fault

Table G.10

Analysis of the Classifications of Incidents

As before, the frequencies of robot related reasons are considered in two groups, those that are robot related and other reasons. Once more this ensures that the conditions for a meaningful Chi-square test are met. Also, the first two categories of the classification of incidents need to be combined since only one incident resulted in an accident to a person. Those incidents where either the underlying reason or classification category are missing are excluded.

	1&2	4	5	6	7	8	Total
Robot Related	(64.8) 80	(14.1) 34	(1.8) 3	(1088.3) 1194	(12.6) 24	(445.5) 292	1627
Other Reason	(156.2) 141	(33.9) 14	(4.2) 3	(2624.7) 2519	(30.4) 19	(1074.5) 1228	3924
Total	221	48	6	3713	43	1520	5551

Table G.11

The null hypothesis H_0 for this test is that the samples in each category of classification of the incidents come from the same population, so that there is no difference in the proportion of robot related or other reasons in any classification category. The alternative hypothesis, H_1, is that the samples differ in terms of the proportions of their total incidents that are robot related or other reasons. The level of significance is once more 0.01. There are five degress of freedom and a total of 5551 incidents.

χ^2 for Table G.11 equals 149.9
Chi-square (critical) equals 15.09.

The chi-square critical value is considerably less than the calculated χ^2 value. Thus H_0 is rejected and the samples for each category of the classification of the severity of incidents are significantly different when considered in terms of their underlying reasons, as expressed in the above groupings.

Since the proportional variations between systems in terms of the two underlying reason groups is at least as large as it would be in terms of individual reasons, we can also say that the categories of classifications are significantly different in terms of the underlying reasons considered separately.

Robot Related Reasons

Variations by system

Table 5.21 is reproduced below as Table G.12 with absolute frequencies instead of percentages for each underlying reason. The totals at the bottom of each column correspond to the number of incidents in each system and overall (in the right-hand column). One can see that some reasons were very common - with over 100 cases in all the systems, whereas others had as few as 3 overall. This creates difficulties for a test, since the conditions required for meaningful calculations are not satisfied. Therefore, categories must be combined as before. In this case, those underlying reasons with a similarity in their propagation are combined. As before, the effect of combination of categories will be to smooth out differences, thereby making the test a conservative one. The resultant table is given below as Table G.13.

The categories to be combined are given below alongside the Roman numeral used in Table G.13 to denote the group.

I - reasons which involve the controls of the robot preventing motion - robot no detail, robot in emergency stop, robot won't move, overheating hydraulics.

II - all failures - cable problem, component failure in robot arm, blown fuses, fault in cabinet, fault in teach pendant, power supply fault - and also stiffness in robot arm.

III - categories that involve some erratic behaviour - robot out of synchronisation, erratic robot and robot collision.

IV - problems in the robots tools.

Thus the 15 categories are reduced to four. Table G.13 also contains the expected frequencies calculated according to the null

	A	B5	B6	B7	F	H	Total
Robot - no detail	5	13	24	34	6	-	82
Robot out of synchronisation	3	1	69	94	2	-	169
Stiffness in robot arm	2	-	8	4	-	-	14
Cable problem	-	6	13	22	8	1	50
Component failure in robot arm	1	3	19	9	3	1	36
Blown fuses	-	-	11	6	-	-	17
Robot in Emergency Stop	8	35	225	217	7	1	493
Fault in cabinet	1	1	12	10	3	1	28
Erratic robot	7	6	35	28	43	3	122
Fault in teach pendant	2	-	1	-	-	-	3
Power supply fault	-	-	-	-	51	-	51
Problem in tools	16	27	165	245	18	2	473
Robot won't move	2	2	10	9	2	-	25
Robot collision	-	-	42	19	-	-	61
Overheating hydraulics	-	-	-	-	11	-	11
Total	47	94	634	697	154	9	1635

Table G.12

hypothesis. The null hypothesis, H_0, in this case is that the systems are the same in terms of frequency of occurrence for each combined category of underlying reasons. The alternative hypothesis, H_1, is that the systems differ in terms of frequencies of robot related reasons.

	A	B5	B6	B7	F	H	Total
I	(17.6) 15	(35.1) 50	(236.9) 259	(260.5) 260	(57.5) 26	(3.4) 1	611
II	(5.7) 6	(11.4) 10	(77.2) 64	(84.8) 51	(18.7) 65	(1.1) 3	199
III	(10.1) 10	(20.2) 7	(136.5) 146	(150.1) 141	(33.2) 45	(1.9) 3	352
IV	(13.6) 16	(27.2) 27	(183.4) 165	(201.6) 245	(44.6) 18	(2.6) 2	473
Total	47	94	634	697	154	9	1635

Table G.13

X^2 for Table G.13 equals 203.86

Chi-square (critical) equals 30.58.

The calculated value for X^2 is far in excess of the critical value and also we reject H_0 in favour of H_1. Thus robot related problems vary significantly in terms of of the frequency of occurrence of the four groups of categories between the systems.

A certain similarity is suggested in Chapter 5 for robot systems B5, B6 and B7. The figures for the three systems are presented below in Table G.14. The same groups of categories are used.

X^2 for Table G.14 equals 27.73

Chi-square (critical) equals 16.81.

Thus the null hypothesis is rejected once more for these three systems.

	B5	B6	B7	Total
I	(37.5) 50	(253.2) 259	(278.3) 260	569
II	(8.2) 10	(55.6) 64	(61.1) 51	125
III	(19.4) 7	(130.8) 146	(143.8) 141	294
IV	(28.8) 27	(194.4) 165	(213.7) 245	437
Total	94	634	697	1425

Table G.14

This test is also performed on B6 and B7 alone. Figures for the two systems are presented in Table G.15.

	B6	B7	Total
I	(247.2) 259	(271.8) 260	519
II	(54.8) 64	(60.2) 51	115
III	(136.7) 146	(150.3) 141	287
IV	(195.3) 165	(214.7) 245	410
Total	634	697	1331

Table G.15

χ^2 for Table G.15 equals 14.21

Chi-square (critical) equals 11.34.

Therefore we also reject the null hypothesis here. However, the difference between the critical and calculated values is not great.

Variations by robot type

Robot related incidents are also considered in terms of the four robot types. The same type of test can be employed and once more the categories have to be combined to produce meaningful results. There is less need to combine categories, because the 1623 incidents (12 less than before because of unspecified robot types) are spread over 4 robot types, rather than 6 robot systems.

The combinations are made according to physical similarities in the reasons. Thus power supply fault and overheating hydraulics are combined, as are stiffness in robot arm and component failure in arm,and fault in cabinet,blown fuses and fault in teach pendant. The table produced as a result is shown below as Table G.16.

	1	2	3	4	Total
10	(4.3) 2.0	(8.2) 6	(23.4) 32	(46.0) 24	82
11	(9.0) 4	(17.0) 2	(48.2) 10	(94.9) 153	169
12 & 14	(2.6) 3	(5.0) 4	(14.3) 8	(28.1) 35	50
13	(2.6) -	(5.0) 9	(14.3) 12	(28.1) 29	50
15,17 & 19	(2.5) 5	(4.8) 4	(13.7) 12	(26.9) 27	48
16	(26.0) 12	(49.3) 8	(140.1) 212	(275.6) 259	491
18	(6.4) 9	(12.1) 46	(34.2) 29	(67.4) 36	120
110 & 150	(3.3) -	(6.2) 62	(17.7) -	(34.8) -	62
120	(24.7) 23	(46.9) 20	(133.2) 138	(262.1) 286	467
130	(1.3) 10	(2.5) 2	(7.1) 4	(4.0) 9	25
140	(3.1) -	(5.9) -	(16.8) 6	(33.1) 53	59
Total	86	163	463	911	1623

Table G.16

χ^2 for Table G.16 equals 1023.68
Chi-square (critical) equals 50.89.
Once more, the calculated value of χ^2 is greater than the critcal value.

Therefore the null hypothesis is rejected, making the robot types significantly different in terms of frequency of occurrence of underlying reasons.

