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# Human Error and Disturbance Occurrence in Manufacturing Systems (HEDOMS): A Framework and a Toolkit for Practical Analysis

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**Abstract:** New demands on modern manufacturing systems, such as increased flexibility, higher quality standards, customer responsiveness, and higher innovative capacities, have emphasised the need for higher levels of overall system reliability. Within this context disturbances play a critical role, because of the effects they may have on production or on safety, which are both strong determinants of overall system performance. The main focus of this paper is the reliability of manufacturing personnel and the way in which this interrelates with overall system performance. A framework – Human Error and Disturbance Occurrence in Manufacturing Systems (HEDOMS) – integrates human reliability with overall system performance, relating human error with disturbance occurrence and handling. HEDOMS has been extended into a toolkit to enable the identification of potential for human error and disturbance occurrence in manufacturing systems, as well as the definition of suitable error reduction measures.

**Keywords:** Disturbances; Human error; Manufacturing; Reliability; Systems analysis

## 1. INTRODUCTION

The main focus of this paper is the reliability of the people in manufacturing systems and how this might affect overall system performance. Within system performance we are particularly concerned with disturbances, defined as any events which have not been planned for or which are undesirable and that reduce or have the potential for reducing overall system performance, in terms of either production or safety requirements and goals.

In order to analyse human reliability in manufacturing systems we need to be clear on the definition adopted for human error in manufacturing, and also have available a range of techniques and tools for human error analysis. Human error we define as any human action (or failure to act) which results in an inappropriate or undesirable state of affairs, generally an outcome which detracts from achieving company targets and goals. Implicit within the definition proposed is the acknowledgement not only of the individual aspects of error, such as cognitive and affective characteristics, but also the context in which the error has occurred; that is, all system conditions likely to contribute towards human error occurrence must be accounted for.

With regard to the techniques and tools available for human reliability analysis, the vast majority of these have been developed for application in high-risk sectors, such as the nuclear and petrochemical industries. These are highly structured methods comprising a number of steps, aimed at the identification of human error probabilities and usually applied within the context of Probabilistic Safety Assessments (Kirwan 1994). The same principles have proved to be applicable for human error analysis in other (lower safety risk) industrial contexts, with a sound example being the development and application of a potential human error audit at the British Coal Corporation (Simpson et al 1991).

The negative impact of disturbances in overall system performance, the role played by human error both in disturbance causation and handling, together with the current situation regarding the range and characteristics of techniques available for human error analysis constitute the main pillars on which this research has been based.

The paper starts with a description of the framework proposed for Human Error and Disturbance Occurrence in Manufacturing Systems (HEDOMS), based on some of the principles underlying other human reliability assessment techniques and tools, and which combines several important human reliability concepts and approaches.

A preliminary assessment of the framework was undertaken by means of interviews with managers from different manufacturing companies. These indicate that managers from different departments across an organisation acknowledge the role played by human error in disturbance causation and handling and that tools for human error and disturbance analysis are regarded as potentially useful. The interview findings were confirmed in a questionnaire sent to a number of manufacturing companies, aimed at gathering opinions on the importance of human error in accident and disturbance causation, perceptions of the causes of human error, and the company's involvement in human error analyses.

The paper proceeds with the description and justification of the HEDOMS toolkit developed on the basis of the framework and the data and comments gathered from the interviews and questionnaires. The toolkit includes a module for disturbance data recording and analysis, a module for identification of the potential for human error and a final module that combines the information gathered and suggests suitable error reduction measures.

## 2. UNDERSTANDING HUMAN ERROR AND DISTURBANCE OCCURRENCE IN MANUFACTURING: THE HEDOMS FRAMEWORK

### 2.1. The Need for a Framework for Analysis of Human Error and Disturbances in Manufacturing

The importance of disturbance occurrence in manufacturing systems can be illustrated by referring to the effects of disturbances at different levels of the system. The studies undertaken by Kuivanen (1990) and Järvinen et al (1996) show that, while the vast majority of disturbances have only minor or no effects in terms of safety, this is not the case as far as the consequences in production terms are concerned. The results obtained by Kuivanen (1990) indicate that between 80% and 94% of disturbances produce a negative effect on production. Material damage has been registered for between 4% and 45% of disturbances (Järvinen at al 1996) and downtime periods of between 15 and 30 minutes have been associated with a considerable proportion of disturbances (Vannas and Mattila 1996).

The importance of human error in manufacturing comes to the fore when analysing the role of humans in modern manufacturing systems. This role has been subject to significant change, mainly associated with increased automation and implementation of information technology to integrate different functions in production systems, as well as the corresponding changes in organisational structure. Developments have been especially noticeable at the operational level, where it is becoming rarer to find single individuals performing clearly defined production tasks assigned to a particular machine; rather they are becoming an integrated part of a wider, more complex and distributed system. Thinking is as much a part of the role of operatives as is acting or doing; their work requires combinations of physical and cognitive skills. In some industries the role of operators is becoming more often associated with the idea of the supervisory controller (Sheridan 1987), which in its most complete form entails a range of different functions such as planning, teaching, monitoring, intervening and learning.

In many industries there is an important paradox regarding the functions performed by operators. On the one hand, it seems that the operator's role may have become simplified since they are merely assigned the task of monitoring and occasionally controlling a highly developed technical system running within a well-adapted organisational context, and for which they have received adequate training. On the other hand, the cognitive and social aspects of their roles may be far more complex than previously, particularly so when deviations to normal system functioning occur. This has been clearly depicted by Bainbridge (1987) as ironies of automation.

The functions of monitoring, planning and intervening have considerable relevance as far as disturbance causation and disturbance handling processes are concerned. In practice, operator interventions to handle deviations or disturbances in manufacturing systems are both crucial for overall system effectiveness and also, more often than not, are made up of tasks which are associated with unusual and high demands. This not only clearly illustrates the importance of operator skills, flexibility and reliability for acceptable overall system performance, but also indicates the complexity associated with any analysis of operators' performance, which must embrace a wide range of factors from all levels across the system. Machinery, workplace and equipment design, task and job design and work organisation, the design of information systems, personnel selection and training issues, target setting, among many other factors, must be taken into consideration when analysing and assessing the efficiency and reliability of operators' performance.

The relationship between human error and disturbances needs to be accounted for. Our own view of this relationship examines the role of operator performance from two different perspectives, as both a potential '*contributor*' to the occurrence of a disturbance, and also the '*recoverer*' or '*rescuer*' of a system which has moved away from its normal state due to some disturbance.

