Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

Evaluation of Human Reliability on the Basis of Operational Experience

Dissertation

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Dissertation of

Oliver Sträter

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Chair of Ergonomics of the Munich Technical University

Evaluation of Human Reliability on the Basis of Operational Experience

Oliver Sträter

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Summary

This dissertation was conducted at the Society for Systems and Reactor Safety, Inc. [GRS - Gesellschaft für Anlagen und Reaktorsicherheit], on the basis of project RS 872 of the Federal Ministry of Research and Technology [BMBF], entitled „Development of Methodological Foundations and Computation Programs for Probabilistic Safety Analyses.“ A central problem in the evaluation of human reliability is represented by the fact that the data needed for the evaluation procedure have thus far been incomplete and have been inadequately validated. Practical experience in the form of error events does constitute a source that thus far has not been used in a systematic manner and is suitable for solving this data problem. The object of this dissertation was to develop a method for the evaluation of events with a view to the human factor and to make the practical experience contained in events useful in terms of qualitative and quantitative evaluations of human reliability. To develop the method, available models were used for the purpose of qualitative evaluation of human error behavior (for instance, Swain, Hacker, Rasmussen) and various approaches providing a quantitative evaluation of human error actions were investigated (for example, Technique for Human Error Rate Prediction [THERP], Accident Sequence Evaluation Programs [ASEP], Human Action Reliability [HCR], Success Likelihood Index Method [SLIM], in an effort to prepare a profile of requirements. On that basis, a method was developed for the acquisition and evaluation of erroneous actions. The method is broken down into the two sectors of event analysis and event evaluation: first of all, events are analyzed regarding all information that is significant for errors in human actions. In addition to data on the course of a particular event, consideration was also given to possible conditions leading to the failure of a particular action. An evaluation of human reliability calls for manifold evaluation possibilities; therefore, to evaluate the collected events, a connectionism method was developed on the basis of a discussion of various approaches from artificial intelligence; this connectionism method facilitates both qualitative and quantitative statements in a uniform approach.

To test the efficiency of the method, a set of 165 events featuring human error behavior were investigated from the „Special Events“ databank of the Society for Systems and Reactor Safety. The analysis of these cases offered new findings regarding the error

mechanisms and the validation of data of existing assessment methods. Among other things, it was also possible to trace errors of confusion back to an interference effect of cognitive skills. Furthermore, 30 factors that influence human reliability were identified from this operational experience. In order to investigate quantitative statements regarding human reliability in addition to qualitative data, the data from practical operational experience were compared to 79 items of the THERP method. Overall, there was good agreement between the predictions derived from practical operational experience with the ones of THERP. Some deviations - that are important to probabilistic analyses - were also found. Wide use of the analysis method presented here would facilitate a better estimate of these deviations. The successful validation also lead to the conclusion that the method presented here might be used as an approach towards a further developed process for the analysis and evaluation of human reliability.[1]

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[1] Many other work has been performed in the area of enhancing the Human Reliability Assessment methods in the years during and after the study presented here. Therefore this study represents only one brick in the wall of progress in this area. Besides this study, the author would like to mention especially the ATHEANA-method, the MERMOS-method, the work conducted in the OECD-PWG5 Task 97-2 on "Errors of Commission", the common project of PSI/Switzerland and GRS/Germany and the CREAM-method. See for these developments the Literature below. The developments couldn't be included in this work since this study was finished end of 1995. All these activities are now concentrated in the MOSAIC-group where the various methods in relation to "Errors of Commission" are discussed and elaborated. For having a look at these, see the section: "Related Bibliography after first Publication of this Book" (p. 276).

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SLI- Success Likelihood Index	69
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SQL - Structured Query Language	140
SWR – *Siedewasserreaktoren*, Boiling Water Reactors [BWR]	177
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Introduction

The safety and availability of nuclear power plants are influenced to a great extent by human interventions, in spite of their high degree of automation. This human influence becomes clear both in events that have actually occurred (see Mosey, 1990) and in Probabilistic Safety Analyses [PSA] (DRS-B, 1990). The apparent contradiction between a high degree of automation and a simultaneously high level of human influence can be explained by saying that the relative proportion of human errors increases as a result of increased and safer automation.

If one wishes to include this factor, regarding the safety and availability of nuclear power plants, into evaluation and optimization, then one finds that the methods used to take into account human influence are inadequate. The main problems consist of the availability of fundamental data, in which connection the concept „data“ covers both qualitative data (for example, factors that exert influence) and quantitative reliability parameters. First of all, the methodology used in acquiring data on human reliability from practical operational experience is inadequate. Practical experience, in other words, all experiences that are acquired when handling a technical system (including trouble events, investigations of operational events or simulator experiments), are currently being evaluated only with regard to the human errors involved, to the extent that the errors are described in the form of taxonomies. Additionally, from the viewpoint of the evaluation of human reliability, so-called Human Reliability Analysis [HRA], it is necessary to validate the available data concerning Human Error Probabilities [HEP] and to supply data for the evaluation of new technologies. Data on human reliability in German safety studies dealing with nuclear power plants are based, for example, essentially on the THERP method by Swain and Guttmann (1983), which for the most part falls back on non-nuclear data from the year 1945 or expert estimates, so that this evaluation method is often criticized on the grounds that it is not in step with the reality found in German plants (for example, Reer & Mertens, 1993). In evaluation, this leads to inaccurate estimated values about human influence which can be caught only by pessimistic estimations and dispersion coefficients in the error probabilities.

The problems described here - the problems of making an evaluation of human reliability - first of all prevent a valid judgement in probabilistic analyses and, additionally, prevent optimization of safety and availability, which would be possible by means of an effective exploitation of realistic data on human error behavior. Accordingly, from the viewpoint of probabilistic analysis and from the angle of systems optimization, it is also required to develop a method that facilitates an empirical determination of data regarding human reliability, springing from practical operational experience.

A quote taken from Dougherty and Fragola (1988; p. 13) can be used to summarize the idea that the methodology for evaluation human reliability on the basis of available data is inadequate and that the methods must be validated by checking the underlying data:

> *„The 'ideal' situation for HRA would consist of a validated theory of behavior that could be translated into a model of human/system performance that then could be quantified probabilistically. An alternative would be for enough data to detect theoretically meaningful patterns in human failures and to quantify the patterns with statistical robustness. Neither alternative exists at this moment."*

To tackle this unsatisfactory situation, the goal of this study is to develop a method for a systematic evaluation of events with a view to human errors which at the same time will make it possible to build up an empirical database for reliability parameters. The method, on the one hand, should facilitate a consistent acquisition of practical operational experience by classifying errors and, on the other hand, it should supply conclusions as to the causes of human errors and furnish data for probabilistic safety analyses. By means of this kind of method, it should be possible, first of all, to find possibilities for error avoidance and, besides, to gain qualitative and quantitative statements from practical operational experience that, among things, could be used to validate existing methods of Human Reliability Analysis [HRA].

To attain this objective, one must first of all find a method by means of which practical operational experience can be acquired such that qualitative and quantitative analyses on human errors will become possible. Types of errors and causes of errors would have to be imaged. Building on that, for purposes of quantitative analysis, one must find a method that will make it possible to analyze data on different events that will cover systems and situations across the board, as well as to gain data on human reliability that can be used for Probabilistic Safety Analyses [PSA].

Such a method - used to validate existing analysis procedures on the basis of practical operational experience - is of great interest both when it comes to estimating optimization measures and for the purpose of evaluating currently working systems. The supply of data on human reliability is also needed when it comes to evaluating new problems connected with PSA; this is true because, with the help of the current data basis, one can evaluate only reliability data for normal, properly routine operation of industrial plants that are important in terms of safety engineering. Currently we have no data to evaluate states outside proper routine operation (for example, maintenance and repair activities, trouble control) or for the purpose of evaluating new technologies (for instance, computer assisted process information) and the attendant new organizational forms (for example, Cockpit Control Stations). With the help of systematic collection and evaluation of events derived from practical operational experience, one can gain valuable information that can be used for an evaluation or optimization of these operating modes and for continued methodological developments.

To attain this goal, we will, below, in introductory Chapter 1, take a closer look at the phenomenon of human error. Starting with an overview, we will present models from cognitive psychology and from work sciences. The considerations presented in this chapter are to be used as foundations for the development of a method to acquire and judge human errors on the basis of practical operational experience.