Type 2 robots appear to be unlike the others. If we consider the three other types alone, we can test to see if there is a significant difference amongst these 3 designs of electric robots. In this case, Table G.17, cable problems are combined with three other failure reasons.

	1	3	4	Total
10	(4.5) 20	(24.1) 32	(47.4) 24	76
11	(9.8) 4	(53.0) 10	(104.2) 153	167
12 & 14	(2.7) 3	(14.6) 8	(28.7) 35	46
13,15 & 19	(5) 5	(27) 24	(53) 56	85
16	(28.5) 12	(153.2) 212	(301.4) 259	483
18	(4.4) 9	(23.5) 29	(46.2) 36	74
120	(26.3) 23	(141.8) 138	(278.9) 286	447
130	(1.4) 10	(7.3) 4	(14.4) 9	23
140	(3.5) -	(18.7) 6	(36.8) 53	59
Total	86	463	911	1460

Table G.17

Categories 110 and 150 can be ignored, since no such incidents occur with any of these three types of robots.

χ^2 for Table G.17 equals 256.32

Chi-square (critical) equals 32.0

Once again the null hypothesis is rejected, showing that there is a significant difference between these 3 robot types.

Table G.18 shows the observed and expected frequencies for types 3 and 4 alone. In this table, cable problems can be considered separately from the other failures, giving one more row to the table.

χ^2 for Table G.18 equals 119.4

Chi-square (critical) equals 21.67.

The calculated χ^2 is once more far larger than the critical value and thus the null hypothesis has to be rejected. Therefore we can draw the general conclusion that each type of robot has its own distinctive set of underlying reasons, which is significantly different from the other robot types.

	3	4	Total
10	(18.9) 32	(37.1) 24	56
11	(54.9) 10	(108.1) 153	163
12 & 14	(14.5) 8	(28.5) 35	43
13	(13.8) 12	(27.2) 29	41
15,17 & 19	(13.1) 12	(25.9) 27	39
16	(158.7) 212	(312.3) 259	471
18	(21.9) 29	(43.1) 36	65
120	(142.9) 138	(281.1) 286	424
130	(4.4) 4	(8.6) 9	13
140	(19.9) 6	(39.1) 53	59
Total	463	911	1374

Table G.18

Incident per Robot Production Hour for Each System and Each Type

It can be postulated that similar number of robot related incidents would occur in each robot production hour if the robots are all from a homogeneous population. Tests for the significance of variations in the number of incidents are presented in this section, first between the systems and then between robot types.

Robot systems

The null hypothesis in this test is that the systems come from the same population, with any period of robot production hours in each system having the same number of robot related incidents. The alternative hypothesis is that the number of incidents per robot production period are not the same. Table G.19 gives the figures for all six systems.

	A	B5	B6	B7	F	H	Total
Robot Related Incidents	(192) 47	(151.7) 94	(630.1) 634	(570.1) 697	(59.3) 154	(31.8) 9	Total 1635
Robot Production Hours	7548	5964	24771	22413.5	2333	1252	64281.5

Table G.19

X^2 for Table G.19 equals 327.31

Chi-square (critical) equals 15.09.

Thus the calculated value exceed the critical value by a factor of 20 or more. Therefore the null hypothesis is rejected. Thus the robot systems are significantly different in terms of the number of robot-related incidents per unit robot production time.(systems B6 and

Table G.20 below represents the figures for the test of systems B6 and B7 alone.

	B6	B7	Total
Incidents	698.8 634	632.2 697	133
Robot Production Hours	24771	22413.5	47184.5

Table G.20

χ^2 for Table G.20 equals 12.65

Chi-square (critical) equals 6.64.

The null hypothesis is rejected here also and so even for these two systems, the difference in the number of incidents per unit robot production time is significant.

Robot types

The null hypothesis (H_0) in this case is that the robot types come from the same population, with the same number of incidents per robot production period. The alternative hypothesis (H_1) is that the robot types differ in the number of incidents per production period. Table G.21 gives the figures for all 4 types of robots.

	1	2	3	4	Total
Incidents (Robot Related)	(242.4) 86	(90.5) 163	(357.8) 463	(932.3) 911	1623
Robot Production Hours	9599.5	3585	14170	36927	64281.5

Table G.21

χ^2 for Table G.21 equals 190.41

Chi-square (critical) equals 11.34.

The null hypothesis is rejected. Thus the robot types differ from each other significantly in terms of the number of incidents per robot production period at a significance level of 0.01.

The Robots in Each System

The null hypothesis for this test (H_0) is that the robots within each system are from the same population, with the same number of robot related incidents in any given period. The alternative hypothesis (H_1) is that the robots differ in the number of robot related incidents in any given period. We can test each system separately, except H, where there are two systems, but too few cases with each robot for a meaningful test. In each system, those incidents with the robot number unspecified have been excluded. Table G.22 represents the figures for the robots in A.

In order to achieve the condition of not more than 20% of expected frequencies less than 5, the robots in Factory A have to be grouped. The natural way to do this is in three groups of 4, since this is the arrangement within the system. Table G.22 shows the figures for this grouping.

Factory A	1-4	5-8	9-12	Total
Incidents	(13.3) 20	(13.3) 8	(13.3) 13	41

Table G.22

χ^2 for Table G.22 equals 5.5
Chi-square (critical) equals 9.21.

The calculated value is less than the critical one, so we accept H_0. Thus these robots have the same propensity to have robot related problems, when grouped together as in the robot system.

Factory B System 5	1	2	3	4	5	6	7	8	Total
Incidents	(9.6) 9	(9.6) 14	(9.6) 10	(9.6) 3	(9.6) 14	(9.6) 18	(9.6) 9	(9.6) 10	77

Table G.23

Table G.23 shows the figures for each robot in B5.

χ^2 for Table G.23 equals 17.3

Chi-square (critical) equals 18.48.

The two values are very close, but the calculated value of χ^2 is less than the critical value. Therefore once more it can be concluded that the robots have no significant difference in their likelihood for robot related problems.

Table G.24 shows the number of robot related incidents for each robot in B6.

Factory B System 6	171	172	173	181	182	211	251	252
Incidents	(26.9) 19	(26.9) 21	(26.9) 51	(26.9) 86	(26.9) 26	(26.9) 12	(26.9) 24	(26.9) 13
	253	261	262	263	291	292	293	301
Incidents	(26.9) 47	(26.9) 35	(26.9) 24	(26.9) 29	(26.9) 11	(26.9) 25	(26.9) 21	(26.9) 8
	302	311	312	321	322	331	322	Total
Incidents	(26.9) 12	(26.9) 13	(26.9) 18	(26.9) 28	(26.9) 31	(26.9) 28	(26.9) 36	618

Table G.24

χ^2 for Table G.24 equals 234.99

Chi-square (critical) equals 40.29.

In this case the robots have a significant difference between them in their likelihood for robot related problems.

Table G.25 shows the number of robot related accidents for all the robots in B7.

Factory B System 7	171	172	173	181	182	211	251	252
Incidents	(29.4) 31	(29.4) 43	(29.4) 48	(29.4) 16	(29.4) 23	(29.4) 27	(29.4) 7	(29.4) 16
	253	261	262	263	291	292	293	301
Incidents	(29.4) 40	(29.4) 8	(29.4) 58	(29.4) 108	(29.4) 34	(29.4) 30	(29.4) 24	(29.4) 9
	302	311	312	321	322	331	332	Total
Incidents	(29.4) 10	(29.4) 14	(29.4) 48	(29.4) 33	(29.4) 18	(29.4) 18	(29.4) 13	676

Table G.25

χ^2 for Table G.25 equals 373.33

Chi-square (critical) equals 40.29.

H_0 is also rejected for this system. Thus the robots in this systems are different in terms of the number of robot related problems.

Table G.26 shows the number of robot related incidents for both robots in F (System I).

Factory F	1	2	Total
Incidents	(75) 63	(75) 87	150

Table G.26

χ^2 for Table G.26 equals 3.84

Chi-square (critical) equals 6.64.