Operator contribution towards disturbance occurrence is essentially related to those situations in which disturbances have occurred as a result of human (operator) error. Review of research on disturbance occurrence in manufacturing systems shows the contribution of human error to account for between 11% and 25% of disturbances (Kuivanen 1990; Döös and Backström 1993; Järvinen et al 1996). The operator role of *recoverer* entails their intervention in order to move the system away from an unstable phase back to the normal operating one, by means of appropriate recovery actions, often associated with the performance of unfamiliar tasks and usually under considerable pressure. There is a potential dual role of operators in intervention for disturbance recovery. They can act as *rescuers* of a system that is patently moving towards an unstable state, but any inappropriate behaviour on their part can also exacerbate the severity of the consequences of disturbances. In the latter case, human errors not only may increase the severity of the system disturbance outcomes, but also may make eventual recovery more difficult.

As a clear illustration of the problems operators have to face while intervening towards disturbance recovery are the studies undertaken on accident causation in manufacturing industries, which suggest that the number of accidents occurring while the operator is involved in troubleshooting or disturbance control tasks varies between one third and two thirds of the total of accidents analysed (Backström and Harms-Ringdahl 1984; Kuivanen 1990; Laflamme 1993; Järvinen and Karwowski 1993, 1995; Backström and Döös 1995; Mattila et al 1995).

What means are currently available for the achievement of that purpose, that is: what means are accessible that enable analysis of human error and disturbance occurrence in manufacturing systems? The availability of techniques for human error analysis is significantly greater than for analysis of disturbance occurrence. Review of the literature on human error and human reliability analysis rapidly brings to light the variety of techniques and methods available, the vast majority of which were developed for application in high-risk sectors, such as nuclear, petrochemical and aviation industries. These are highly structured methods comprising a number of stages including human error identification, quantification and definition of error reduction measures, and which are generally applied within the context of Probabilistic Safety Assessments.

Although the predominance of human error analysis is in high-risk contexts, evidence exists which suggests that the same principles may be successfully applied in other, usually lower safety risk, industrial situations. Examples include the development and application of 'potential for human error audits' at the British Coal Corporation (Mason and Simpson 1993; Rushworth et al 1991; Simpson et al 1991; Simpson 1992), the analysis of human reliability in manual and computer-numerically controlled lathe operations using THERP (Pines and Goldberg 1992), the analysis of information requirements in CIM systems (Prabhu et al 1992), and the analysis of error potential and identification of error reduction measures in the electricity supply industry (Glendon 1993). Other situations in which similar human error analysis principles have been applied include the development of procedures for high-risk industries (Sharit 1998), the analysis of human error in driving tasks (Blockey and Hartley 1995), error analysis in medicine (Ostrom 1994), and the evaluation of a ticket vending machine (Connell 1998). However, despite the diversity of human error analysis applications, their use is not a well-established practice in the context of advanced manufacturing; Wilson et al (1994) state, with respect to human error analysis in advanced manufacturing, that 'human error has not been subjected to nearly as formal an analysis' (p. 385).

Despite the scarcity of applications, human error analysis in manufacturing systems seems to be generally regarded as important for disturbance occurrence and also accident causation (e.g. Järvinen et al 1996; Jiang and Gainer 1987; Karwowski et al 1997; Kuivanen et al 1988; Nagamachi et al 1984; Nicolaisen 1985; Norros 1996; Vannas and Mattila 1996; Zimolong and Duda 1992; Zimolong and Trimpop 1994). This idea is further corroborated by the results gathered from a questionnaire survey,[1] conducted by the first author in a group of Portuguese manufacturing companies and which was aimed at gathering the reactions and opinions towards the importance of human error and disturbances in industrial settings. The results of the survey indicate that human error is unequivocally acknowledged as an important factor for both disturbance and accident occurrence (see Table 1).

**Table 1.** Importance assigned to human error as a cause of disturbances and accidents (results from the questionnaire survey)

| Question | Answers | |
|---|---|---|
| | 'Very important' | 'Important' |
| Importance of human error for disturbance occurrence | 54% of responses | 46% of responses |
| Importance of human error for accident occurrence | 67% of responses | 33% of responses |

As well as highlighting the importance attributed to human error and disturbance causation, the results from the questionnaire have brought to light another interesting fact—it seems as if a relatively large proportion of the companies surveyed actually performs human error analysis already (see Table 2).

When asked about the reasons underlying the scarce application of practical human error analyses, the answers

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[1] The questionnaire was sent to 47 different companies, addressed to either production or safety department. The sample involved different company sizes and industrial contexts, such as textile, tobacco processing, oil and lubricants, electronic assembly, engine and mechanical component production and assembly, among other. Response rate was of above 55%.

**Table 2.** Application of human reliability analysis (results from the questionnaire survey)

| Frequency with which human error analysis is carried out? | Responses given |
|---|---|
| On a regular basis | 37% |
| Only once in a while, on an experimental basis | 50% |
| Never done | 13% |

**Table 3.** Reasons highlighted for scarce application of human reliability analysis (results from the questionnaire survey)

| Reasons underlying the scarce application of human error analysis techniques | Responses given |
|---|---|
| Unavailability of the means required | 60% |
| Unavailability of techniques for HRA | 20% |
| Complexity associated with the available techniques for HRA | 20% |

given suggest that the main cause is associated with the unavailability of the required means (see Table 3).

A possible explanation for the scarcity of applications of human error analysis in manufacturing systems seems to be closely related to the limitations associated with the practical application of inherently complex and resource-demanding techniques, such as the vast majority of human error analysis techniques and methods. The majority of the respondents (70%) have characterised as *very important* the development of a procedure for human error analysis, and the remainder considers this enterprise as being *important*. With regard to requirements associated with such a procedure the data suggest that:

- the procedure should be easy to apply, it should lead to the identification of specific error reduction measures, and that these aspects are regarded as being more important than the time required for its practical application;
- the procedure should be defined so that it can be applied to any workplace;
- the procedure should be usable by non-specialists, i.e. individuals with no detailed or specific background on human reliability.

On the basis of the evidence, development of a procedure for human error analysis in manufacturing systems appears to be useful and potentially beneficial, with extensive applicability towards the improvement of overall system performance.

## 2.2.The HEDOMS Framework

The main goal of the HEDOMS framework is to understand the roles of human error and disturbance causation and the way in which these affect overall system performance. A key element of the framework is the concept of disturbances, analysed in terms of the associated consequences at both production and safety levels. Additionally the framework aims to provide the basis upon which a comprehensive and effective analysis of human error can be performed. A number of concepts have been extracted from human reliability analysis in high-risk industries and incorporated into the framework, including:

- the Skill-, Rule-, and Knowledge model proposed by Rasmussen (1986) and the GEMS model suggested by Reason (1990), which constitute the basis upon which human error will be classified and analysed and the most relevant error shaping factors and mechanisms identified;
- the distinction between active and latent failures (Reason 1990), enabling consideration of a wide range of factors across all levels of the organisation likely to promote occurrence of either disturbances or human error;
- the concept of performance shaping factors (e.g. Swain and Guttman 1986), which will be used essentially as a means of identifying potential for human error at individual workplaces.