In Chapter 2, we are deriving the requirements for an evaluation of practical operational experience. To this end, we investigate the information needs for an evaluation of human actions as well as methods used so far to acquire human errors from operational events. The various requirements are then combined to tell us what a method for acquisition and evaluation based on practical operational experience must do for us.

Building on that, we develop a method that will be used to acquire and evaluate human reliability in the context of events. The method contains two essential steps: in the first step, we systematically analyze an event during which a human error was observed. In the second step, we use all of the collected information to evaluate the reliability of the human individual in a hypothetical situation. For both of these steps, we draft a description model and an evaluation model which will be presented separately in Chapters 3 and 4.

In Chapter 5, we apply the method to 165 events from German nuclear power plants. First of all, the results are presented in a qualitative analysis. Then we make a quantitative comparison to the voluminous data of the THERP Method of Swain and Guttmann (1983). In conclusion, we discuss the significance of the results. Chapter 6 summarizes the essential results of the entire endeavor in terms of methodological developments and the analysis of events.

1 Concepts and Model Ideas about Human Errors

Human error is an extremely multi-layered phenomenon. It extends from doubt about ones' own abilities, the moment one failed to note, for example, a typo after dozens of editorial readings, up to legal consequences when a person or an object was damaged as a result of an error. It is precisely the aspect of damage that clearly shows that human error is also tied to the culpability of a pertinent person in terms of the damage and with corresponding legal consequences. For example, Goethe suggested that printers be reprimanded in public whenever they made a printing error in their work (see Zimolong, 1988; Wehner, 1984). Goethe's view, at first sight, appears rather odd when one considers human reliability in large scale technical systems. But it shows clearly that, in many cases, human error cannot be separated from the culpability of the individual and from the attendant punishment.

On the basis of the problem of culpability, one unfortunately also often avoids a disputation with this topic although it is about standing significance in terms of the safety and productivity of modern industrial systems. The discussion in this first chapter, accordingly, is intended to show among other things that the question as to the guilty person is used neither for the purpose of clarifying the materialization of the mistake, nor the evaluation, optimization, or avoidance of human errors in technical systems. For this purpose, we first of all present a brief historical overview of ideas concerning human error and some significant definitions and models on the subject of human error.

1.1 Historical Overview

The brief historical overview presented in this chapter is intended to show clearly that the human factor plays a by far more important role when it comes to the acquisition and use of human skills than the concept of „error“ would seem to indicate. The idea is to gain further understanding concerning human error in which connection human error is not to be construed as the blemish of a human individual or, as stated elsewhere, where the human factor is not to be viewed as „the other side of the coin“ and thus as an unavoidable disadvantage, when one wishes to use the capacity of the individual within a technical process (for example, in Reason, 1990; p. 1). For this purpose, we want to address here, in historical terms, three areas in which human errors were investigated: Philosophy, Psychology, and the Engineering Sciences.

1.1.1 Human Error in Philosophy

The problem of human error was and is investigated not only as a result of the existence of psychology or of work sciences or ergonomics. In the course of philosophical considerations, there was, far in the distant past, a search for explanations on the materialization of human error because - from the viewpoint of philosophy - it clearly brings out the boundaries of the cognition capacity of the human individual and because in this part of philosophy, the theory of cognition, it represents a central target of investigation.

For example, Aristotle described human error as a false subordination and concatenation of data, supplied by the senses, in our thinking processes. Descartes' opinion regarding human error may be summarized as follows: „free will enables man to accept one idea and reject another one. The source of all error lies only in this activity of the will, not in the ideas themselves." Hume saw error as the interplay of ideas and impressions: all error comes about as a result of the application of false ideas to correct impressions or due to the interconnection of false impressions with correct ideas (see Störig, 1988; p. 180, p. 316, p. 355). Kant also observed, regarding human error in the form of prejudices, that the source of prejudices is to be found in novelty, misinterpretation, imitation, habit, inclination, and self love (see Keller, 1990; p. 87). If one investigates these various concepts regarding their similarities and differences, then one finds that all concepts can be boiled down to three determining factors that are important to human error. They are:

- The Procedure of Processing Information by Man (Concatenation in the case of Aristotle and Hume, Activity of the Will in Descartes, Misinterpretation and Habit in Kant).
- The selected target of human action (the Will in Descartes; Application of false ideas in Hume; Inclination and Self Love in Kant).
- Information available via the senses or thinking processes (data delivered by the senses in the case of Aristotle; the Idea in the case of Descartes; Impressions in Hume; Imitation and Novelty in Kant).

The two last named points (selected goal and underlying information) are always subjected to a procedure of information processing in man so that one may conclude that information processing plays a central role in the materialization of human error. It can happen either consciously or unconsciously. Whereas unconscious information processing takes place automatically and triggers accustomed ways of behavior, conscious information processing always presupposes that an accustomed process is disturbed; as a result, former natural and unnoticeable aspects of a situation become conscious only by disturbance (Bollnow, 1970; p. 298). An attempt is then made to integrate the contrasts on a higher level of abstraction via thinking processes.

This compensatory behavior of human information processes - which, in the final analysis, is intended to reduce information - is described rather aptly in the Theory of Cognitive Dissonance (Festinger, 1957): If there is a disturbance in human habits which cannot be remedied by automatic forms of behavior, then this generates a cognitive dissonance and an attempt is then made to correct this by means of efforts to achieve consonance. Consonance efforts in the final analysis again utilize experiences and habits to bring about consonance.

Accordingly, one can also say that a human error in the final analysis is always also an expression of habits that were not useable in certain situations and thus led to human error. This is also backed up by the Theory of Coherence of the Concept of Truth which says that an individual considers something to be true when it can be fitted without contradiction into the other substantive statements of his past experience (Keller, 1990; p. 108).

Summarizing, we can then say that a human error, in the end, comes about due to habit or learned ways of action and moreover, presupposes the certainty that the selected target or the underlying information is true. From this we can furthermore conclude that any human action harbors within it the potential of an error because a human being can never, in the final analysis, gain valid certainty about the correctness of a statement because a human being can only falsify generally valid statements (see Popper in Störig, 1988).

Furthermore, human error is certainly to be viewed as a positive event from the philosophical angle as presented here. Only by errors and by virtue of the doubt about the correctness of statements and thinking activities connected therewith any cognitive progress and thus a further improvement in the capacity of human information processing is possible. Human error thus has the following positive properties which are demanded precisely in human monitoring of technical systems and which cannot in long range terms be relieved by automation efforts:

- Steady cognitive progress by means of independent improvement and adaptation of human capacity to new situations;

- Deep thinking about the correctness of a measure in a certain (extreme) situation where automatic systems are not effective.

These philosophical considerations concerning the subject of human error thus offer fruitful approaches also for the practice oriented area of an engineering psychology analysis of human errors which is the objective of this study. Accordingly, they will be referred to repeatedly in the course of this chapter.

1.1.2 Human Error in Psychology

The second point of departure for an understanding of human error is psychology, which has concerned itself with this topic ever since its early development.

In psychology, human error is often referred to as the „window to consciousness." This phrase underscores the fact that any and all psychological exploration of the causes of human error - from the very first beginnings up to the present - was guided by the effort, from the observation of human error, to gain a handle on a theory of human information processing and predictions concerning human behavior. It is thus not surprising that many psychological models on human errors are aimed at obtaining specific ideas about human information processing and the way human consciousness works.

The analogy furthermore clearly shows that the different psychological research directions must directly or indirectly tackle human error. All psychological research directions (from clinical via mathematical psychology all the way to engineering psychology) contain investigations and experiments designed to explore human error. It is furthermore interesting to note that error research has outlasted the most varied research paradigms from psychoanalysis via behaviorism all the way to cognitivism or that even essential impetus had been gained for the particular paradigms from error research. The exploration of human error thus is of great significance in psychology as a science because, compared to paradigms, it represents an invariant research topic.

Wehner (1984) summarized the various prevailing paradigms under which investigations are conducted regarding human error. He differentiates the following paradigms that can be subdivided into two approaches that must be differentiated from each other:

- Cognitivism approaches:

  These approaches build on paradigms that need a model idea about human information processing. Typical cognitivism approaches must be listed under the subject of Psychology of Memory, the Theory of Decisions, as well as the Psychology of Thinking. Advocates of these approaches, that have become part of the evaluation of human errors in technical systems, are, among others, Sternberg (1969), Broadbent (1958) and Miller (1956). The results of investigations conducted by these authors regarding human information processes to this very day represent central assumptions in error research and are also used in the error models that are being depicted in the next chapter. Other representatives of these approaches are the mental models (for example, Gentner & Stevens, 1983).