The calculated value is well below the critical value, so the null hypothesis is accepted. The robots in this system have similar numbers of robot related incidents at a significance level of 0.01.

The distribution of downtime periods

The length of downtime for incidents in each system can be compared by splitting them into short, medium and long periods. The test for significance here is a comparison between observed numbers in these three categories and those expected if the proportions were uniform across the systems. The null hypothesis H_0, is that the incidents in all systems are from the same population, with the same proportions of incidents distributed between short, medium and long periods of downtime. The alternative hypothesis is that there is a difference in the proportions of incidents in these three categories of downtime length.

	A	B5	B6	B7	F	H	Total
Short	(301) 264	(288.9) 281	(1054) 1150	(1185.9) 1333	(628.4) 438	(8.6) 1	3467
Medium	(68.4) 87	(65.6) 62	(239.2) 169	(269.2) 161	(142.7) 307	(2.0) 1	787
Long	(16.3) 35	(15.6) 27	(56.8) 31	(64.0) 25	(33.9) 60	(0.5) 9	187
Total	386	370	1350	1519	805	11	4441

Table G.27

The unusual distribution of downtime in Factory H makes a test with the expected figures in Table G.27 unacceptable. If H is excluded, then a test can be performed on the other 5 systems which by inspection would appear to have more similar distributions of downtime. Table G.28 presents the observed and expected frequencies of these 5 systems.

	A	B5	B6	B7	F	Total
Short	(302.0) 264	(289.5) 281	(1056.2) 1150	(1188.5) 1333	(629.8) 438	3466
Medium	(68.5) 87	(65.6) 62	(239.5) 169	(269.5) 161	(142.8) 307	786
Long	(15.5) 35	(14.9) 27	(54.2) 31	(61.0) 25	(32.3) 60	178
Total	386	370	1350	1519	805	4430

Table G.28

X^2 for Table G.28 equals 437.08

Chi-square (critical) equals 20.08.

The calculated value is clearly well in excess of the critical value so the null hypothesis is rejected. The systems have a significantly different distribution of downtime periods, at a significance level of 0.01.

The two systems most alike, B6 and B7, have distributions that appear quite similar. These two are tested below for differences in isolation, with the figures presented in Table G.29.

	B6	B7	Total
Short	(1168.4) 1150	(1314.6) 1333	2483
Medium	(155.3) 169	(174.7) 161	330
Long	(26.4) 31	(29.6) 25	56
Total	1350	1519	2869

Table G.29

χ^2 for Table G.29 equals 4.34
Chi-square (critical) equals 9.21.

Thus, the null hypothesis is accepted for these two systems. Therefore the distribution of incidents in B6 and B7 are not significantly different.

Robot Failures

This section presents the statistical analysis of robot failures for the robot systems and robot types. The frequency of each failure category and the number of robot failures per unit robot production time is given.

Robot systems

Table G.30 presents the absolute frequency of each category of robot failure in each system. This table shows that there is some similarity between the frequencies in the three systems in Factory B, but little similarity between these and any of the other systems.

	A	B5	B6	B7	F	H	Total
Cable problem	-	6	13	22	8	1	50
Manipulator fault	1	3	19	9	3	1	36
Blown fuses	-	-	11	6	-	-	17
Fault in cabinet	1	1	12	10	3	1	28
Fault in teach pendant	2	-	1	-	-	-	3
Power supply fault	-	-	-	-	51	-	51
Total	4	10	56	47	65	3	185

Table G.30

If A and H are excluded, one can compare the three robot systems in B with F, which is the only other system with a similar number of robot failures. Table G.31 presents the failures in these four systems, showing two combined categories.

	B5	B6	B7	F	Total
Cable problem	(2.75) 6	(15.42) 13	(12.94) 22	(17.89) 8	49
Manipulator fault/ Blown fuses	(2.87) 3	(16.04) 30	(13.47) 15	(18.62) 3	51
Fault in cabinet/ Fault in teach pendant	(1.52) 1	(8.49) 13	(7.13) 10	(9.86) 3	27
Power supply fault	(2.87) -	(16.04) -	(13.47) -	(18.62) 51	51
Total	10	56	47	65	178

Table G.31

χ^2 for Table G.31 equals 138.66

Chi-square (critical) equals 21.67.

The calculated value greatly exceeds the critical value, and so the null hypothesis is rejected. B5, B6 and B7 are considered alone below. Table G.32 presents the failures for these three systems. Only one combined category is needed for this analysis.

	B5	B6	B7	Total
Cable problem	(3.63) 6	(20.32) 13	(17.05) 22	41
Manipulator fault	(2.74) 3	(15.36) 19	(12.89) 9	31
Blown fuses	(1.5) -	(8.42) 11	(7.07) 6	17
Fault in cabinet/ Fault in teach pendant	(2.12) 1	(11.89) 13	(9.98) 10	24
Total	10	56	47	113

Table G.32

χ^2 for Table G.32 equals 10.82
Chi-square (critical) equals 16.81.

For these three systems, the null hypothesis is accepted. Thus there is no significant variation between the failure category proposition in the three systems in B, but there is elsewhere. A and H have too few cases of robot failure to allow a meaningful test.

If we compare the number of failures per unit production time, we can produce a table of frequency and robot production hours as in Table G.33.

	A	B5	B6	B7	F	H	Total
Number of incidents of robot failure	(21.12) 4	(17.16) 10	(71.3) 56	(64.51) 47	(6.7) 65	(3.6) 3	185
Robot production hours	7548	5964	24771	22413.5	2333	1252	65281.5

Table G.33

χ^2 for Table G.33 equals 532.88
Chi-square (critical) equals 15.09.

The calculated figure is in excess of the critical figure. Therefore the null hypothesis is rejected.

Table G.34 below presents the failures for all systems except F, shown above to have the greatest difference from the expected frequencies.

	A	B5	B6	B7	H	Total
No incident	(14.62) 4	(11.55) 10	(47.98) 56	(43.42) 47	(2.43) 3	120
Robot production hours	7548	5964	24771	22413.5	1252	61948.5

Table G.34

χ^2 for Table G.34 equals 9.68

Chi-square (critical) equals 13.28.

The calculated figure is below the critical value and so the null hypothesis is accepted. Thus, excluding F, the robots systems do not have a significant difference in the number of failures per robot production hour.

Robot types

Table G.35 below is for each category of robot failure with each robot type. Two combinations are necessary, as before.

	1	2	3	4	Total
Cable problems	(1.62) -	(18.38) 9	(8.65) 12	(21.35) 29	50
Manipulator fault and Blown fuses	(1.72) 1	(19.48) 4	(9.17) 14	(22.63) 34	53
Fault in cabinet and Teach pendant	(1.01) 5	(11.39) 4	(5.36) 6	(13.24) 16	31
Power supply fault	(1.65) -	(18.75) 51	(8.82) -	(21.78) -	51
Total	6	68	32	79	185

Table G.35

χ^2 for Table G.35 equals 140.23

Chi-square (critical) equals 21.67.

Therefore the null hypothesis is rejected.

Table G.36 presents the failures for three types of robot (excluding type 2, the hydraulically powered type of robot).

	1	3	4	Total
Cable problems	(2.10) -	(11.21) 12	(27.68) 29	41
Manipulator fault and Blown fuses	(2.51) 1	(13.40) 14	(33.09) 34	49
Fault in cabinet and Teach pendant	(1.38) 5	(7.38) 6	(18.23) 16	27
Total	6	32	79	117

Table G.36

χ^2 for Table G.36 equals 13.22

Chi-square (critical) equals 13.28.

In this test, the calculated value is just less than the critical value, and so the null hypothesis is accepted.

MEANS OF DOWNTIMES

The section on distribution of downtime in Chapter 5 has shown that the log-normal distribution is a reasonable approximation for the distribution of the length of downtime of the incidents. Any statistical testing of the mean values of the downtime to discover if there is a significant variation between groups must take the kind of distribution into account. A commonly used test of significant differences in mean values is the t-test (Siegel, 1956, pp. 19-20), which takes as one of its assumptions that the cases being tested are drawn from normally distributed populations. It will therefore be possible to use logarithm values of the downtime in a T-test of the means of the logarithms of downtime. At high degrees of freedom, that is, over 120 cases,the t-test is simplified to a z-test which is a perfect normal distribution in itself. For a t-test, the variances are very important whereas for a z-test with a larger sample size, the values of the variances do not need to be known.