Figure 1 illustrates the overall structure of the HEDOMS framework; a detailed description of the way in which the

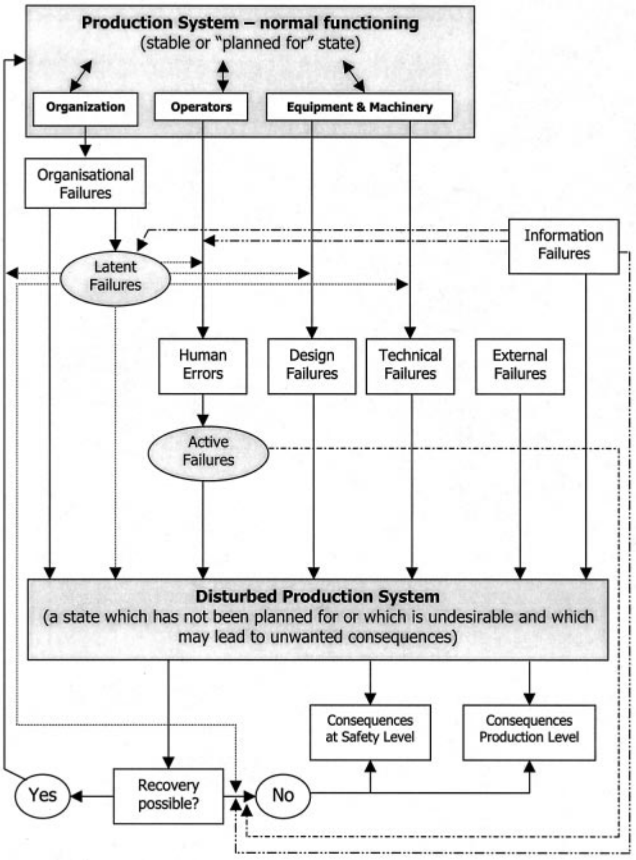


**Fig. 1.** The HEDOMS framework.

different concepts and theories have been integrated in HEDOMS can be found in Paz Barroso and Wilson (1999).

## 3. THE HEDOMS TOOLKIT

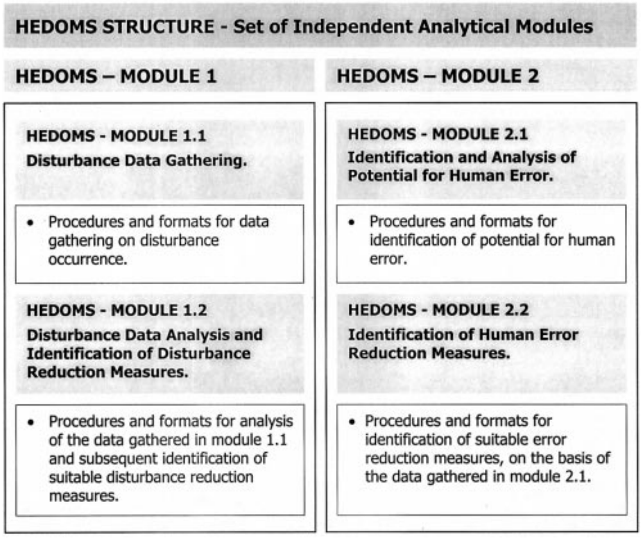
The main goal of the HEDOMS toolkit is to allow for the systematic recording and analysis of disturbance data, and also an in-depth analysis of the potential for human error and the identification of adequate error reduction measures. It comprises a set of two analytical modules which have been developed so that each of them could be applied on an individual basis. Each of the modules comprises a sub-module for data collection and another for data analysis and identification of suitable error or disturbance reduction measures. The structure of the toolkit is illustrated in Figure 2.

A feature of the toolkit, and one which has determined many of its characteristics, is the requirement for its practical application by people within a company who do not necessarily possess qualifications or much knowledge about ergonomics or human reliability. This requirement has become explicit through initial interviews carried out with different personnel in a variety of manufacturing companies, as well as from the results obtained from the questionnaire survey carried out in Portuguese industrial companies.

### 3.1. HEDOMS – Module 1: Disturbance Data Gathering and Identification of Disturbance Reduction Measures

#### 3.1.1. HEDOMS – Module 1.1: Disturbance Data Gathering

A procedure was developed for disturbance data gathering. This is structured in three main stages, starting with the detection of an event that represents a disturbance, and proceeding with the classification of the causes and consequences associated with the event. Figure 3 summarises the stages and illustrates the different taxonomies defined for disturbance classification (see Paz Barroso and Wilson 1999 for an extensive description of the taxonomies).



**HEDOMS STRUCTURE - Set of Independent Analytical Modules**

**HEDOMS – MODULE 1**

**HEDOMS - MODULE 1.1**
**Disturbance Data Gathering.**

- Procedures and formats for data gathering on disturbance occurrence.

**HEDOMS - MODULE 1.2**
**Disturbance Data Analysis and Identification of Disturbance Reduction Measures.**

- Procedures and formats for analysis of the data gathered in module 1.1 and subsequent identification of suitable disturbance reduction measures.

**HEDOMS – MODULE 2**

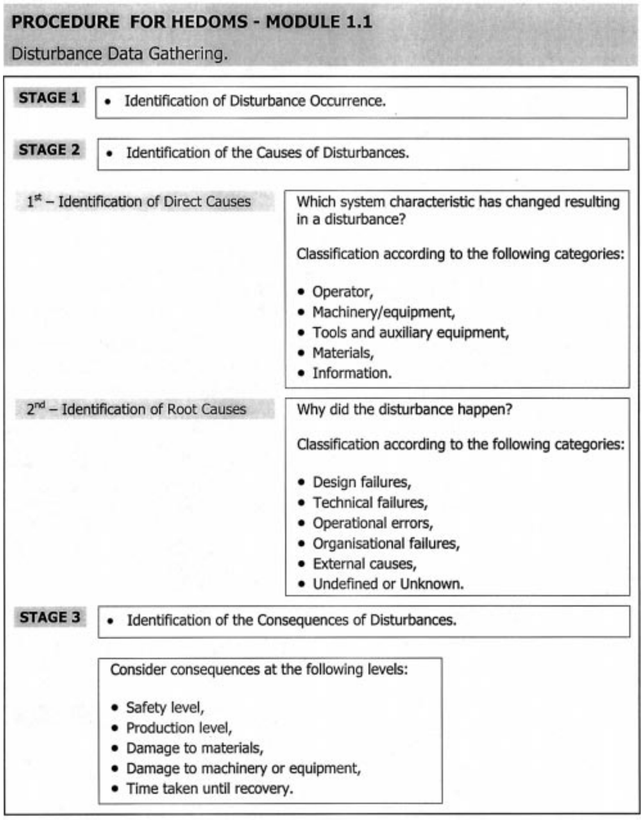
**HEDOMS - MODULE 2.1**
**Identification and Analysis of Potential for Human Error.**

- Procedures and formats for identification of potential for human error.