- Behaviorism approaches:

  These approaches are built on paradigms that use observations to come up with predictions about human behavior. Typical behaviorism approaches are neurophysiology, perception psychology, linguistics, as well as paradigms that relate to action psychology or activity psychology, such as, for example, the Stimulus Reaction Models. A classical representative of these approaches is Lorenz (1978). When it comes to error research, it is particularly the action psychology paradigm that was of importance so far.

1.1.3 Human Error in the Engineering Sciences

With the start of the industrial revolution, observations and research results regarding human error - which earlier had been ascribed to basic research, and, which at best, were of scientific interest - also found their way into the engineering sciences and the fashioning and evaluation of technical systems. This branch of research, just as other technical developments, also received an essential impetus during WWII. Investigations of errors in handling artillery pieces clearly showed that the power of these guns was again diminished by human error in spite of considerable practice with the equipment (see Wickens, 1984; p. 4).

At present, the exploration of human errors has become an essential factor in the safety and output capacity of large scale industrial systems and for the protection of the environment against environmental disasters covering large surfaces of the earth. A number of accidents in the chemical and nuclear industries and also in the transportation industry (aviation, as well as motor vehicle and rail traffic) will show that man is an essential factor in the origin but also in the control of events that can lead or have led to heavy losses of human lives, to contamination of the environment, or to the severe loss of funds.

The reason for the augmentation of the so-called human factor here, first of all, can be seen to reside to a considerable extent in the increasing complexity of technical systems. Efforts to diminish this influence by means of a higher level of automation have failed for two reasons: first of all, the automatic systems must still be designed and maintained by human beings so that the problem area may be shifted. Second, even automatic systems have failure probabilities so that one cannot and does not want to dispense with the positive qualities of human capacity that have already been described in philosophical considerations, when it comes to areas that are significant to the safety of man as the very last instance of process monitoring and surveillance.

An increase in the degree of automation and the reliability of technical systems necessarily leads to an augmentation of the relative proportion of human errors. This effect is supported in that increasing automation also leads to developments that are not adapted to human capacities. This is shown, for example, by the 1992 Airbus Accident in France (VDI Nachrichten [News of the Association of German Engineers], 1992): The pilot of the crashed aircraft presumably had confused the glide angle setting with the descent rate setting. Both flying modes are set via a single operating button. Another mode switch decides whether one and the same operating button is used to set the glide angle or the descent rate. In addition to this muddling of operating functions - which is impermissible from the ergonomics viewpoint - there was no complete feedback from the system about its state (an installed Head-Up Display did not provide information about the current flying mode of glide angle setting or descent rate setting, and a direct feedback report from engine noises could not be heard because of the good sound insulation of the cockpit).

This ambivalent attitude toward man in technical systems (man as the last safety device and as the weakest element in reliability) is again closely tied in with the above mentioned question of culpability; that this ambivalent attitude does not do justice to the actual condition prevailing in highly automated systems from the viewpoint of the operators is something that Bainbridge (1987), in an article that by now has become a standard work, referred to as „Ironies of Automation." Regarding the reciprocal relationships between automation and operator, it notes that increasing automation causes three main problems for human capacity:

- Basically less manual activities by operators are required due to a high level of automation. As a result, the operators are less well practiced in their jobs and their abilities to take over the process when an automatic unit fails are caused to deteriorate. This deterioration results from the fact that the manual skills and also the cognitive skills decline due to the absence of active participation in the process. Furthermore, it becomes more difficult to gain access to available knowledge and no new knowledge is acquired about the behavior of the process or the effectiveness of problem solutions.
- During a process that takes its course without any trouble, the operator has the job of monitoring and checking the error free course of the process. This presumably simple task however introduces two essential problems as far as the operator is concerned: First of all, from the view of the operator, this state (which is desirable from the technical angle) is a typical problem of vigilance that heavily impairs his capacity. Furthermore, checking the trouble free operation of the automatic systems is an additional task (that is difficult to recognize), a task that must be performed parallel to the basic assignment which is to control the process.

- Man must take over process control when there is trouble in highly automated systems. This takeover creates additional problems: for example, the individual must first of all empathize his way into the event because he is not actively involved in the event represented by the process. In highly automated systems, this task is made more difficult because feedback of the system state that are required for functional takeover, are only present on the abstract level of the automated systems and are thus inadequate for detailed analyses that are required of the operator when an automatic unit fails. One therefore cannot assume that process control becomes simpler and that there is less need for training the operators as a result of a high level of automation.

1.1.4 Summary

The sections above show that the exploration of human error is a very comprehensive and interdisciplinary problem. The philosophical considerations show clearly that man cannot gain experience without coming to grips with his environment and that human errors also constitute an important source for cognitive progress. As in the case of technical errors, there is thus always the possibility of a human error.

This concept is also being advocated increasingly in engineering science considerations, as shown clearly by the requirement for active involvement of the operator in the process, tied to the catch word about the „error tolerance system.“ This view about human error should also be used as a foundation for the understanding of human reliability in this study. Among other things, the definition, given in the next chapter, and the description model, presented in Chapter 3, will rest on this understanding of human error.

The psychological considerations furthermore show that one must basically differentiate between two approaches to the modeling of human errors: the cognitivism approach and the behaviorism approach. In the chapter after the next, we will show to what extent these two approaches are suitable for the acquisition and evaluation of human errors.

1.2 Concepts of Human Error

To summarize the considerations we have presented, and to be able to differentiate them from other concepts about human error, we will in the following attempt to arrive at a definition of human error that would apply to this entire study.

1.2.1 Definition of Human Errors

Let us first of all present three definitions that are customary as part of the process involved in analyzing human reliability.

> ***Definition of human error according to Rigby (1970):*** *A human action is to be evaluated as an error if, as a result of it, the requirements established by the system are not met or are not met adequately.*

In Rigby's definition, human error is defined in a manner strictly oriented by the requirements of the system. The background of this definition is a categorization of human actions that is used to come up with an engineer-style evaluation of technical systems. Looking at it from the perspective of the human role, this definition represents the most unfavorable of all possibilities because it looks at human error in the light of technical performance limits but without considering human performance limits. It is thus defined rather one-sidedly and definitely boils the question of culpability down to human failure.

This view about human error is not altered by the definition given by Swain (1992) which is currently customary in the analysis of human reliability.

> ***Definition of human error according to Swain (1992):*** *The term „human error“ covers all activities or omissions by a person that either cause something undesirable or that have the possibility of causing something undesirable.*

In the definition given by Swain, man is seen as a component of a technical system. As in the case of Rigby, the definition of human error is guided by the performance limits of the system. To allow for the question of culpability, Swain tones his definition down by making the following supplementary statement in a kind of post-script:

> ***Addition to the definition of Swain (1992):*** *This definition of the human error is taken in the context of the system, even though the main factors that contribute to an error, for example, can be due to absence of ergonomic design, procedures, training, or a combination of the above. This is why no guilt should be connected with the term „human error.“*

In this addition, Swain emphasizes that the causes of human error can certainly also be found outside the individual. The first part of the definition, however, clearly states that human error is always an error in the performance of a requirement of the system. In Swain, likewise, human error is thus defined on the basis of technical performance limits and without consideration of human performance limits.

To find a definition guided by human performance limits, we will now, thirdly, take a look at the definition by Reason (1990):

> ***Definition of human error according to Reason (1990):*** *A human error is construed as a generic term that covers all occasions in which a planned sequence of mental or physical activities can fail to achieve an intended result and where this failure cannot be blamed on the intervention of an accidental triggering source.*

Reason construes man as an information processing component within the technical system. According to the above considerations concerning psychological approaches, we are thus dealing here with a definition that is guided by the cognitivism approach. Although this definition tries to give a view of human error that is guided by man, it intensifies the above described problem complex (without intending to do so). Human error is defined without considering human performance limits. This means that this definition likewise indirectly represents a definition guided by technical performance limits.

Looking at them altogether, the definitions spell out human error in terms of the requirements derived from the system. The technical system determines whether the individual behaves erroneously or faultlessly. This one-sided orientation in favor of the technical system is not changed either by virtue of the fact that one defines the human factor in relation to human information processing.