The significance of differences in means was tested using the SPSS subroutine 'T-TEST' (SPSS, pp. 267-275). This carries out t-tests for any number of degrees of freedom. It compares the mean values and variances of a variable, giving three different test values. The first is of the F-value, which is a statistical measure of the difference between the variances of the two samples being compared. This allows a decision to be made on whether it is correct to assume that the variances of the two samples are the same. The probability value supplied for the F-value in the SPSS printout must be above the selected level of significance. Thus if the level of significance (α_1) is taken to be 0.01 and the F-value has a probability of 0.03, one would accept that the samples had the same variance. If α_1 is taken as 0.05, then the hypothesis that the samples have the same variance would be rejected.

The two other figures produced by the SPSS T-TEST routine are the t-test calculation for the samples, one with the variances assumed to be the same, the other with them not. Thus the decision taken over the F-value will decide which t-test calculation to use.

The first, the pooled variance test, would be used if the variances were accepted as the same, whilst the second, the separate variance test, would be used if they were not. Both of these have probability values which once more have to be above the level of significance for the null hypothesis to be accepted. The level of significance for these tests is α_2. In these tests the null hypothesis would be that the samples had the same means. Each of these three measures are calculated with two-tail probability values, that is the means of one sample could be either above or below the mean of the other.

The level of significance chosen for the F-value and the t-test can affect whether the means are shown to be the same. Such borderline cases are shown in the tests given below. Throughout, the borderline area for both F-values and t-tests is taken as α_1 or α_2 between 0.01 and 0.05 (that is between 95% and 99% confidence).

For each calculation, a table has been produced summarising the results. This table is triangular, giving one box for each pairing of the groups tested. For instance when the six systems are compared in the first test, a 5 by 5 triangular table is produced. The possible alternative results are represented by crosses or ticks according to the scheme below:-

✓ Accept H_0 for the F-test when α_1 is either 0.05 or 0.01 and accept H_0 for the t-test when α_2 is either 0.05 or 0.01.
(The means are not significantly different).

(✓) Accept H_0 for the F-test when α_1 is either 0.05 or 0.01 but accept H_0 for the t-test when α_2 is 0.01, but not 0.05.
(Borderline means for the pooled variance t-test).

✓X Reject H_0 for the F-test when α_1 = 0.01 or 0.05. Accept H_0 for t-test when α_2 = 0.01 or 0.05.
(Different variances).

✓y Accept H_0 for the F-test when α_1 = 0.01 but not when α_1 = 0.05. Accept H_0 for the t-test when α_2 = 0.01 or 0.05.
(Borderline case for the F-test, variances could be considered different).

(✓X) Reject H_0 for the F-test when $\alpha_1 = 0.01$ or 0.05. Accept H_0 for the t-test at $\alpha_1 = 0.01$ only.
(Different variances, but borderline mean for the separate variance t-test).

(✓Y) Accept H_0 for the F-test at $\alpha_1 = 0.01$ but not at 0.05. Accept H_0 for either t-test when α_2 is 0.01 but not at 0.05.
(Borderline case for both variances and mean).

(X) Accept H_0 for the F-test at $\alpha_1 = 0.01$ but not at 0.05. If accept H_0 for F-test, then pooled variance t-test value H_0 for the t-test is rejected. If reject H_0 for the F-test, then separate variance t-test value means H_0 for the t-test is accepted at $\alpha_2 = 0.01$ or 0.05.
(Borderline variances produces the possibility of two actions on the significance means - different means if variances the same, same means if variances are different).

(Y) Accept H_0 for the F-test at $\alpha_1 = 0.01$ or 0.05. If reject H_0 for the F-test, the separate variance t-test value means H_0 is accepted at $\alpha_2 = 0.01$ but not 0.05.
(Borderline variances produces a borderline mean values if variances are considered to be different).

X Accept H_0 for the t-test at $\alpha_1 = 0.01$ or 0.05. Reject H_0 for the t-test at $\alpha_2 = 0.01$ or 0.05.
(Different means).

The means for all incidents in each system

The SPSS t-test routine was run for all incidents, to compare the means of log times in each system. This showed a highly significant difference between the means, except between Factory A and B5.

This calculation for each pair of systems can be represented by Figure G.1 below. For all the other pairs of samples, the t-value probability was less than 0.000, making the differences highly significant, even for B6 and B7.

	A	B5	B6	B7	F
B5	✓				
B6	X	X			
B7	X	X	X		
F	X	X	X	X	
H	X	X	X	X	X

Figure G.1 T-Tests on Means of Logarithms of Downtime for All Incidents

The means for the incidents associated with robots in B6 and B7

A t-test on all incidents associated with each robot in B6 and B7 system was performed. This is shown in Figures G.2 and G.3 below. For B6 it was noted that the robots numbered 172, 253, 261 and 321 had high mean downtimes. Figure G.2 shows that three of these four have a high number of tests where the null hypothesis is rejected at either confidence level. However, these are not the only ones to show significant differences from the other robots. Robot number 251 has 11 tests giving rejection at either α_2 = 0.01 and 0.05 (out of 22) and 3 where the t-test probability lies between α_2 = 0.01 and 0.05. The changes in the distribution of downtime when logarithms are used has been discussed in Chapter 5. It is clear that the order of rank of means for the robots has been changed to some extent by taking logarithms, with some having higher values relative to the others than when the ordinary means are compared. Robot numbers 172, 251, 253, 261 and 332 have the highest means for the logarithm values of downtime, and these five account for 49 of the 54 rejections of the null hypothesis in Figure G.2. The remaining five rejections involve robot number 331, which has one of the lowest means. Of the 39 borderline rejections of the null hypothesis, the majority also involve the six robots mentioned above.

The same pattern is found for System B7 in Figure G.3. Robot numbers 172, 181, 251, 253, 262, 302 and 312 account for the vast majority of the rejections of the null hypotheses. The remaining cases of rejection occur with the robots with the lowest means (robot numbers 171, 261, 291, 292 and 293).

	171	172	173	181	182	211	251	252	253	261	262	263	291	292	293	301	302	311	312	321	322	331
172	X																					
173	✓	X																				
181	✓	X	(✓)																			
182	✓	X	✓	✓																		
211	✓	✓	✓	✓	✓																	
251	X	✓	X	X	X	✓																
252	✓	(X)	✓	(✓)	✓	✓	(✓)															
253	X	✓	X	X	X	✓	✓	X														
261	X	✓	X	X	X	X	✓	X	(✓)													
262	(✓)	✓	✓	(X)	(✓)	✓	✓	✓	✓	X												
263	(✓)	(X)	✓	X	✓	✓	(✓)	✓	✓	X	✓											
291	✓	(✓)	✓	✓	✓	✓	X	✓	(✓)	X	✓	✓										
292	✓	X	✓	(✓)	✓	✓	X	✓	(X)	X	✓	✓	✓									
293	✓	X	✓	✓	✓	✓	X	✓	(✓)	X	✓	✓	✓	✓								
301	✓	(✓)	✓	✓	✓	✓	(✓)	✓	✓	X	✓	✓	✓	✓	✓							
302	✓	(✓)	✓	✓	✓	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓						
311	✓	(X)	✓	(✓)	✓	✓	X	✓	(X)	X	✓	✓	✓	✓	✓	✓	✓					
312	X	✓	(✓)	X	X	✓	✓	✓	✓	✓	✓	✓	(✓)	(✓)	(✓)	✓	(✓)	(✓)				
321	✓	(✓)	✓	(X)	✓	✓	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	✓	✓			
322	X	X	(✓)	X	X	✓	✓	✓	✓	X	✓	✓	(✓)	✓	(✓)	✓	✓	✓	✓	✓		
331	✓	X	(✓)	✓	✓	✓	X	(✓)	X	X	X	X	✓	(✓)	✓	✓	✓	(✓)	X	(✓)	X	
332	✓	(✓)	✓	X	✓	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