**HEDOMS - MODULE 2.2**
**Identification of Human Error Reduction Measures.**

- Procedures and formats for identification of suitable error reduction measures, on the basis of the data gathered in module 2.1.

**Fig. 2.** Overall structure of the HEDOMS toolkit.



**PROCEDURE FOR HEDOMS - MODULE 1.1**
Disturbance Data Gathering.

**STAGE 1**
- Identification of Disturbance Occurrence.

**STAGE 2**
- Identification of the Causes of Disturbances.

1st – Identification of Direct Causes

Which system characteristic has changed resulting in a disturbance?

Classification according to the following categories:

- Operator,
- Machinery/equipment,
- Tools and auxiliary equipment,
- Materials,
- Information.

2nd – Identification of Root Causes

Why did the disturbance happen?

Classification according to the following categories:

- Design failures,
- Technical failures,
- Operational errors,
- Organisational failures,
- External causes,
- Undefined or Unknown.

**STAGE 3**
- Identification of the Consequences of Disturbances.

Consider consequences at the following levels:

- Safety level,
- Production level,
- Damage to materials,
- Damage to machinery or equipment,
- Time taken until recovery.

**Fig. 3.** Structure and classification systems for HEDOMS – Module 1.1.

Two different data recording sheets, for application by supervisors and operators respectively, have been developed on the basis of the procedure and taxonomies proposed. The data recording formats and the taxonomies for disturbance classification have been assessed through interviews[2] carried out with six people from three different companies. The formats were subsequently tested out in one manufacturing company for a period of a week, both by operators from five different workplaces and three supervisors. The results have shown that the procedure provides a simple, systematic disturbance data gathering process. Furthermore, the company participating in the practical

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[2] Respondents were either production or safety managers. The interviews were conducted in a structured way and included questions aimed at assessing the different characteristics of the formats proposed – language used, clarity and distinctiveness of the categories proposed, layout of the formats, feasibility of practical application. A range of four different formats was presented to the interviewees who were asked to select that which they judged to be the most suitable.

**Table 4.** Results gathered from application of HEDOMS – Module 1.1 for disturbance data gathering

| Category of root cause | % of disturbances registered |
|---|---|
| Design error | 16% |
| Component/technical failure | 12% |
| Human error | 13% |
| Organisational failure | 50% |
| External failure | 0% |
| Undetermined | 9% |

application of the data recording formats has also reported the successful application of the taxonomy and procedures within their TPM (Total Production Maintenance) program.

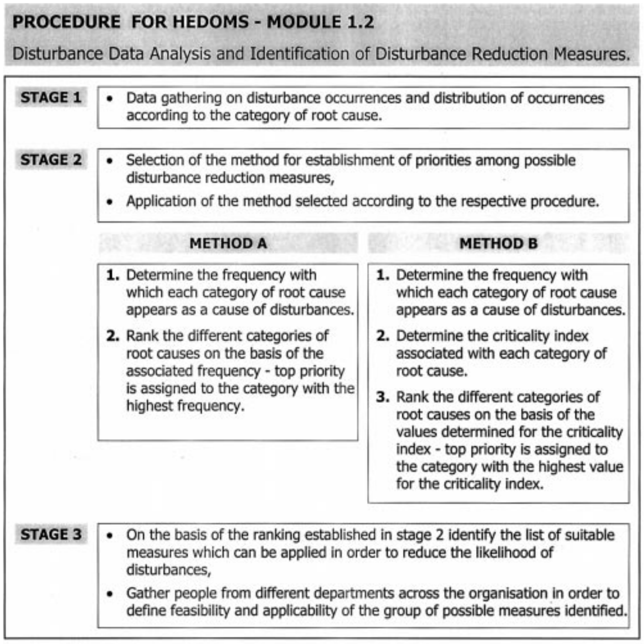
The results gathered from the practical application of HEDOMS – Module 1.1, which comprise data from a total of 27 disturbances, have highlighted the importance of organisational failures in disturbance causation (see Table 4).

The importance of organisational failures as contributory factors towards disturbance causation, the role they play in determining the success of disturbance recovery, and the considerable variety of factors involved, suggest that an additional taxonomy for more detailed classification into organisational failures could be beneficial. This would not only enhance the identification of measures aimed at disturbance reduction but would also contribute to a more extensive analysis of human error causation. However, our initial attempts to develop an additional classification system of organisational failures have highlighted a serious concern. The toolkit and its classification system must be comprehensive enough to be of value, yet succinct enough to ensure that people are motivated to use it and to continue to do so. One way of overcoming this problem, also discussed while assessing the applicability of the procedure of HEDOMS – Module 1.1, is to distinguish the organisational failures in terms of the most dominant organisational function involved. Accordingly, each organisational failure identified would subsequently be classified into one of the categories of Table 5.

### 3.1.2. HEDOMS – Module 1.2: Disturbance Data Analysis and Identification of Disturbance Reduction Measures

Fundamentally, HEDOMS – Module 1.2 utilises the analysis and interpretation of the data gathered through application of Module 1.1, in order to pinpoint the most important contributory factors for disturbance causation and identify a range of suitable disturbance reduction measures.

Two alternative methods have been devised for identifying which categories of root causes play dominant roles in disturbance causation. The first (method A) is based solely on the percentage of disturbances associated with each category; i.e., the higher the proportion of disturbances due to a category of root causes, the more important that category is. An alternative, more elaborate, procedure (method B) can be accomplished if the



**PROCEDURE FOR HEDOMS - MODULE 1.2**

Disturbance Data Analysis and Identification of Disturbance Reduction Measures.

**STAGE 1**

- Data gathering on disturbance occurrences and distribution of occurrences according to the category of root cause.

**STAGE 2**

- Selection of the method for establishment of priorities among possible disturbance reduction measures,
- Application of the method selected according to the respective procedure.

**METHOD A**

1. Determine the frequency with which each category of root cause appears as a cause of disturbances.
2. Rank the different categories of root causes on the basis of the associated frequency - top priority is assigned to the category with the highest frequency.

**METHOD B**

1. Determine the frequency with which each category of root cause appears as a cause of disturbances.
2. Determine the criticality index associated with each category of root cause.
3. Rank the different categories of root causes on the basis of the values determined for the criticality index - top priority is assigned to the category with the highest value for the criticality index.

**STAGE 3**

- On the basis of the ranking established in stage 2 identify the list of suitable measures which can be applied in order to reduce the likelihood of disturbances,
- Gather people from different departments across the organisation in order to define feasibility and applicability of the group of possible measures identified.