These definitions are thus suitable only for an analysis oriented by the technical system. But, directly or indirectly, they are oriented one-sidedly to the technical system. No consideration is given to the relationship between human performance limits and the technical system (for example, the system overloads the individual or there are interactions between man and machine). The definition given by Reason thus shows that a cognitivism-oriented definition of the problem of culpability does not diffuse but rather further restricts it to man (especially his information processing). This means that these definitions are not suitable - even with a view to a meaningful clarification of the question of culpability - because the answer to this question is the same in all definitions and always hits the person who performs the action.

1.2.2 A Simple Example of a Human Error

Before we can propose a definition that applies to this study, we want to show the significance of a commensurate definition of human error from the practical viewpoint in a large scale technical installation. For this purpose, we will discuss in this chapter the example in Table 1 according to Reason (1990), and Mosey (1990) with the help of the definitions given above. The table presents a summary overview of the TMI (Three Mile Island) accident.

If one applies the above mentioned definitions of Rigby, Swain and Reason to the example, then one finds that the definitions are insufficient both for the identification of the errors and for the search for error causes: for example, in all three definitions, the events, listed in the left column of the table, are always viewed as human errors, the moment an individual was involved in the event. The actual causes of human behavior are mentioned as contributory conditions and as latent errors in the right hand column.

All of these three definitions thus, at best, are in a position to separate the errors of the technical system from the required actions of the operator. They are not in a position to differentiate the required actions of the operators to the extent as to whether:

- the error of the individual took place as a reciprocal action with errors in the technical system (No. 1: Operating personnel put the instruments underwater because a valve was not closed) or

- a human error was assumed because the individual basically could have taken action (Nos. 4 and 5: the ergonomic design of the control station makes it impossible to notice the open pressurizer valve although the operator basically would have been in a position to notice that, or whether
- human error is a consequence of false assumptions whose causes are to be found in the technical process as such (No. 6: the operators turned the high pressure pumps off because they did not notice the open pressurizer valve and because they could not figure out the effect of the filling level rise in the pressurizer).

The applications of the definitions to the example shows that none of the above mentioned definitions can be considered suitable for analyzing a human error. It thus does not make any sense to define the error of a human individual in the light of the requirements of the technical system. One main problem in the definitions given here has to do with the fact that, to a certain extent, they bear tautological features; in other words, they are self explanatory and do not produce any gain in knowledge because they define the human factor on the basis of the existence of man in the technical system. We can thus say that a classification of the „human factor“ on the basis of a single differentiating feature (man) is not permissible.

The above mentioned addition to the definition of Swain (1992) already clearly shows that this reduction to the level of man is impracticable when it comes to analyzing human reliability. Furthermore, this reduction to the level of the human individual is far of reaching significance from the viewpoint of the question of culpability because it is connected with a one sided causal allocation related to the acting human individual and a one sided search for error avoidance.

Summarizing, the definitions presented so far thus represent an impermissible abstraction and reduction of errors in technical systems to the level of human individuals. In the following, we will propose a definition that takes into consideration the aspect of complexity of the error situation.

Table 1 The Three Mile Island event - An example of a human error

Nr.	***Sequence of Events***	***Contributory Conditions and Latent Errors***
1	Operating personnel places the instruments of the condensation purification unit under water because a valve got stuck in the open position. Condensate supply and feed to the reactor failed.	The operating company did not initiate any precautionary measures against repetition although this error had already occurred twice before.
2	Turbine fails. Feed water pumps are shut off. Emergency feed pumps are turned on automatically but feeding is prevented because two valves are closed.	Probably during maintenance activities two days before the trouble event, the two blocking valves were erroneously left in the close position. A warning light at the control panel, that indicates that the valves are closed, was covered up by a maintenance instruction plaque.
3	Rapid rise in core temperature and pressure in reactor. Pressurizer valve opened automatically but got stuck in open position. This resulted in a so-called coolant loss trouble case (about 13 seconds after the trouble began).	A pressurizer valve was also left open during trouble that occurred in David Besse in September 1977. Although this incident was investigated thoroughly by the operator and the supervisory authority, the lessons learned from the prior event were not adequately used and the information concerning appropriate operator actions was not disseminated to a sufficient degree.
4	The operators do not notice the open pressurizer valve. The radioactive water from the primary circuit is blown off at high pressure into the containment.	The operation was falsely reported by the display at the control panel. A state display for the pressurizer valve was installed on account of trouble that occurred one year earlier. The state display only indicates whether a command was given to open or close; it does not indicate whether the valve is actually in the open or closed position. The operators mistakenly assumed that the temperature on the blow off section of the pressurizer valve is high on account of a chronic leakage and not due to the open valve (a high temperature was also indicated in the routine system state by a permanent leakage).
5	The operators likewise did not note the open pressurizer valve even two hours later.	The control panel was poorly designed and the alarms were not properly structured: many of the key data had been affixed on the reverse wall of the control panel. More than 100 alarms were activated and important ones were not separated from unimportant ones. Several instruments were displaying recordings and the message printer was more than two hours behind the system state. Operator training consisted mostly of lectures and work with the system simulator that did not provide adequate preparation for real emergency cases. The training program was inadequately developed and there was not feedback to the trainees.
6	The operators turned the high pressure feed into the reactor off and thus reduced the cooling for the reactor core which thereupon was damaged.	On account of the high filling level in the pressurizer, the operators assumed that there was sufficient water in the primary circuit. They were not aware that the filling level had risen on account of the system state (bubble formation due to excessively high temperature was not recognized because the temperature display was considered unreliable). Training was concentrated on hazards of core flooding and did not consider the possibility of a coolant loss. The supervisory authority offered a publication on this subject that did not mention with a single word that the operators had turned the high pressure feet off there. The heading read „malfunction of a valve.“

1.2.3 Definition of Human Error in this Study

The following definition is hereby proposed to summarize the above considerations:

> *A human error exists always in a working system and is characterized by an undesired or faulty state of the working system. It then leads to a situation where the requirements of the system are not met or are met inadequately. The individual is only one part of the working system and interacts together with other portions of the working system. All portions within the working system may be dependent upon each other or may be in a reciprocal action state.*

Just as in the above-presented definitions by Rigby and Swain, this definition also starts with the requirement of the system. It thus is in line with the engineer-style ideas to the effect that the system predetermines whether or not there is a human error. In this definition, the individual - in case of an undesired system state – however, is not automatically designated as the cause of the error. This means that, in this definition, there is no exclusive blame placed on the human individual who made a mistake in a presumably error-free working system. In terms of the load-cope model that is customary in ergonomics (see Bubb, 1992), this definition represents both the load aspect (the working system) and the cope aspect (the human individual); on the other hand, the above-mentioned definitions of Rigby, Swain, and Reason merely consider the coping aspect. In this definition we state that man, as a component, always has a share, among other shares, within the working system, when it comes to the error event as such and that all shares together lead to the error event. This means that this definition requires a different understanding of the concept of cause and the question of culpability.[2]

In order to specify the cause of a human error more precisely, it is helpful to differentiate between necessary conditions (prerequisite) and sufficient condition (trigger): if an error happens due to other parts of the working system, then man is the necessary condition for

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[2] The concept mentioned here is the so-called stress/strain concept (in German: Belastungs-/Beanspruchungs-Konzept). This very old ergonomic concept received lots of discussions. Though the concept originally was not designed to be understood like this, the main point against this approach is that it might assume a more or less passive human being that only reacts on the stressors the person is exposed to. However, humans are also active of course. Hence we translated it with load/cope-concept here. Load describes the situational characteristics a person is exposed to (the external PSF) and cope is related to the active or passive characteristics a person uses to mange the situation. This also includes to actively change the situation, a man is exposed to.

the error. The sufficient condition s are found outside the individual (for example, defective switches, wrong display of information). If man is the sufficient condition for the faulty state for the faulty state of the working system, then he is the cause of such a state. This differentiation regarding the cause is also important with regard to the question of culpability: if man is only a necessary condition for an error, then he can be no more culpable than any other component of the working system. In case of errors in an working system, however, we often speak in terms of „human failure“ and thus often turn man into the sufficient condition - even though he only was the necessary condition for the error. In any event that involves human participation, one must, however, always check to see whether man actually was a sufficient condition for the error.