Figure G.2 B6: All Incidents

	171	172	173	181	182	211	251	252	253	261	262	263	291	292	293	301	302	311	312	321	322	331
172	X																					
173	✓	X																				
181	X	✓	(✓)																			
182	✓	(✓)	✓	✓																		
211	(X)	✓	✓	✓	✓																	
251	(✓)	✓	✓	✓	✓	✓																
252	(✓)	✓	✓	✓	✓	✓	✓															
253	X	✓	X	✓	(✓)	✓	✓	✓														
261	✓	X	✓	X	✓	(✓)	(✓)	(✓)	X													
262	X	✓	(✓)	✓	✓	✓	✓	✓	✓	X												
263	X	X	✓	✓	✓	X	✓	✓	X	X	✓											
291	✓	X	✓	X	✓	X	(✓)	(✓)	X	✓	X	X										
292	✓	X	(✓)	X	(✓)	(X)	(X)	(X)	X	✓	X	X	✓									
293	✓	X	✓	X	(✓)	✓	✓	✓	X	✓	X	X	✓	X								
301	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	(✓)	X	✓							
302	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	X	✓	✓						
311	X	(✓)	✓	✓	✓	✓	✓	✓	(✓)	(✓)	✓	✓	(✓)	X	✓	✓	✓					
312	X	✓	(✓)	✓	✓	✓	✓	✓	✓	X	✓	X	X	X	X	✓	✓	✓				
321	✓	X	✓	(✓)	✓	✓	✓	✓	X	✓	(✓)	(✓)	✓	X	✓	✓	✓	✓	(✓)			
322	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓		
331	✓	X	✓	(✓)	✓	✓	✓	✓	X	✓	(✓)	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	
332	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	(✓)	X	✓	✓	✓	✓	✓	✓	✓	✓

Figure G.3 B7: All Incidents

The Means of Classification Categories

Differences between the means of downtime for each classification were recognised in Chapter 5. A t-test was performed to see if there was a significant difference between each one. Figure G.4 summarises the results.

	2	4	5	6	7
4	X				
5	✓	✓			
6	X	X	X		
7	✓	X	✓	X	
8	X	X	✓	X	X

2 - Accident with damage to machine
4 - Accident no damage
5 - Near misses
6 - Incident - no damage
7 - Hazard anticipated
8 - No hazard and no damage likely

Figure G.4 T-Tests on the Means of Log-Downtime for Classification Categories

The order of means has also been slightly altered once more. From Figure G.4, we can see that no significant difference was found between the means of the logarithms of downtime for accidents with damage to equipment, near misses and hazards anticipated. These are the three category with the highest means. The means for near misses has no significant difference with any other mean except for incidents with no damage or harm caused. Accidents with no damage also show some similarity with incidents with no damage and no hazards likely, but the variances of these two categories both differ from that of accidents with no damage. Incidents with no damage caused or with no hazard or damage likely are significantly different from each other. The main reason for the lack of significant differences between near misses and 4 of the other 5 categories is the small number of incidents with this category which also have downtime figures.

Robot related incidents in each system

A t-test of the robot related incidents was performed for each system. This is summarised in Figure G.5.

	A	B5	B6	B7	F
B5	✓				
B6	X	X			
B7	X	X	✓		
F	X	X	X	X	
H	X	X	X	X	X

Figure G.5 T-Tests on the Robot Related Incidents in Each System

A certain amount of similarity is found with the figure for all incidents (Figure G.1) but here the null hypothesis is accepted in more comparisons. A and B5 were once more found to have no significant difference were once more found to have no significant difference with A and B5, but the samples had significantly different variances in both cases. The different variances suggest that the samples do not come from the same population even though the means are not significantly different.

Robot related incidents for each robot in each system

Within each system there is some variation in the mean downtimes for robot related incidents with each robot. A separate t-test was carried out for each system. Figures G.6 to G.10 give the results of this in summary form. Figure G.10 has both F and H together, since only one test was run for each system.(there being just two robots in each for which comparable production data was collected).

In Factory A the presence of 5 robots with no robot related incidents with downtime (5,6,7, 8 and 11) meant that a large number of invalid tests were carried out. Invalid tests also occurred because some robots only had one robot related incident with downtime. With such incidents, means and variances are not meaningful. These have been represented in Figure G.6 by a dash. No significant differences were found between robots with valid cases of downtime. Robot number 9 had a majority of tests that were borderline. The only test involving robot number 9 that was unequivocally acceptable was with No. 10. Two others showed up a significant difference in variance if $\alpha_1 = 0.05$ (with nos. 1 and 4). The rest of the tests showed no significant differences in the means of the log-downtime values. However it needs to be pointed out with this system that the total number of robot related incidents with downtime was only 19 (a further one had an unspecified robot number). This limits the use of any statistical test in A.

In Factory B5, only one test showed up a significant difference at $\alpha_2 = 0.01$. This was Nos. 122 and 128. Five other t-tests would have the null hypothesis rejected if $\alpha_2 = 0.05$. Four of these were also with No. 122 (and 121, 124, 125, 127). The other test was between 125 and 126. The remaining 22 tests showed no significant differences between means of log-downtime although one test (123 and 125) would have given a significant difference in variances if a significance level of 0.05 were taken.

In B6 and B7, a similar pattern emerges to that in Figures G.2 and G.3 (for all incidents associated with robots). In B6, 50 out of 53 rejections of the null hypothesis occur with seven robots (robot numbers 172, 252, 253, 261, 262 and 332). The other 3 rejections occur with two robots with low means (robot numbers 181 and 331). In B7, fewer rejections of the null hypothesis occur, but the majority -19 out 22 - are with 5 robots (robot numbers 172, 181, 253, 262 and 312) which have high means of the logarithms of downtime.

2	✓										
3	✓	✓									
4	✓	✓	✓								
5	-	-	-	-							
6	-	-	-	-	-						
7	-	-	-	-	-	-					
8	-	-	-	-	-	-	-				
9	y	(✓)	(✓)	y	-	-	-	-			
10	✓	-	✓	✓	-	-	-	-	✓		
11	-	-	-	-	-	-	-	-	-	-	
12	✓	-	✓	✓	-	-	-	-	(✓)	-	-
	1	2	3	4	5	6	7	8	9	10	11

Figure G.6 Factory A: Robot Related Incidents with Each Robot

122	(✓)						
123	✓	✓					
124	✓	(✓)	✓				
125	✓	(✓)	y	✓			
126	✓	✓	✓	✓	(y)		
127	✓	(✓)	✓	✓	✓	✓	
128	✓	X	✓	✓	✓	✓	✓
	121	122	123	124	125	126	127

Figure G.7 Factory B5: Robot Related Incidents with Each Robot

	171	172	173	181	182	211	251	252	253	261	262	263	291	292	293	301	302	311	312	321	322	331
172	(X)																					
173	✓	(X)																				
181	✓	X	✓																			
182	✓	(X)	✓	✓																		
211	✓	✓	✓	(✓)	✓																	
251	X	✓	X	X	X	✓																
252	✓	X	✓	(✓)	✓	✓	✓															
253	X	✓	X	X	X	✓	✓	✓														
261	X	✓	X	X	X	(✓)	✓	X	✓													
262	X	✓	(✓)	X	X	✓	✓	✓	✓	(✓)												
263	✓	X	✓	X	✓	✓	(✓)	✓	✓	X	✓											
291	✓	✓	✓	✓	✓	✓	X	✓	(✓)	X	(✓)	✓										
292	✓	(X)	✓	✓	✓	✓	X	✓	X	X	(✓)	✓	✓									
293	✓	X	✓	✓	✓	✓	X	(✓)	X	X	X	(✓)	✓	✓								
301	✓	X	✓	✓	✓	✓	X	✓	(✓)	X	(✓)	✓	✓	✓	✓							
302	✓	X	✓	✓	✓	✓	(✓)	✓	(✓)	X	✓	✓	✓	✓	✓	✓						
311	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	X	✓	✓	✓	✓	✓	✓	✓					
312	X	✓	X	X	X	✓	✓	✓	✓	✓	✓	✓	(✓)	(✓)	X	(✓)	✓	✓				
321	✓	✓	✓	(X)	X	✓	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	✓	✓			
322	(✓)	✓	(✓)	X	X	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	X	(✓)	✓	✓	✓	✓		
331	✓	X	✓	✓	✓	✓	X	X	X	X	X	X	✓	(✓)	✓	✓	✓	✓	X	(X)	X	
332	✓	✓	✓	(X)	✓	✓	(✓)	✓	(✓)	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	(✓)