**Fig. 4.** Structure for HEDOMS – Module 1.2.

**Table 5.** Classification system proposed for organisational failures

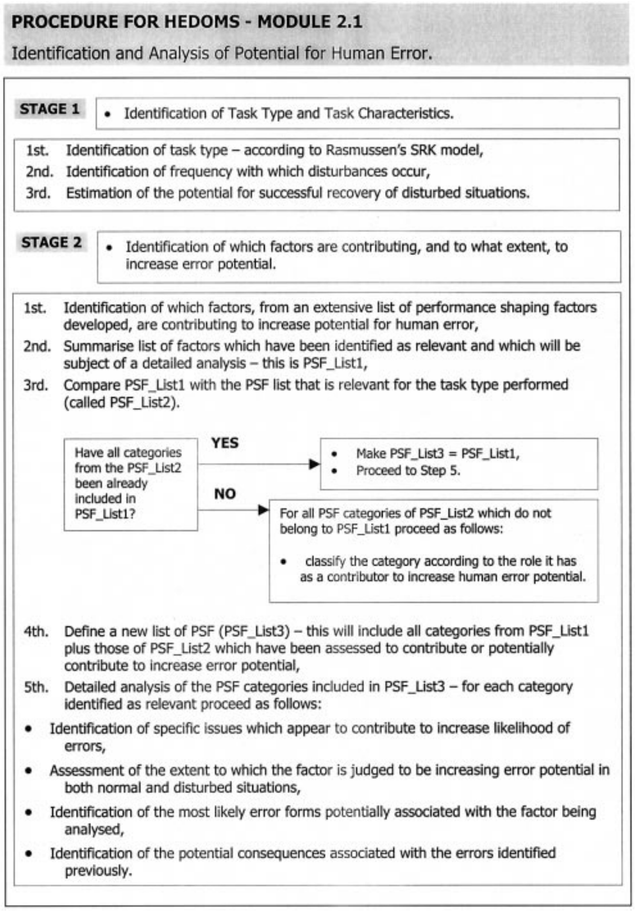
| HEDOMS – Module 1.1: taxonomy developed for detailed classification of organisational failures<br>Organisational function involved | Examples |
|---|---|
| Production control and organisation | Planning and scheduling failures, rush orders, changes in orders |
| Engineering | Inadequate definition of working methods or maintenance programs, problems with machine installation |
| Quality | Inadequate design of inspection procedures, definition of quality standards |
| Purchasing | Delays and errors in materials and parts ordering |
| Warehousing/logistics | Failures in control or distribution of spares and materials |
| Personnel | Personnel selection problems, inadequate definition of training programs |
| Commercial/sales | Problems with demand forecasting, communication failures with warehousing/ logistics |
| Financial | Problems with investment allocation, research and development constraints |

identification of the most important root causes is based both on the percentage of disturbances and on the severity of the associated consequences. A criticality index has been developed which combines the frequency with which each of the categories has been involved in disturbance causation and the severity of the consequences of disturbances. Figure 4 illustrates the procedure of HEDOMS – Module 1.2.

## 3.2. HEDOMS – Module 2: Identification and Analysis of Potential for Human Error and Identification of Human Error Reduction Measures

### 3.2.1. HEDOMS – Module 2.1: Identification and Analysis of Potential for Human Error

The main aim of Module 2.1 of HEDOMS is the assessment of potential for human error. A procedure has been developed which assists in gathering sufficient information on task, worker and workplace characteristics to allow for subsequent identification of those factors most likely to play an important role in human error occurrence. This comprises two main stages, as illustrated in Figure 5.



**PROCEDURE FOR HEDOMS - MODULE 2.1**

Identification and Analysis of Potential for Human Error.

**STAGE 1**

- Identification of Task Type and Task Characteristics.

1st. Identification of task type – according to Rasmussen's SRK model,
2nd. Identification of frequency with which disturbances occur,
3rd. Estimation of the potential for successful recovery of disturbed situations.

**STAGE 2**

- Identification of which factors are contributing, and to what extent, to increase error potential.

1st. Identification of which factors, from an extensive list of performance shaping factors developed, are contributing to increase potential for human error,
2nd. Summarise list of factors which have been identified as relevant and which will be subject of a detailed analysis – this is PSF_List1,
3rd. Compare PSF_List1 with the PSF list that is relevant for the task type performed (called PSF_List2).

Have all categories from the PSF_List2 been already included in PSF_List1?

YES

- Make PSF_List3 = PSF_List1,
- Proceed to Step 5.

NO

For all PSF categories of PSF_List2 which do not belong to PSF_List1 proceed as follows:

- classify the category according to the role it has as a contributor to increase human error potential.

4th. Define a new list of PSF (PSF_List3) – this will include all categories from PSF_List1 plus those of PSF_List2 which have been assessed to contribute or potentially contribute to increase error potential,
5th. Detailed analysis of the PSF categories included in PSF_List3 – for each category identified as relevant proceed as follows:

- Identification of specific issues which appear to contribute to increase likelihood of errors,
- Assessment of the extent to which the factor is judged to be increasing error potential in both normal and disturbed situations,
- Identification of the most likely error forms potentially associated with the factor being analysed,
- Identification of the potential consequences associated with the errors identified previously.

**Fig. 5.** Structure for HEDOMS – Module 2.1.

Stage 1 is a series of questions to identify the main task characteristics, classifying them according to Rasmussen's (1986) SRK model. The underlying premise is that this classification can subsequently be combined with the taxonomy of error types suggested by Reason (1990) and hence allow the identification of the most predominant psychological error mechanisms and error-shaping factors. The SRK model, the distinction between slips, lapses and mistakes, and the Generic Error Modelling system have all been extensively analysed and applied previously.

As with Module 1, the main reasons underlying the selection of the model and taxonomy are to do with the practical application for the toolkit. The need is for a simple, precise and robust model of human behaviour usable by people within companies with no specific training in ergonomics or human reliability. The model of human behaviour should enable clear identification of main task features, preferably in an overt form. This has been incorporated into the toolkit in the form of a series of statements that describe the main distinguishable characteristics associated with each of the categories of behaviour considered in the SRK model. In addition, the procedure developed for this stage also includes questions to assess the frequency with which disturbance handling situations occur and the overall success of disturbance recovery actions. The latter information will be used subsequently, in Module 2.2, for a more accurate assessment of the role of the different error influencing factors in both normal and disturbance handling situations.

Stage 2 comprises assessment of a range of Performance Shaping Factors (PSFs): the factors, conditions or circumstances known to influence human reliability. Table 6 presents the range of factors considered, structured into two main categories of internal and external factors. This categorisation has been developed on the basis of an extensive review and analysis undertaken of different techniques and tools for human reliability assessment (Cacciabue 1997; Carnino and Griffon 1982; Embrey 1994; Glendon et al 1994; Glendon and Mckenna 1995; Hollnagel 1993; Kirwan 1992a, 1992b, 1994, 1996, 1997; Kirwan et al 1997; Lucas 1997; Miller and Swain 1987; Rasmussen 1982; Rouse and Rouse 1983; Swain and Guttman 1986; Williams, 1988a, 1988b).