If we pursue the question as to the cause for a human error further, then we necessarily run into the question as to what significance must be assigned to the determination of the cause. Basically, the concept of the cause is significant in figuring out whether or not we are dealing with a human error. The following consideration shows that this decision cannot readily be made within an working system: separated from the human factor, one can observe - in increasingly complex, technical or physical systems - that it is impossible to perform an unambiguous causal analysis and to blame the behavior of the complex system on a single component. This is demonstrated both by the field of software reliability and by chaos research.

Research on software reliability shows besides that software basically cannot be completely tested. In other words, one cannot assign a certain cause to every faulty system state of a software product, as being caused by its complexity and interaction with hardware failures (see Mehl, 1995).

The concept of cause was completely avoided in chaos research which we cannot go into detail here. Chaos research deals with the analysis of changes within the system that as such are observable but whose underlying cause was not observable or was not replicable. Here it is assumed that the causal connection between the observable cause and effect is lost due to the complex interaction of a plurality of interfering underlying factors. Furthermore, a procedure that was describable deterministically concerning its individual steps, can no longer be described in a complex system. In order, nevertheless, to be able to make predictions about the behavior of the system, approaches other than the cause/effect principle were developed as part of this research topic. The central concepts of this approach are chaotic attractors and trajectors as well as fractals. Fractals represent a possible construction instruction of a chaotic system. Attractors and trajectors are means for displaying the properties of the system. This means that the cause/effect principle is replaced by a systematic description of the properties (for further details, see Crutchfield et al., 1989). Without describing this approach in detail, we can draw the following conclusions regarding the causes of human errors:

- If one understands man as a complex system, then we can conclude that man cannot be described by simple deterministic causal allocations. A deterministic explanation of the causes of human errors, relating to man alone is impossible and would not make any sense either. The human factor is always multi-causal and is determined by several conditions inside and outside the individual human being.
- Even if the human error can be observed, this observation alone will not make it possible to explain the cause of this error. To provide a meaningful analysis of human errors, one must therefore first of all clear up the interrelationships between errors and error-triggering conditions. The concept of cause plays a subordinate role here.

This last point is not new in psychology. We know of similar ideas, for example, in the theory of testing (see Fischer, 1974). There, human performances in test procedures with a view to certain behavior dispositions are not measured by a single item but rather by several items that are combined in test batteries. The contributions from the items are then construed as indicators of a certain latent (that is to say, non-observable) psychic property (for example, intelligence) and are not seen as psychic property itself.

In the light of these considerations regarding the cause of human errors, one can thus conclude, finally, that the question as to the culpability of the individual is basically falsely posed in connection with human errors. The concept of „cause“ therefore will hereinafter, in this study, be construed in the sense of „condition for“ or „property of.“ The properties or conditions underlying human error must be expressed in a structured form and that is much more important than determining the cause. The next section will provide an approach for this structuring effort.

1.3 Model Ideas Concerning Human Error

In the last section, we showed that the environment in which man is active is of decisive significance in connection with the origin, appearance, or effect of the error. In this section, we will now investigate what model is suitable for structuring this concept of human error such that it can be used for description and evaluation of human errors.

This presentation is based on a bibliography study of existing models to describe human errors and is concentrated on those models that are also used or discussed in the analysis of human reliability. By no means does it represent a complete listing of all models. The models about human error behavior are arranged according to their explanatory value; in that way, one can categorize error models in the following manner (see Eberhard, 1987):

1. Phenomenological Error Models. In phenomenological error models, one tries to figure out what happens. The error is classified in observable categories and is described in this way. Here, we thus ask the question as to the types of errors (What were the errors?).

2. Causal Error Models. In causal error models, we should pin down possible conditions that led to the error. In other words, they go beyond a description of what happened by locating possible conditions for erroneous action. Here, we ask about the conditions for errors (Why does the error happen?).

3. Actional Error Models. In actional error models, we go after remedial measures so that similar errors will not happen in the future. Here, we ask about the possible avoidance of errors (How can one avoid errors?).

Bubb (1992) made a similar subdivision. He described the phenomenological error models as occurrence-oriented classification approaches and the causal and actional error models as cause-oriented classification approaches. This procedure, which is guided by the explanatory value as such, makes it possible to judge error models according to their usefulness in the acquisition and evaluation of human actions and, together with the past considerations, leads to a modeling approach for human errors.

1.3.1 Phenomenological Model Ideas

Phenomenological errors models try to describe the error and to classify it in the form of various error types. Various subdivisions, summarized in Table 2, can be found in the bibliography on the subject.

As shown in the table, Norman, Hacker, Meister and Swain differentiate human errors depending on whether they materialized due to the absence of any kind of activity (omission) or because of a false action (commission). False actions, furthermore, can be differentiated according to whether the action resulted in an error because it was faulty in terms of time (too early, too late) or whether it was faulty in terms of qualitative aspects (too much, too little).

Table 2 Approaches to the phenomenological classification of human error actions

Authors	***Sub-divisions***
Norman (1981) Hacker (1986) Meister (1977) Swain & Guttmann (1983)	- Something is neglected (Error of Omission [EOO]) - Something is done wrong (Error of Commission [EOC]) - Something is done erroneously - Time error (too early, too late) - Qualitative errors (too much, too little)
Reason (1990)	- Active errors - Latent errors
Weimer (1931)	- Making an error - Being mistaken
Rigby (1970)	- Sporadic errors - Accidental errors - Systematic errors
Reason (1990)	Unintentional errors - Oversight (slip) - Lapse Intentional errors - Misunderstanding, mistake - Violation

Reason draws a dividing line between latent and active errors: latent errors are errors that have an effect only when an action is demanded (for example, a defective hand brake in a car; operator has insufficient knowledge on system component which is noticed only when the operator has to work on that component). Active errors are errors that occur when handling technical systems. Latent errors are originated in the past and can materialize both as a result of an error by human individual and also as a result of a technical defect.

According to Weimer, a person can either make an error or be mistaken. If the person makes an error, than the person is the element triggering a faulty state. The person is being mistaken when it acts in good faith, believing that he or she is doing the right thing.

Rigby differentiates between sporadic, accidental, and systematic errors. Sporadic errors are individual errors and are often also referred to as single failures. Accidental errors exhibit a high scatter around the desired target state but do not reveal any tendency in a specific direction. Systematic errors, on the other hand, show a clear trend in a certain direction.

Finally, Reason mentions so-called intentional errors that must be distinguished from unintentional errors. Intentional errors are erroneous actions that are taken by an individual with the intention of doing the right thing. The subdivision given by Reason thus can be compared to the subdivision given by Weimer. Weimer and Reason, finally, also draw a distinction as to whether the individual is the sufficient or necessary condition for the error. Looking at the various subdivisions from the viewpoint of information needed to perform these classifications, one can say the following: the subdivisions given by Norman, Hacker, Meister and Swain are guided by the information that is directly observable within the event. The definition given by Reason, in terms of latent and active errors, draws a distinction according to the underlying system state and is of significance, especially in probabilistic analysis (see Chapter 2).

Considerations concerning the concept of the cause showed that both a subdivision confined to the system state and confined to the individual does not make any sense when it comes to the acquisition and evaluation of human errors. One can thus conclude that the subdivisions given by Norman, Hacker, Meister and Swain represent a meaningful base of departure for a phenomenological subdivision of error types. In the next section, we will cast light on causal model ideas in order to determine what there use for the acquisition and evaluation of human errors.

1.3.2 Causal Model Ideas

Causal error models go beyond a description of what happened in that the possible causes of erroneous actions are matched up. Earlier, we mentioned that human error in error research is often described as the „window to consciousness.“ From this statement, we can also derive the comment that causal models deal with the structure of human cognition or information processing. Accordingly, one can subdivide the causal error models further according to the fundamental psychological areas from which the essential structure of the error model is taken. These are models relating to the psychology of memory, to the theory of decision making, and to information processing. Because of research done in the field of engineering psychology, there is a fourth area that is built on these fundamental areas. In the following we will present error models from these four areas that are important in research on human reliability.