Figure G.8 B6: Robot Related Incidents with Each Robot

	171	172	173	181	182	211	251	252	253	261	262	263	291	292	293	301	302	311	312	321	322	331
172	X																					
173	(√)	X																				
181	X	√	√																			
182	√	√	√	√																		
211	y	√	√	√	√																	
251	(√)	√	√	√	√	√																
252	y	√	√	√	√	√	√															
253	X	√	X	√	(√)	√	√	√														
261	√	(√)	√	√	√	√	√	√	(√)													
262	X	√	(√)	√	√	√	√	√	√	√												
263	X	X	y	y	√	y	√	y	X	√	√											
291	√	X	√	X	√	y	√	y	X	√	X	X										
292	√	X	X	X	(√)	X	(√)	(X)	X	√	X	X	√									
293	X	(√)	√	√	√	√	√	√	(√)	√	√	X	y	X								
301	(√)	√	√	√	√	√	√	√	√	√	√	√	√	(√)	√							
302	y	√	√	√	√	√	√	√	√	√	√	y	y	(X)	√	√						
311	(√)	y	y	y	√	y	√	y	(y)	√	√	√	√	(√)	y	√	y					
312	X	√	(√)	√	√	√	√	√	√	(√)	√	√	X	X	(√)	√	√	y				
321	(√)	(√)	√	(√)	√	√	√	√	X	√	√	y	√	y	√	√	√	y	(√)			
322	√	(√)	√	√	√	√	√	√	(√)	√	√	√	√	y	√	√	√	y	√	√		
331	√	√	√	√	√	√	√	√	(√)	√	√	√	√	√	√	√	√	√	√	√	√	
332	y	(√)	√	√	√	√	√	√	√	√	√	y	y	X	√	√	√	y	√	√	√	√

Figure G.9 B7: Robot Related Incidents with Each Robot

In Factory F, the t-test shows that although the robots do not have significantly different means, the differences in the variances are significant (see Figure G.10). This suggests that the figures for these two robots do not come from the same populations, even though the robots are identical in design and task. In Factory H, the means were found to be highly similar.

F	H
√X	√

Figure G.10 T-Test in Factories F and H

Robot types

A t-test of the logarithm of downtimes for robot related incidents with each robot type was carried out and is summarised in Figure G.11.

	1	2	3
2	X		
3	√X	X	
4	√X	X	X

Figure G.11 T-Test Results on Robot Types

From this we can see that there is a significant difference between each type, except between types 1 and 3 or 4. However these have a significant difference in the variances at $\alpha_1 = 0.05$.

Robot failures

a) Analysed by systems

A t-test for the overall means for all robot failures in each system was undertaken. This is summarised in Figure G.12.

B5	√				
B6	(X)	(√)			
B7	(X)	√	√		
F	X	(√)	√	√	
H	√	X	X	(√X)	X
	A	B5	B6	B7	F

Figure G.12 T-Test of Means of Logarithms of Downtime for Robot Faults in Each System

From this it is clear that Systems A and H have the most significant difference from the other systems even though there is no significant difference between them. It should be noted that both have very few incidents of robot failure. The other systems have far more incidents of robot failure. Thus the systems with a number of robot failures have similar downtime patterns.

(b) Analysed by robot types

When the mean logarithm of downtime of robot failures for robot types are compared, a different picture emerges. Whereas some similarity between robot failures and robot related incidents can be seen for robot systems (c.f. Figure G.5 and G.12), for robot types no obvious similarity appears. Figure G.13 shows robot failures with robot types and should be compared with Figure G.11.

2	(✓)		
3	(✓)	✓	
4	X	X	✓
	1	2	3

Figure G.13 T-Tests for Mean of Logarithms of Downtime for Robot Failures with Robot Types

Type 1 is significantly different from all three other types at $\alpha_2 = 0.05$, and one (4) at $\alpha_2 = 0.01$.

All other comparisons between the other 3 types (2, 3 and 4) show no significant differences, except type 2 which has a significantly different variance from types 3 and 4 at $\alpha_1 = 0.05$ and from type 4 at $\alpha_1 = 0.01$. This suggests that, whereas type 1 is significantly different from the others in terms of means (at $\alpha_1 = 0.05$) the sample of type 2 robot failures comes from a different population, even though the means are not significantly different.

APPENDIX K

Computer Coding of Data Variables and SSPS Programme

COMPUTER CODING

Number of Digits Provided for Each Piece of Information

Place Number		1	digit
Case Number		4	digits
Robot Type		1	digit
Robot Number		1	digit (alpha-numeric)
Robot Task		1	digit
Downtime	Mins	2	(in real units)
	Hrs	1	(alpha-numeric)
Action taken		8	digits (1 column per option)
Reason for action		14	digits (1 column per option)
Means of interruption		1	digit
Classification		1	digit
Persons involved		6	digits (3 for identifying and 3 for solving)
Underlying reason		2	digits
TOTAL		43	digits

Details on Each Category of Information

Place Number

Factory A	1
Factory B, Station 5	2
Factory C	3
Factory D	4
Factory E	5
Factory F	6
Factory G	7
Factory H	8
Factory B, Station 6	A
Factory B, Station 7	B

Case Number

For each place, a maximum of 9,999 cases are available.

Robot Type

Each type has a unique identifying number. For example, Type 1 is denoted by the number '1'.

Robot Number

In each place, those robots of the same type are numbered.

An alpha-numeric code is used, i.e. 1-9, then A, B, C, ... to denote 10, 11, 12, ... respectively.

U denotes an unspecified number. If the system as a whole is at fault, then 0 is given.

Robot Task

Arc-Welding	1
Spot-Welding	2
Materials Handling	3
Adhesive Bonding	4
Routing	5
Missing	9

Downtime

Minutes 00 → 59 mins
Hours 0 → 9, B = < 2 shifts
C = < 3 shifts
.
.
Z = < 26 shifts
Not given (AAA)

Action Taken

A separate column is used for each of the options shown, including one for OTHER. These are to be coded:-

9 - NO
7 - YES

Reason for Action

Separate columns for each of the options shown including one for OTHER. These are to be coded:-

9 - NO
7 - YES

Means of Interruption

Personal:	Emergency Stop	1
	Other	2
Automatic Action	Controlled Stop	3
	Signals for Sensory Equipment	4
	(Missing)	9

Classification of Incident

Accident to Person	1	
Accident to Machinery	2	(N.B. Includes parts being produced)
Accidents to (Both of above)	3	
Accident No Damage	4	
Near Miss	5	
Incident No Damage	6	
Hazard Anticipated	7	
No Damage Likely	8	
Missing	9	

Persons Involved

a) In identifying problem
3 columns, each for one of:-

Maintenance fitter	1
Maintenance electrician	2
Production engineer	3
Operator	4
Foreman	5
Chargehand	6
Service engineer	7
Other	8
Missing	9

b) In solving problem:-
As above for a).