The list of PSFs has been assessed in a structured evaluation involving 15 human factors/ergonomics experts and 10 people from manufacturing companies. Both questionnaires and interviews were employed in this assessment of the applicability of the PSF list for the purposes for which it was intended, and also of the relative importance assigned to the individual categories of PSF for the performance of different task types.

Results from this assessment exercise suggest that the list of PSF categories is suitable, having scored highly in characteristics such as usefulness for human reliability

**Table 6.** Categories of performance shaping factors considered in HEDOMS

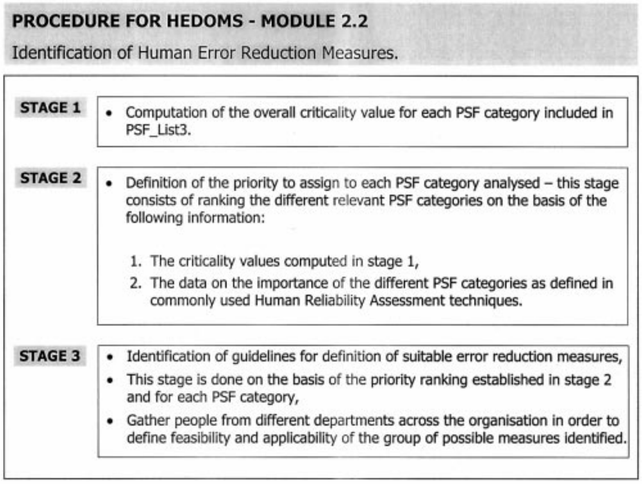
| Internal performance shaping factors | External performance shaping factors |
|---|---|
| • Training and experience in the task | • Design of displays and controls |
| • Knowledge about task requirements | • Information |
| • Motivation and/or morale | • Feedback |
| • Stress | • Workplace layout |
| • Attitudes toward task and conditions | • Movements around workplace |
| • Physical condition of the operators | • Environmental conditions |
| • Other factors (age, gender, health, etc.) | • Task complexity |
| | • Physical requirements |
| | • Time available and other task characteristics |
| | • Incompatibility between tasks |
| | • Design of procedures and instructions |
| | • Training methods |
| | • Frequency and duration of training |
| | • Definition of roles and responsibilities |
| | • Organisation of production system |
| | • Task design and organisation |
| | • Communication |
| | • Supervision |
| | • Company climate |
| | • Family problems |
| | • Social pressures and external activities |

analysis, applicability in different industrial contexts, clarity and meaning of the categories defined and potential contribution towards systematic analysis of human error.

The initial assessment of the PSF list proposed (PSF_List1) is aimed at identifying those aspects or circumstances of the workplace, environment or organisation which are contributing to increasing human error potential. This list is subsequently combined with a list of factors known to be important for the task type being performed by the operator[3] (PSF_List2). The final list produced (PSF_List3) includes a range of PSF categories, all of which are considered to be having an impact in human error potential.

### 3.2.2. HEDOMS – Module 2.2: Identification of Human Error Reduction Measures

The aim of Module 2.2 is to analyse the data gathered in Module 2.1 and identify a range of guidelines that promote the subsequent identification of specific and effective error reduction measures. Figure 6 illustrates the general structure proposed for HEDOMS – Module 2.2.



**PROCEDURE FOR HEDOMS - MODULE 2.2**

Identification of Human Error Reduction Measures.

**STAGE 1**

- Computation of the overall criticality value for each PSF category included in PSF_List3.

**STAGE 2**

- Definition of the priority to assign to each PSF category analysed – this stage consists of ranking the different relevant PSF categories on the basis of the following information:
  1. The criticality values computed in stage 1,
  2. The data on the importance of the different PSF categories as defined in commonly used Human Reliability Assessment techniques.

**STAGE 3**

- Identification of guidelines for definition of suitable error reduction measures,
- This stage is done on the basis of the priority ranking established in stage 2 and for each PSF category,
- Gather people from different departments across the organisation in order to define feasibility and applicability of the group of possible measures identified.

**Fig. 6.** Structure for HEDOMS – Module 2.2.

According to the structure illustrated in Figure 6, Module 2.2 will enable the identification of guidelines for definition of error reduction measures on the basis of the PSF categories analysed in Module 2.1. In order to assess the importance of each PSF category, and correspondingly establish priorities among possible error reduction measures, a criticality index for each PSF category ($CI_{PSF}$) is proposed. This is calculated according to the following expression, and accounts for the impact the category is judged to have in increasing potential for human error and for the severity of the consequences associated with potential errors.

$$CI_{PSF} = C_i \times SI \times [HEP_n \times (1 - f_i + f_i \times w_i) + HEP_d \times f_i \times (1 - w_i)]$$

The different variables in the expression include:

| | |
|---|---|
| $C_i$ | assessment of the contribution of the PSF category to increasing error potential; |
| SI | severity index to account for the severity associated with potential consequences of error forms identified; |
| $HEP_n$ | estimation of error likelihood in normal working situations; |
| $HEP_d$ | estimation of error likelihood for disturbed situations; |
| $f_i$ | assessment of frequency with which disturbances occur in the workplace; |
| $w_i$ | assessment of the success of disturbance recovery. |

The values of $CI_{PSF}$ provide information on the importance that the different categories of PSF have towards increasing error potential for the workplace or task being analysed. A final refinement of the overall importance of the resulting

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[3] A set of three lists has been defined, one for each performance level, on the basis of the theoretical principles of both the SRK and GEMS models and the most relevant error mechanisms and error shaping factors.

PSF list will be accomplished by accounting for the guidelines on the relevance of the different PSF categories as extracted from HRA techniques. Accordingly, the $\mathrm{CI}_{\mathrm{PSF}}$ for each PSF category will be rectified and the final criticality value used as a basis for the establishment of priorities among possible error reduction measures.

A list of guidelines is being developed for definition of error reduction measures. This considers an extensive range of factors, from those closely related to individual intrinsic characteristics to those relevant to different levels of an organisation, such as the characteristics of the workplace, information and communication systems, instructions, task characteristics, organisational structure and training. The list of guidelines is structured in different main categories, corresponding to the categories defined for the PSF (Table 6). Error reduction measures will be identified and defined according to the final rank obtained for the priority of critical PSF categories. This final stage should be undertaken with the participation of representatives from different departments or functions across the organisation so that the measures defined are seen to be feasible.