- **Error Model of Norman based on the Psychology of Memory**

Error models based on the psychology of memory start with some fundamental notions about the acquisition, retention, and reproduction of information (Mandl & Spada, 1988). A central concept in the psychology of memory - that has also found use in error research - is the scheme. The concept of the scheme goes back to Head (1926) and was transposed by Schank (1975) to the formal description of knowledge structures and by Schmidt (1975) to the description of motor activities. In terms of general structure, schemes represent prefabricated knowledge structures that have certain attributes which, in turn, may assume certain values. These standardized knowledge blocks are used to store courses or actions. Depending on whether they contain procedural or declarative attributes and value, they are called „scripts“ or „frames.“

Norman (1981) used the theory of schemes to describe errors. He subdivided erroneous actions into mistakes, mode errors, and captures. Mistakes are falsely triggered schemes; mode errors are falsely activated schemes; captures are finally falsely triggered schemes in a correct context. The triggering of a scheme requires time coordination of the sequence of schemes so that, to be sure, something „correct is done“; but, of course, it is turned into an error because the timing is wrong. The subdivision according to Table 3 now can be derived from this approach.

The scheme approach has one very serious disadvantage: knowledge structuring (and thus also a description of a human errors) always takes place via a scheme. This means that scheme-oriented approaches are always also a forcibly algorithmic description of fixed individual sequences, so-called production systems, or fixed states, so-called object structures.

In the case of errors that cannot be described in algorithmic terms - such as, for example, time variability of errors due to learning or diagnosis procedures - scheme approaches run into the limitations of their description possibilities.

Table 3 Distribution by Norman

Description of error	***Error types***
Mistakes	Errors in the selection of a scheme (decision making error)
Mode Errors	Errors during the application of a scheme (Stereotyping error and error of habit)
Captures	Errors in time sequence of different schemes (Temporal and qualitative errors)

- **An approach by Rouse and Rouse based on the Theory of Decision Making**

Approaches based on the decision making theory start with a description of the general procedure needed for problem solution (see Dörner, 1976). Rouse and Rouse (1983) according to this approach differentiate action steps with pertinent error types (Figure 1).

In a decision situation, one must first recognize the deviation of an actual value from a required value. Then one must discover those measures by means of which an adjustment of the existing difference becomes possible. This requires three steps: formation of an assumption as to what happened; selection of the desired target state; and selection of the procedures by means of which this target can be attained.

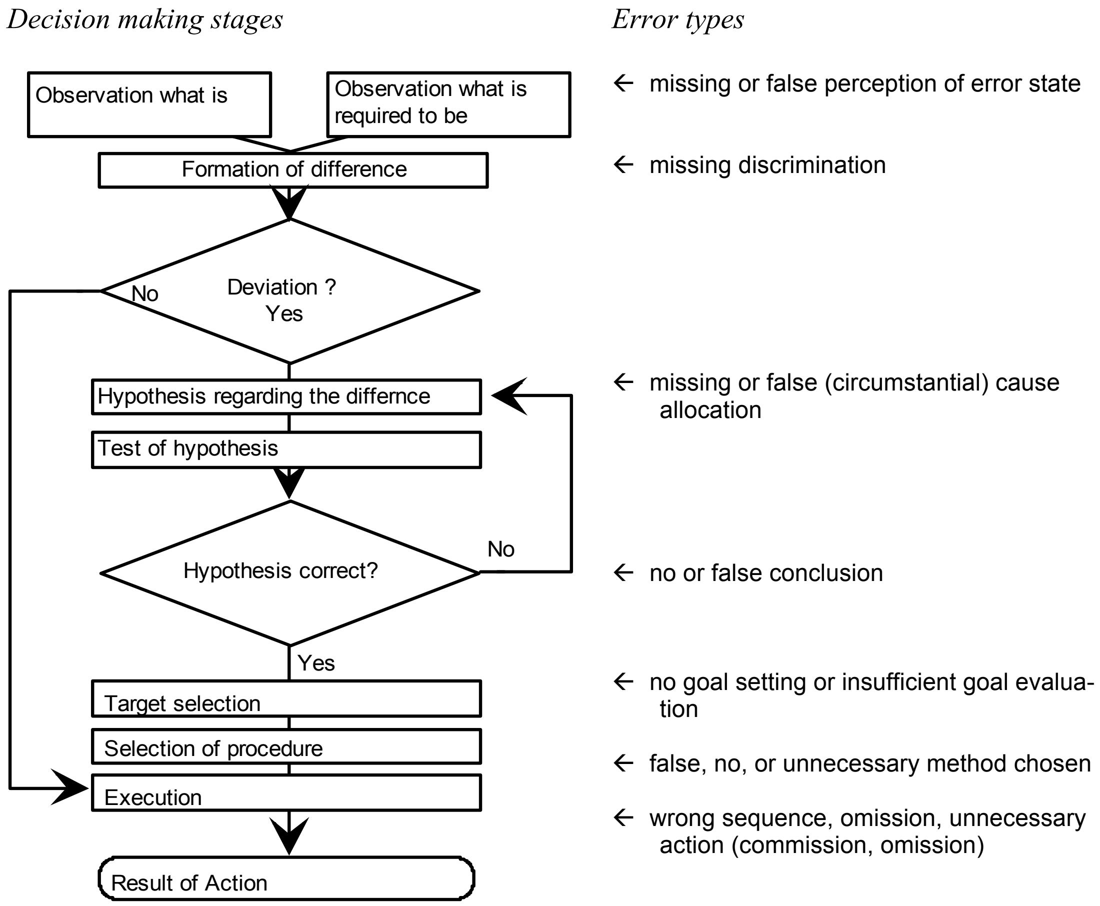

Figure 1 Subdivision of human errors according to Rouse and Rouse (1983)

- **An Information Processing Error Model by Reason (1983)**

Error models from the psychology of information processing relate to the processing stages one must go through in order to convert the information that is offered on the perception site into information that is put out altered on an action side (see Wickens, 1984).

One of the best known of these so-called stage models is the one by Sternberg (1969). Sternberg starts with a strictly sequential stage by stage processing. Reason (1976) developed his early error model along the lines of these stages that were found with the help of perception experiments. Table 4 illustrates which action stages and error possibilities Reason distinguishes.

Table 4 Subdivision by Reason (1976)

Processing stage	***Error possibilities***
Perception and recognition (Input Detection)	Discrimination errors in connection with signal discovery
Comparison and Decision (Comparison and Decision)	Errors in blending of action programs
Selection of Response (Response Selection)	Errors due to forgetting of actions or false recall
Selection of Action (Action Selection)	Errors during the selection of automated action components
Feedback on action (Action Feedback)	Errors due to absence of feedback from actions

- **Information Processing Error Model by Rasmussen**

A classical experiment by Schneider and Shiffrin (1977) for the psychology of information processing showed that the various processing stages depend heavily on the level of practice on the part of the persons and that one thus cannot assume any strictly sequential stage processing. Instead, certain actions are automated as a result of frequent practice of certain forms of behavior. Highly practiced actions then take place without any attention and in an automated fashion. Accordingly, one can distinguish certain phases of processing quality (novel, practiced, highly practiced).

All of the more recent approaches to error modeling considered this aspect of different exercise and practicing phases (for example, Reason, 1990; Swain & Guttmann, 1983; Rasmussen, 1986). The classical approach to the integration of the stage approach and the phase approach is represented by the model of Rasmussen (1986). He subdivided the organization of knowledge in three levels: the skill-based level, the rule-based level, and the knowledge-based level. Automated processing of sensory and motor information prevails on the skill-based level which stands out by a high level of practice and experience. A number of automated ways of behavior are combined to a new pattern of behavior on the rule-based level using rules. Information processing on the knowledge-based level occurs in unpracticed or novel situations. Here, there is a new combination of automated ways of behavior and rule-based knowledge, using specific target notions so that new action plans are drawn up. Every level has error types that are characteristic of it (Figure 2).