Underlying Reason	(2 columns)
Robot Fault	1-
Other Component Failure (on associated equipment)	22
System Failure	33
Process Problem	44
Services Problem	55
Peripheral Production Equipment Problem	66
Safety Functions Problem	77
Human Error	88
Weld Failure	AA
Sequence Fault (no recognisable piece of equipment)	BB
Missing	99
Check on components running through the system	41
Part/component variation or problem	42
Checks on the system as a whole	34
Problem with the quality of the process	43

Detail on Robot Fault

(1)0	No detail
(1)1	Out of synchronisation
(1)2	Mechanical stiffness in components in the manipulator
(1)3	Transmission problem and cables broken
(1)4	Component failure (on manipulator)
(1)5	Fuses blown
(1)6	Robot goes into emergency stop
(1)7	Faulty component(s) in control cabinet
(1)8	Erratic behaviour - unspecified

(1)9	Faulty component(s) on teach pendant
(1)A	Power supply failure
(1)B	Fault/problem in tools carried by robot
(1)C	Robot won't move - unspecified
(1)D	Collision
(1)E	Overheating in hydraulics unit.

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

SPSS BATCH SYSTEM                                                                                    06/15/85          PAGE     1

SPSS FOR OS/360, VERSION M, RELEASE 9.1, FEBRUARY 1, 1982

                                   CURRENT DOCUMENTATION FOR THE SPSS BATCH SYSTEM
ORDER FROM MCGRAW-HILL:   SPSS, 2ND ED. (PRINCIPAL TEXT)          ORDER FROM SPSS INC.:   SPSS STATISTICAL ALGORITHMS
                          SPSS UPDATE 7-9 (USE W/SPSS,2ND FOR REL. 7, 8, 9)                 KEYWORDS: THE SPSS INC. NEWSLETTER
                          SPSS POCKET GUIDE, RELEASE 9
                          SPSS INTRODUCTORY GUIDE:  BASIC STATISTICS AND OPERATIONS
                          SPSS PRIMER (BRIEF INTRO TO SPSS)

DEFAULT SPACE ALLOCATION..      ALLOWS FOR..     102 TRANSFORMATIONS
WORKSPACE      71680 BYTES                       409 RECODE VALUES + LAG VARIABLES
TRANSPACE      10240 BYTES                      1641 IF/COMPUTE OPERATIONS

                    1 RUN NAME          FIRST STATS OF ROBOT PERFORMANCE
                    2 FILE NAME         ROBOTS1
                    3 VARIABLE LIST     PLACE,CASE,TYPE,NO,TASK,MIN,HOUR,FAULTY,ADJUST,RESET,REPRO,
                    4                   ROUT,UNPLAN,DIAG,OTHER,MECHROB,MECHOTH,ELECROB,ELECOTH,
                    5                   ELECINT,INSPECT,PROGPROB,QUAL,ERRAT,DROP,DAMROB,DAMPERS,
                    6                   DAMMACH,OTH,MEANS,CLASS,IDENT1 TO IDENT3,SORT1 TO SORT3,UNDER
                    7 INPUT FORMAT      FIXED(A1,F4.0,F1.0,A1,F1.0,A2,A1,30F1.0,A2)

                     ACCORDING TO YOUR INPUT FORMAT, VARIABLES ARE TO BE READ AS FOLLOWS

                     VARIABLE  FORMAT  RECORD       COLUMNS

                     PLACE        A 1        1        1-     1
                     CASE       F 4. 0       1        2-     5
                     TYPE       F 1. 0       1        6-     6
                     NO           A 1        1        7-     7
                     TASK       F 1. 0       1        8-     8
                     MIN          A 2        1        9-    10
                     HOUR         A 1        1       11-    11
                     FAULTY     F 1. 0       1       12-    12
                     ADJUST     F 1. 0       1       13-    13
                     RESET      F 1. 0       1       14-    14
                     REPRO      F 1. 0       1       15-    15
                     ROUT       F 1. 0       1       16-    16
                     UNPLAN     F 1. 0       1       17-    17
                     DIAG       F 1. 0       1       18-    18
                     OTHER      F 1. 0       1       19-    19
                     MECHROB    F 1. 0       1       20-    20
                     MECHOTH    F 1. 0       1       21-    21
                     ELECROB    F 1. 0       1       22-    22
                     ELECOTH    F 1. 0       1       23-    23
                     ELECINT    F 1. 0       1       24-    24
                     INSPECT    F 1. 0       1       25-    25
                     PROGPROB   F 1. 0       1       26-    26
                     QUAL       F 1. 0       1       27-    27
                     ERRAT      F 1. 0       1       28-    28
                     DROP       F 1. 0       1       29-    29
                     DAMROB     F 1. 0       1       30-    30
```

```
            DAMPERS     F 1. 0         1        31-     31
            DAMMACH     F 1. 0         1        32-     32
            OTH         F 1. 0         1        33-     33
            MEANS       F 1. 0         1        34-     34
            CLASS       F 1. 0         1        35-     35
            IDENT1      F 1. 0         1        36-     36
            IDENT2      F 1. 0         1        37-     37
            IDENT3      F 1. 0         1        38-     38
            SORT1       F 1. 0         1        39-     39
            SORT2       F 1. 0         1        40-     40
            SORT3       F 1. 0         1        41-     41
            UNDER          A 2         1        42-     43

THE INPUT FORMAT PROVIDES FOR   38 VARIABLES.   38 WILL BE READ
IT PROVIDES FOR    1 RECORDS ('CARDS') PER CASE.  A MAXIMUM OF      43 'COLUMNS' ARE USED ON A RECORD.

           8 SUBFILE LIST     AYE(743)EFF(811)BEE(1551)HAY(13)BEEB(1820)BEES(664)
           9 MISSING VALUES   PLACE('9')/TYPE(9)/NO(999)/TASK(9)/MIN(999)/HOUR(99)/
          10                  FAULTY TO OTH(9)/MEANS TO SORT3(9)/UNDER(999)
          11 VAR LABELS        PLACE,SITE OF ROBOT INSTALLATION/CASE,CASE NUMBER/TYPE,ROBOT TYP
          12                 E/NO,DESIGNATED ROBOT NUMBER/TASK,ROBOT TASK/MIN,DOWNTIME MINUTES
          13                  /HOUR,DOWNTIME IN HOURS AND DAYS/FAULTY,REPLACEMENT OF FAULTY
          14                 EQUIPMENT/ADJUST,ADJUSTMENTS TO EQUIPMENT OR CLEANING/RESET,RESET
          15                 TING OF EQUIPMENT/REPRO,REPROGRAMMING/ROUT,ROUTINE MAINTENANCE/
          16                 UNPLAN,UNPLANNED MAINTENANCE/DIAG,FAULT DIAGNOSIS/OTHER,ANY OTHER
          17                  ACTION/MECHROB,MECHANICAL PROBLEMS WITH A ROBOT/MECHOTH,MECHANIC
          18                 AL PROBLEMS WITH OTHER EQUIPMENT/ELECROB,ELECTRICAL PROBLEMS WITH
          19                 A ROBOT/ELECOTH,ELECTRICAL PROBLEMS WITH OTHER EQUIPMENT/ELECINT,
          20                 ELECTRICAL PROBLEMS WITH THE INTERFACE/INSPECT,INSPECTION OF
          21                  THE PROCESS/PROGPROB,PROGRAMME PROBLEM/QUAL,QUALITY PROBLEMS/
          22                 ERRAT,ERRATIC ROBOT BEHAVIOUR/DROP,DROPPED PART/DAMROB,THREATENED
          23                 DAMAGE TO A ROBOT/DAMPERS,THREATENED DAMAGE TO PERSONS/DAMMACH,TH
          24                 REATENED DAMAGE TO MACHINERY/OTH,ANY OTHER REASON FOR ACTION/
          25                 MEANS,MEANS OF INTERRUPTION OF THE PROCESS/CLASS,CLASSIFICATION
          26                 OF THE INCIDENT/IDENT1 TO IDENT3,PERSON INVOLVED IN IDENTIFYING P
          27                 ROBLEM/SORT1 TO SORT3,PERSON WHO SORTED OUT PROBLEM/UNDER,UNDERLY
          28                 ING REASON FOR PROBLEM
          29 VALUE LABELS     PLACE ('1')COMPANY A ('2')COMPANY B STATION5 ('3')COMPANY C
          30                  ('4')COMPANY D ('5')COMPANY E ('6')COMPANY F ('7')COMPANY G
          31                  ('8')COMPANY H ('A')COMPANY B STATION6 ('B')COMPANY B STATION7
          32                  ('C')COMPANY B STATION8/TYPE (1)ASEA IRB6 (2)CINCINNATI HT3 (3)
          33                  KUKA (4)NIMAK (5)UNIMATE 2000 (6)PUMA (7)YASKAWA(9) IRRELEVANT/
          34                  MIN (999)NOT GIVEN/HOUR (99)NOT GIVEN (20)UP TO 2 DAYS (30)UP TO
          35                   3 DAYS (40)UP TO 4 DAYS (50)UP TO 5 DAYS (60)UP TO 6 DAYS (70)U
          36                 P TO 7 DAYS (80)UP TO 8 DAYS (90)UP TO 9 DAYS (100)UP TO 10 DAYS
          37                  (110)UP TO 11 DAYS (120)UP TO 12 DAYS (130)UP TO 13 DAYS (140)U
          38                 P TO 14 DAYS (150)UP TO 15 DAYS (160)UP TO 16 DAYS(170)UP TO 17 D
          39                 AYS (180)UP TO 18 DAYS (190)UP TO 19DAYS (200)UP TO 20 DAYS (210)
          40                 UP TO 21 DAYS (220)UP TO 22 DAYS (230)UP TO 23 DAYS (240)UP TO 24
          41                 DAYS (250)UP TO 25 DAYS(260)UP TO 26 DAYS/NO (1) ONE
          42                   (2) TWO  (3) THREE  (4) FOUR  (5) FIVE  (6) SIX  (7) SEVEN
          43                   (8) EIGHT  (9) NINE  (10)TEN  (11)ELEVEN  (12)TWELVE  (0) NONE
          44                  (999)NOT GIVEN/TASK (1)ARC WELDING (2)SPOT WELDING (3)MATERIALS
          45                 HANDLING (4)ADHESIVE BONDING(5)ROUTING(9)NOT RELEVANT/
          46                        FAULTY TO OTHER (7)ACTION TAKEN                         (8)S
          47                 ECONDARY ACTION (9)ACTION NOT TAKEN/MECHROB TO OTH (7)MAJOR REASO
          48                 N (8)MINOR REASON (9)NOT THE REASON/MEANS (1)E-STOP PRESSED (2)OT
          49                 HER ACTION (3)AUTOMATIC STOP (4)SENSOR STOP(9)NOT KNOWN/CLASS (1)
          50                  ACCIDENT TO PERSON
          51                        (2)ACCIDENT TO MACHINE (3)ACCIDENT TO BOTH (4)ACCIDENT-NO
          52                   DAMAGE (5)NEAR MISS (6)INCIDENT NO DAMAGE (7)HAZARD ANTICIPATED
```