## 4. ASSESSMENT OF THE DIFFERENT MODULES OF THE TOOLKIT

Practical evaluation of Module 1 has been undertaken in three different manufacturing companies and comprised full application of the procedures suggested for both Modules 1.1 and 1.2. The practical application of the data gathering formats was broadly shown to be feasible both for operators and supervisors. Opinions on any difficulties have been collated and changes made to the formats for data gathering. The versions originally proposed (Paz Barroso and Wilson 1999) have been amended and new formats put forward. A general assessment was also undertaken for the entire procedure suggested for Module 1.1 and Module 1.2. This assessment involved a total of seven assessors, chosen on the basis of their experience either in ergonomics issues or production management. The sample used comprised two industrial ergonomists, two safety managers from manufacturing companies, and three human factors researchers also with vast experience in industrial consultancy. The opinions gathered are summarised in Tables 7 and 8. Module 2 is still under development and assessment

**Table 7.** Summary of the results gathered on the assessment of Module 1.1

| Issues evaluated | Average rating obtained | |
|---|---|---|
| • Usefulness of data gathering on disturbance occurrence | 4.6 | (5 for 'very useful') |
| • Importance assigned to the development of procedures for systematic data recording | 4.9 | (5 for 'very important') |
| • Suitability of the procedure of Module 1 | 4.4 | (5 for 'adequate') |
| • General characteristics of the classification systems used in Module 1 (5 for 'adequate') | 4.6 | Comprehensiveness |
| | 4.6 | Distinctiveness |
| | 4.7 | Usefulness of information |
| • General characteristics of the formats developed for data gathering (5 for 'adequate') | 4.4 | Feasibility of application |
| | 4.8 | Structure adopted |
| | 4.8 | Language used |
| • General characteristics of the instruction manual for Module 1 (5 for 'adequate') | 4.8 | Structure of the manual |
| | 4.8 | Content of the manual |
| | 4.8 | Level of detail adopted |
| | 4.4 | Language used |

**Table 8.** Summary of the results gathered on the assessment of Module 1.2

| Issues evaluated | Average rating obtained | |
|---|---|---|
| • General characteristics of the procedure proposed for identification of disturbance reduction measures (5 for 'adequate') | 4.4 | Suitability of the procedure |
| | 4.4 | Usefulness of the procedure |
| | 4.0 | Feasibility of application |
| • General characteristics of Method A for establishment of priorities among disturbance reduction measures (5 for 'adequate') | 4.4 | Suitability of the method |
| | 5.0 | Usefulness of the method |
| | 4.8 | Feasibility of application |
| • General characteristics of Method B for establishment of priorities among disturbance reduction measures (5 for 'adequate') | 4.6 | Suitability of the method |
| | 3.0 | Usefulness of the method |
| | 3.4 | Feasibility of application |
| • General characteristics of the instruction manual for Module 1 (5 for 'adequate') | 4.8 | Structure of the manual |
| | 4.6 | Content of the manual |
| | 4.6 | Level of detail adopted |
| | 4.2 | Language used |

of its practical application will be conducted in the same manner to that adopted for assessing Module 1.

Preliminary evaluation of Module 2.1 has focused on the applicability and design of the procedures and formats for data recording. The information gathered has been analysed and been used in the definition of a final version, currently being assessed for practical application. This assessment again will include identification of the problems arising during practical application of the different steps of the module, such as whether the procedures for use are clear and can be applied adequately by different users, and whether there are any significant inconsistencies in the data collected by different users.

## 5. CONCLUSIONS AND FURTHER DEVELOPMENTS

The results from the assessment already undertaken suggest that the procedures of the HEDOMS toolkit are both feasible and useful for application in manufacturing systems. Some changes are still required, mainly in the design of the formats developed for data gathering and analysis (Module 1.1). One of the participant companies has acknowledged the usefulness of the classification systems for disturbance data gathering within a Total Production Maintenance system, which further emphasises the applicability and potential utility of Module 1.

Further developments include the assessment of applicability of Module 2.2 and full integration of the two modules into a toolkit for practical disturbance and human error analysis in manufacturing systems, to be carried out in-house by company shopfloor, engineering and management staff. Also planned is the conversion of the procedures for both Modules 1.2 and 2.2 into a software application, to simplify its practical application and overcome some of the limitations found in the practical assessment.

### References

Backström T, Döös M (1995). A comparative study of occupational accidents in industries with Advanced Manufacturing Technology. International Journal of Human Factors in Manufacturing 5(3):267–282.

Backström T, Harms-Ringdahl L (1984). A statistical study of control systems and accidents at work. Journal of Occupational Accidents 6:201–210.

Bainbridge L (1987). Ironies of Automation. In Rasmussen J, Duncan K, Leplat J (eds). New technologies and human error. Wiley, New York, pp 271–283.

Blockley PN, Hartley LR (1995). Aberrant driving behaviour: errors and violations. Ergonomics 38(9):1759–1771.

Cacciabue PC (1997). A methodology of human factors analysis for systems engineering: theory and applications. IEEE Transactions on Systems, Man and Cybernetics. Part A: Systems and Humans 27(3):325–339.

Carnino A, Griffon M (1982). Causes of human error. In Green AE (ed.). High risk safety technology. Wiley, New York, pp 171–179.

Connell IW (1998). Error analysis of ticket vending machines: comparing analytical and empirical data. Ergonomics 41(7):927–961.

Döös M, Backström T (1993). Disturbances in production: a safety risk or a chance for development in the human–computer interaction context. In Smith MJ, Salvendy G (eds). Proceedings from the conference on human computer interaction: Vol 19A, applications and case studies, Orlando, pp 809–814.

Embrey D (1994). Guidelines for preventing human error in process safety. Center for Chemical Process Safety, American Institute of Chemical Engineers, New York.

Glendon AI (1993). Human error incidents in electricity supply. In Lovesey EJ (ed.). Contemporary ergonomics 1993: Proceedings of the Ergonomics Society's 1993 annual conference, Edinburgh, Scotland, April 1993. Taylor & Francis, London, pp 288–233.

Glendon I, McKenna E (1995). Human safety and risk assessment. Chapman & Hall, London.

Glendon I, Stanton NA, Harrison D (1994). Factor analysing a performance shaping concepts questionnaire. In Robertson SA (ed.). Contemporary ergonomics 94: 'Ergonomics for all'. Taylor & Francis, London, pp 340–345.

Hollnagel E (1993). Human reliability analysis: context and control. Academic Press, London.

Järvinen J, Karwowski W (1993). A questionnaire study of accidents in advanced manufacturing systems. In Proceedings of the Human Factors and Ergonomics Society 37th annual meeting, 11–15 October, Seattle, WA, pp 1004–1008.

Järvinen J, Karwowski W (1995). Analysis of self-reported accidents attributed to advanced manufacturing systems. International Journal of Human Factors in Manufacturing 5(3):251–266.

Järvinen J, Vannas V, Mattila M, Karwowski V (1996). Causes and safety effects of production disturbances in FMS installations: a comparison of field survey studies in the USA and Finland. International Journal of Human Factors in Manufacturing 6(1):57–72.

Jiang BC, Gainer CA (1987). A cause and effect analysis of robot accidents. Journal of Occupational Accidents no 9:27–45.

Karwowski W, Warnecke HJ, Hueser M, Salvendy G (1997). Human factors in manufacturing. In Salvendy G (ed.). Handbook of human factors and ergonomics (2nd edn). Wiley–Interscience, Chichester, 1865–1925

Kirwan B (1992a). Human error identification in human reliability assessment. Part 1: overview of approaches. Applied Ergonomics 23(5):299–318.