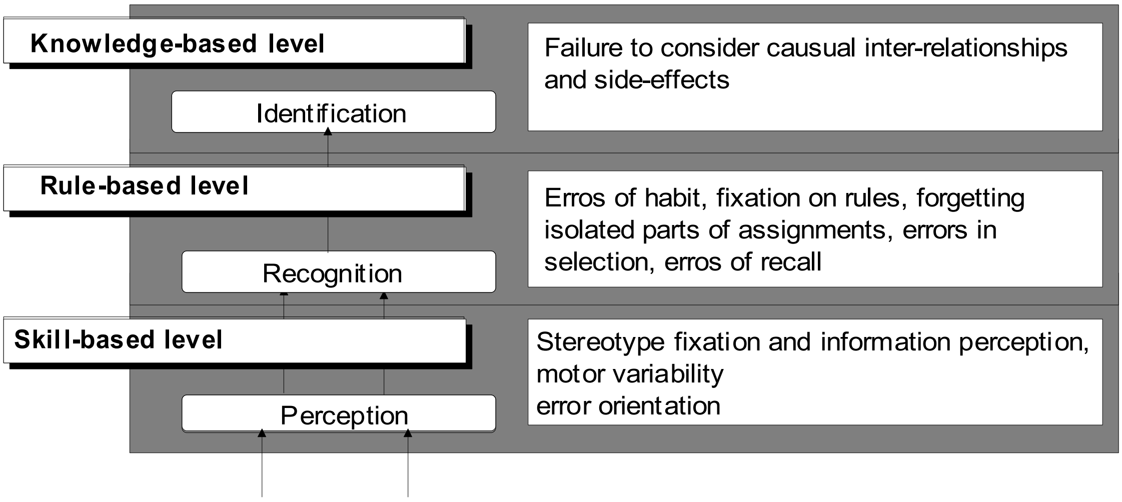

Figure 2 Errors in the Three-level model according to Rasmussen (1986)

Depending on the degree of routine connected with an action, the various processes on the levels, as shown in Figure 2, will run through the following in case of a specific action: in a routine activity, one will rather run through only the skill-based level; in the case of unpracticed actions, in emergency situations, the procedure of information processing extends all the way to the knowledge based level.

Depending on the level from which the information flow springs, one can roughly divide actions into two procedures according to Rasmussen (1986): topographic (top down) search and systematic search (bottom up). In case of a topographic proceeding, the expert, in searching for the location of the problem, confines himself to an investigation of certain possible problem causes and evaluates them in that he derives, from his own mental model, hypotheses as to the cause and its correctness. The top down search thus starts with assumptions about possible causes on the knowledge-based level. In the case of bottom-up search, the expert tries, via pattern recognition procedures, again to recognize the causes corresponding to the problem in his own internal model of the problem space so that he can then classify the problem. The bottom-up search starts with information perception on the skill-based level.

Both search strategies are heavily involved in the pattern recognition procedures because information perception takes place only on the skill-based level. In the case of the top-down proceeding, information perception takes place during the check on the hypothesis proposal (comparison of hypothesis and pattern) and in the case of bottom-up proceeding, it takes place during the renewed recognition of directly accessible information patterns. The skill-based level is used also during renewed recognition on the rule-based level, and during identification on the knowledge-based level; therefore, this information processing stage represents a basic pre-requisite for information processing also on the higher stages. Possible error types, that may be considered in connection with these search strategies, according to this model, thus always contain effects of habit. Errors thus arise particularly because the individual automates often recurring actions or action complexes (see also discussion, Section 1.1). Problems occur in Rasmussen's model when one tries to classify a given situation with the help of the various practice levels because the subdivisions of the practice levels are not tied to any objectively observable situation parameter.

- **The Generic Error Modeling System [GEMS] of Reason**

In 1990, Reason integrated the various psychological approaches that had been employed in the error models until then: the subdivision based on the psychology of memory (for example, Norman), the approaches under the heading of decision making psychology, such as the one of Rouse and Rouse, as well as the stage subdivision and phase subdivision by Rasmussen. Reason thus presents a causal error model that considers several psychological approaches on a broad theoretical basis. Figure 3 shows the structure of the generic error model (Generic Error Modeling System [GEMS]) of Reason.

At this point, we do not want to go into any detailed comments on Reasons' model; nevertheless, we may say that the GEMS Model broadens the behavior levels of Rasmussen by an approach in terms of decision making theory. A consciously intentional mastery of a task comes about here only due to actions on the rule-based or knowledge-based level. Actions on the skill-based level can be performed within this model only in work environments with which the individual is very familiar. On the skill-based level, however, errors for which conscious attention processes are required cannot be committed. There are no mechanisms for error correction on the skill-based level. According to Reason, on that level, only unintentional errors - such as, for example, an oversight due to inadequate attention- are possible. Error correction mechanisms can be found only on the rule-based and knowledge-based levels by looking for known rules or analogies. The subdivision into various practice levels was adopted most extensively by Rasmussen. Therefore, the same problems crop up also in connection with the GEMS Model if one wishes to apply to a given situation.

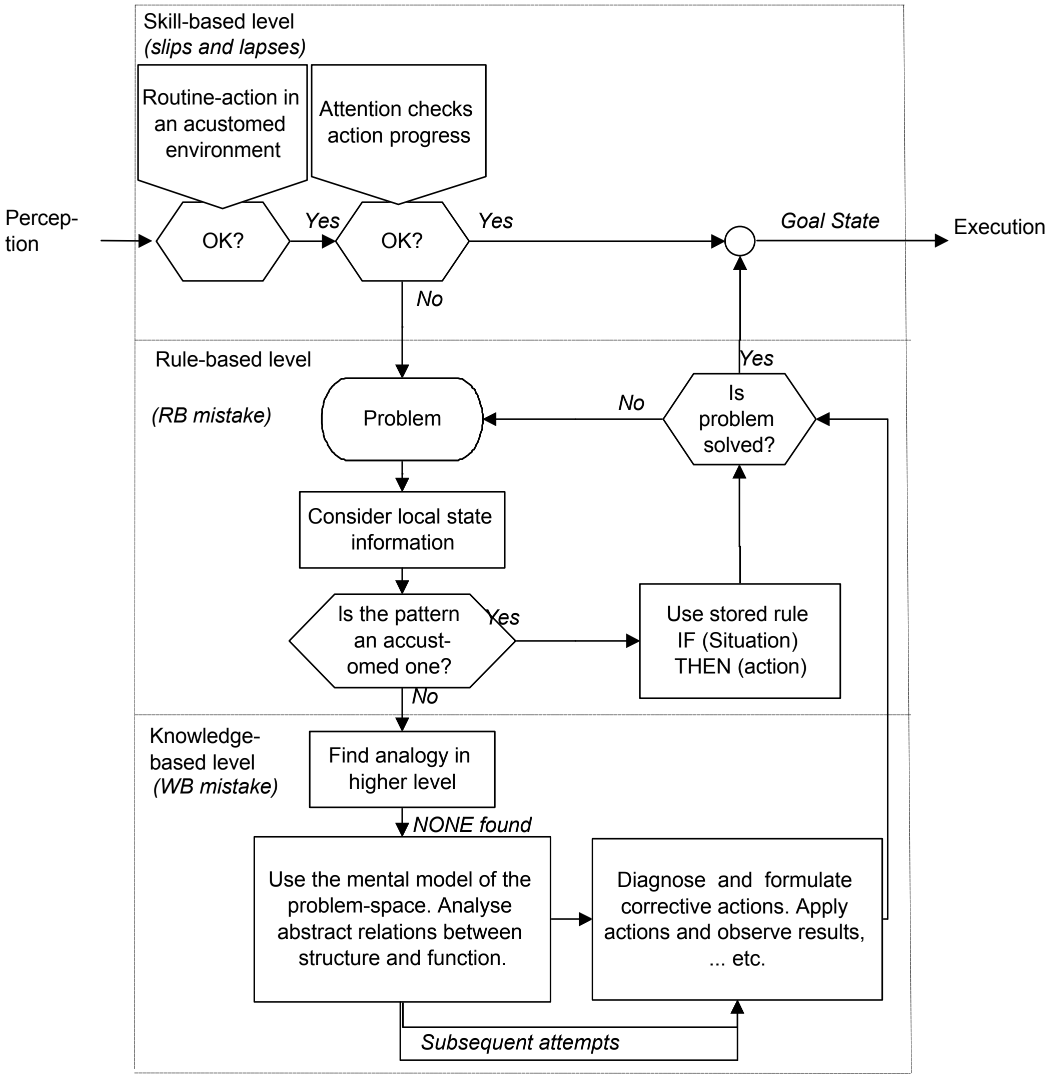

Figure 3 The GEMS Model according to Reason (1990, p. 64)

1.3.3 Actional Model Ideas

Strategies for error avoidance for remedial measures are to be found in actional error models. The object of observation must be chosen here such that it will comprise all possibilities that can also lead to improvements. The models of Hacker and Swain represent a first step in this direction of considering human errors. Further developments by Brauser and Seifert and by Rasmussen are presented.