```
 53                 (8)NO DAMAGE LIKELY(9)NOT GIVEN/IDENT1 TO SORT3 (1)FITTPR (2)ELEC
 54                 TRICIAN                                                       (3)
 55                 PRODUCTION ENGINEER (4)OPERATOR (5)FOREMAN (6)CHARGEHAND (7)SERVI
 56                 CE ENGINEER (8)OTHER(9)NO-ONE/UNDER (10)RCBOT-NO DETAIL(11)ROBOT
 57                 OUT OF SYNCH'(12)STIFFNESS IN ARM (13) CABLE PROBLEM  (14) MANIFU
 58                 LATOR FAULT  (15) FUSES BLOWN  (16) RCBOT IN E-STCP  (17) FAULT I
 59                 N CABINET  (18) ERRATIC ROBOT  (19) FAULT ON PENDANT  (110)PCWER
 60                 SUPPLY FAULT  (120)PROBLEM IN TOOLS  (130)ROBOT WCNT MOVE  (140)R
 61                 OBOT COLLISION  (150)OVERHEATING HYD.  (22) OTHER COMP FAULT
 62                  (33) SYSTEM FAILURE  (34) CHECKS ON THE SYSTEM  (41) CHECK CN
 63                 PARTS  (42) PART VARIATION  (43) QUALITY PROPLEM  (44) PRCCESS
 64                 PROBLEM  (55) SERVICES PROBLEM  (66) EQUIPMENT PRCBLEM  (77) SAFE
 65                 TY PROBLEM  (88) HUMAN ERROR  (200)WELD FAILURE
 66                  (210)SEQUENCE FAULT (999) MISSING
 67 INPUT MEDIUM    CARD
 68 COMPUTE         X=0
 69 IF                (PLACE EQ '2' AND NO='1') NO='121'
 70 IF                (PLACE EQ '2' AND NO='2') NO='122'
 71 IF                (PLACE EQ '2' AND NO='3') NO='123'
 72 IF                (PLACE EQ '2' AND NO='4') NO='124'
 73 IF                (PLACE EQ '2' AND NO='5') NO='125'
 74 IF                (PLACE EQ '2' AND NO='6') NO='126'
 75 IF                (PLACE EQ '2' AND NO='7') NO='127'
 76 IF                (PLACE EQ '2' AND NO='8') NO='128'
 77 IF                (PLACE EQ 'A' OR PLACE EQ 'B' AND TYPE EQ 3) X=1
 78 IF                (PLACE EQ 'A' CR PLACE EQ 'B' AND TYPE EQ 4) X=2
 79 IF                (PLACE EQ 'A' CR PLACE EQ 'B' AND TYPE EQ 1) NO='211'
 80 IF                (X EQ 1 AND NC='1') NO='173'
 81 IF                (X EQ 1 AND NC='2') NO='253'
 82 IF                (X EQ 1 AND NC='3') NO='263'
 83 IF                (X EQ 1 AND NC='4') NO='293'
 84 IF                  (X EQ 2 AND NO='1') NO='171'
 85 IF                  (X EQ 2 AND NO='2') NO='172'
 86 IF                  (X EQ 2 AND NO='3') NO='181'
 87 IF                  (X EQ 2 AND NO='4') NO='182'
 88 IF                  (X EQ 2 AND NO='5') NO='251'
 89 IF                  (X EQ 2 AND NO='6') NO='252'
 90 IF                  (X EQ 2 AND NO='7') NO='261'
 91 IF                  (X EQ 2 AND NO='8') NO='262'
 92 IF                  (X EQ 2 AND NO='9') NO='291'
 93 IF                  (X EQ 2 AND NO='A') NO='292'
 94 IF                  (X EQ 2 AND NO='B') NO='301'
 95 IF                  (X EQ 2 AND NO='C') NO='302'
 96 IF                  (X EQ 2 AND NO='D') NO='311'
 97 IF                  (X EQ 2 AND NO='E') NO='312'
 98 IF                  (X EQ 2 AND NO='F') NO='321'
 99 IF                  (X EQ 2 AND NO='G') NO='322'
100 IF                  (X EQ 2 AND NO='H') NO='331'
101 IF                  (X EQ 2 AND NO='J') NO='332'
102 RECODE              NO ('A'=10)('B'=11)('C'=12)('U'=999)(CONVERT)
103 RECODE              MIN ('AA'=999)(CONVERT)
104 RECODE             HOUR ('A'=99)('B'=20)('C'=30)('D'=40)('E'=50)('F'=60)('G'=70)
105                      ('H'=80)('I'=90)('J'=100)('K'=110)('L'=120)('M'=130)
106                      ('N'=140)('O'=150)('P'=160)('Q'=170)('R'=180)('S'=190)
107                      ('T'=200)('U'=210)('V'=220)('W'=230)('X'=240)('Y'=250)
108                      ('Z'=260)(CONVERT)
109 RECODF             UNDER ('AA'=200)('BB'=210)('1A'=110)('1B'=120)('1C'=130)
110                    ('1D'=140)('1E'=150)('99'=999)(CONVERT)
111 FREQUENCIES        GENERAL=PLACE, TYPE TO UNDER
GIVEN WORKSPACE ALLOWS FOR   5120 VALUES AND   1536 LABELS PER VARIABLE FOR 'FREQUENCIFS'
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