Kirwan B (1992b). Human error identification in human reliability assessment. Part 2: detailed comparison of techniques. Applied Ergonomics 23(6):371–381.

Kirwan B (1994). A guide to practical human reliability assessment. Taylor & Francis, London.

Kirwan B (1996). The validation of three human reliability quantification techniques: THERP, HEART and JHEDI. Part I: technique descriptions and validation issues. Applied Ergonomics 27(6):359–373.

Kirwan B (1997). The validation of three human reliability quantification techniques: THERP, HEART and JHEDI. Part III: practical aspects of the usage of the techniques. Applied Ergonomics 28(1):27–39.

Kirwan B, Kennedy R, Taylor-Adams S, Lambert B (1997). The validation of three human reliability quantification techniques: THERP, HEART and JHEDI. Part II: results of validation exercise. Applied Ergonomics 28(1):17–25.

Kuivanen R (1990). The impact of safety disturbances in flexible manufacturing systems. In Karwowski W, Rahimi M (eds). Ergonomics of hybrid automated systems II. Elsevier, Amsterdam, pp 951–956.

Kuivanen R, Lepistö J, Tiusanen R (1988). Disturbances in flexible manufacturing. IFAC Man–Machine Systems. Oulu, Finland, pp 217–220.

Laflamme L (1993). Technological improvements of the production process and accidents: an equivocal relationship. Safety Science 16:249–266.

Lucas D (1997). The causes of human error. In Redmill F, Rajan J (eds). Human factors in safety-critical systems. Butterworth-Heinemann, Oxford, pp 37–65.

Mason S, Simpson G (1993). Ergonomics: promoting human reliability. In Ergonomics in process industries: proceedings from the Symposium, 23 June, Wilmslow, UK. Symposium Papers 1993, no 3. Institute of Chemical Engineers, North Western Branch, Rugby, pp 8.1–8.14.

Mattila M, Tallberg T, Vannas V, Kivisto-Rahnasto J (1995). Fatalities at advanced machines and dangerous incidents at FMS implementations. International Journal of Human Factors in Manufacturing 5(3):237–250.

Miller DP, Swain AD (1987). Human error and human reliability. In Salvendy G (ed.). Handbook of human factors. Wiley, New York, pp 219–250.

Nagamachi M, Yukimachi T, Anayama Y, Ito K (1984). Human factor study of industrial robot 2: human reliability on robot manipulation. Japanese Journal of Ergonomics 20:55–64.

Nicolaisen P (1985). Occupational safety and industrial robots: present stage of discussions with the Tripartite Group on robotic safety. In Rathmill K, MacConaill P, O'Leary S, Browne J (eds). Robot technology and applications: proceedings on the 1st robotics Europe Conference, Brussels, June 1984, pp 74–89.

Norros L (1996). System disturbances as springboard for the development of operators' expertise. In Engeström Y, Middleton D (eds). Cognition and communication at work. Cambridge University Press, Cambridge, pp 159–178.

Ostrom LT (1994). The pros and cons of using HRA techniques to analyse misadministration events. In Apostolakis GE, Wu JS (eds). Proceedings PSAM-II, an international conference devoted to the advancement of system-based methods for the design and operation of technological systems and processes, Vol 3, San Diego, CA, pp 100-1–100-6.

Paz Barroso M, Wilson J (1999). Human error and disturbance occurrence in manufacturing systems: towards the development of an analytical framework. Human Factors and Ergonomics in Manufacturing 9(1):1–18.

Pines E, Goldberg JH (1992). Task and reliability analysis of lathe operation. International Journal of Human Factors in Manufacturing 2(4):311–324.

Prabhu P, Sharit J, Drury C (1992). Classification of temporary errors in CIM systems: development of a framework for deriving human-centered information requirements. International Journal of Computer Integrated Manufacturing 5(2):68-80.

Rasmussen J (1982). Human errors: a taxonomy for describing human malfunction in industrial installations. Journal of Occupational Accidents 4:311–333.

Rasmussen J (1986). Information processing and human–machine interaction: an approach to cognitive engineering. North-Holland, New York.

Reason J (1990). Human error. Cambridge University Press, Cambridge.

Rouse WB, Rouse SH (1983). Analysis and classification of human error. IEEE Transactions on System, Man and Cybernetics SMC-13(4):539–549.

Rushworth AM, Mason S, Simpson GC (1991). The ergonomics of root bolting operations. Final report on ECSC research project, CEC contract 7249/12/036. British Coal Corporation, Operations Directorate, Eastwood, Nottingham.

Sharit J (1988). Applying Human and System Reliability Analysis to the Design and Analysis of Written Procedures in High-Rick Industries. Human Factors and Ergonomics in Manufacturing Vol. 8 (3), p. 265–281. John Wiley and Sons.

Sheridan TB (1987). Supervisory control. In Salvendy G (ed.). Handbook of human factors. Wiley, New York, pp 1243–1268.

Simpson GC (1992). Human error in accidents: lessons from recent disasters. Safety, hygiene and health in mining technical papers, Vol 1. An international mining symposium organised by the Institution of Mining Engineers, Harrigate, UK, pp 244–254.

Simpson G, Mason S, Rushworth AM, Talbot CF (1991). Risk perception and hazard awareness as factors in safe and efficient working. Final report on ECSC research project CEC contract 7249/12/067. British Coal Corporation, Nottingham.

Swain AD, Guttman HE (1986). Handbook of human reliability analysis with emphasis on nuclear power plant applications, NUREG-CR-1278, Sandia National Laboratories, U.S. Regulatory Commission, Washington, DC.

Vannas V, Mattila M (1996). Safety aspects in FMS implementations. International Journal of Human Factors in Manufacturing 6(2):163–179. Taylor & Francis, London.

Williams JC (1988a). A data-base method for assessing and reducing human error to improve operational performance. In IEEE 4th conference on human factors in power plants, Monterey, CA, pp 436–450.

Williams JC (1988b). A human factors data-base to influence safety and reliability. In Safety and reliability symposium. Elsevier, Amsterdam, pp 223–240.

Wilson JR, Koubek RJ, Salvendy G, Sharit J, Karwowski W (1994). Human factors in advanced manufacturing: a review and reappraisal. In Karwowski W, Salvendy G (eds). Organisation and management of advanced manufacturing. Wiley, New York.

Zimolong B, Duda L (1992). Human error reduction strategies in advanced manufacturing systems. In Rahimi M, Karwowski W (eds). Human–robot interaction, Taylor & Francis, London, pp 242–265.

Zimolong B, Trimpop R (1994). Managing human reliability in advanced manufacturing systems. In Salvendy G, Karwowski W (eds). Design of work and development of personnel in advanced manufacturing. Wiley, Chichester, pp 431–461.

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