- **Error Subdivision by Hacker**

The model of Hacker (1986) represents a continued development of causal error models in the direction toward an actional error consideration. Hacker distinguishes between no use and false use of available information. False use of available information can again be caused by errors of information processing (Figure 4).

Available information not used		- Oversight - Forgetting/neglecting - Skipping - Redundance conditioned information reduction (Stereotypes, expectation errors of the first kind)
False use of available information	false orientation	- Misidentification (Sensory deception, expectation error of the second kind) - Memory deception - Misjudgment
	wrong drafting of action programs	- Motion programs with spatial and/or temporally wrong parameters - Miscalculation (calculation error, planning error)
	wrong decision	
	inappropriate condition demands in action programs	- Wrong sequencing in terms of time (Time error) - Wrong sequencing in terms of space - Confusion (Under given conditions, in terms of population stereotypes)

Figure 4 Subdivision by Hacker (1986)

The model produced by Hacker thus - compared to the models presented so far - constitutes a basic innovation in looking at human error. The concept of the human error is broadened to include the information available to the individual and thus also to the environment of the individual.

- **Error subdivision by Swain**

The model of Swain and Guttmann (1983) is also based on the information processing approach. He draws a distinction between the following processing stages: perception, cognition, and action. Something new in Swain and Guttmann is represented by the fact that consideration is also given to the interface by means of which an individual is in communication with a technical process. Compared to Hacker, the model thus represents a further step toward an actional error model because the components with which the individual is in contact are explicitly included in the model. In addition, similar to what was proposed by Rasmussen, the model includes both the sequential information processing approach and the phase approach (Figure 5). Various phases are modeled here as shortcuts within sequential processing. The uppermost level corresponds to the skill-based level, the middle one corresponds to the rule-based level, and the bottom one corresponds to the knowledge-based level.

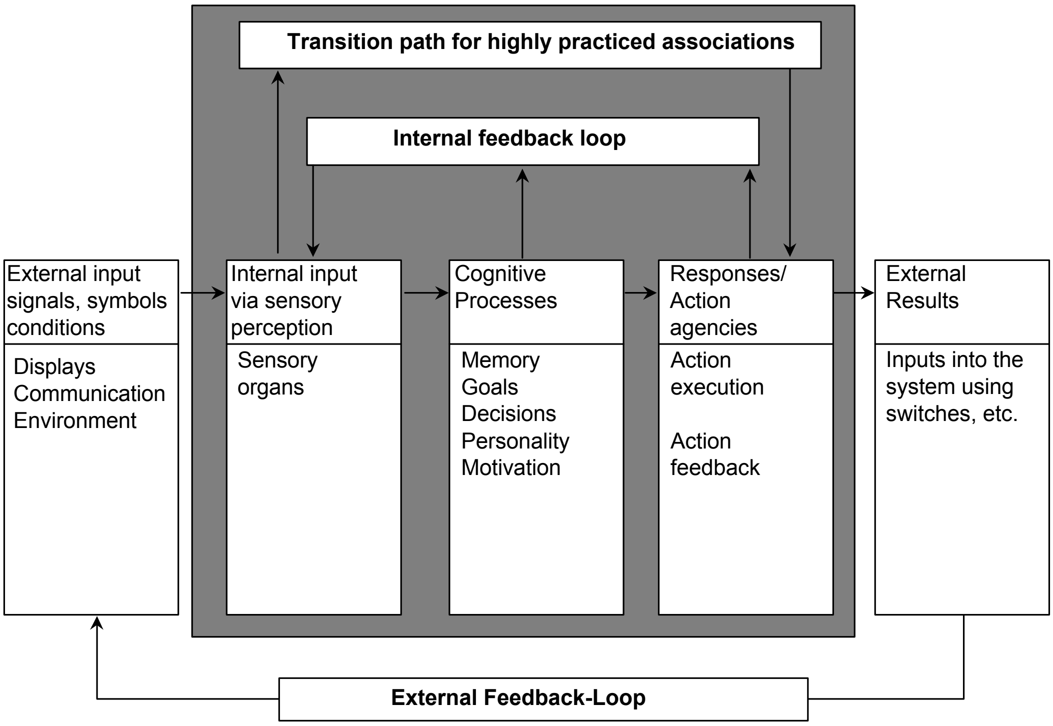

Figure 5 Subdivision of Swain and Guttmann

Errors within the stage model of Swain and Guttmann can be described by stating that the phenomenological error subdivision from Table 2 is applied to these stages. For example, external information may be missing or may be offered too early or too late. In a corresponding manner, errors can be indicated in the other stages.

Furthermore, the individual processing stages can be influenced by so-called performance shaping factors [PSF] (for example, stress, time pressure, work station layout, etc.). The action can be influenced by psychological, psycho-physical, situation-related and other factors that work on the stages. The performance shaping factors mentioned by Swain and Guttmann are shown in Table 5. A distinction is made in the table between external performance shaping factors and internal performance shaping factors as well as performance shaping factors that act as psychic or physical stressors. The performance shaping factors act as error-promoting factors and are used to describe error likely situations. A typical example is the previously mentioned Airbus accident that was impaired [sic] by the performance shaping factor under the heading of „ergonomic design of glide angle setting operation.“

Table 5 Factors influencing human actions according to Swain & Guttmann (1983)

External Performance Shaping Factors		***Stressors***	***Internal Performance Shaping Factors***
Situational factors	*Factors in tasks and work resources*	*Psychological stressors*	*Factors relating to the organism*
Design features Quality of environment Temperature, air humidity, air quality, radiation exposure, illumination, noise, vibration, cleanliness Working hours Work breaks Availability of special work resources Job manning Organizational structure (for example, authority, responsibility, channels of communication) Actions by shift leader, worker, manager, supervisory authority Remuneration structure (Recognition, payment)	Requirements for perception Requirements for motor system (speed, power expenditure, accuracy) Relationship between operators and display Requirements for adaptation Interpretation Decision making Complexity (Information loading) Narrow nature of task Frequency and repetition of task Criticality of task Short term and long term memory Calculations Feedback (Knowledge regarding results of an action) Dynamic or gradual actions Group structure and communication	Suddenness of occurrence Duration of stress Task speed Task load High hazard risk Threats (fear of failure, loss of job) Monotony, degrading or meaningless activities Duration of uneventful periods of alertness Work performance motive conflicts Reinforcement of missing or negative sensory deprivation Distractors (noise, blinding, motion, flickering, coloration) Inconsistent labeling	Prior training, experience State of momentary practice or abilities Personality and intelligence variables Motivation and attitude Emotional state Stress (mental or physical) Knowledge about demanded performance prerequisites Gender differences Physical conditions Attitudes deriving from family or groups Group dynamic processes
Work and Task Instructions		*Physiological Stressors*	
Required procedures (written, non-written) Written and verbal communication Warnings and danger signs work-methods plant policy	Man-machine factors Interface (Design of work resources, test instruments, maintenance equipment, work aids, tools, accessories)	Duration of stress Fatigue Pain or discomfort Hunger or thirst Extreme temperatures Radiation Extreme gravitational forces Extreme pressure conditions Inadequate oxygen supply Vibration Restricted movements Absence of physical exercise Interruption of circadian rhythm	

Taking a closer look at the table, it of course becomes clear that Swain and Guttmann do not explicitly specify how the performance shaping factors act on human errors or whether certain performance shaping factors trigger certain error types. In the table, similar performance shaping factors are partly categorized under different classes (for example, noise as external performance shaping factor or as stressors). The connection between error types and performance shaping factors in this model emerges only implicitly from the data on the quantification of human errors that were described by Swain and Guttmann (1983) in tables dealing with the reliability with human actions and that no longer have any direct relation to Table 5, for example, the error probability is doubled during transition from normal stress to high stress. Other subdivisions of performance shaping factors can be found among others in Embrey (1983) who compiled a noncommittal selection of performance shaping factors. The relationship between performance shaping factors and error types must be structures to facilitate a clear match up of performance shaping factors. The following two error subdivisions show how this connection can be established.

- **Error Subdivision of Seifert and Brauser**

Seifert and Brauser (1987) structured the connection between human errors, error types and influencing factors by combing the relationships between influencing factors and certain error types in one model (Figure 6). For this purpose, they combined a causal error categorization with an actional subdivision of possible main causes.

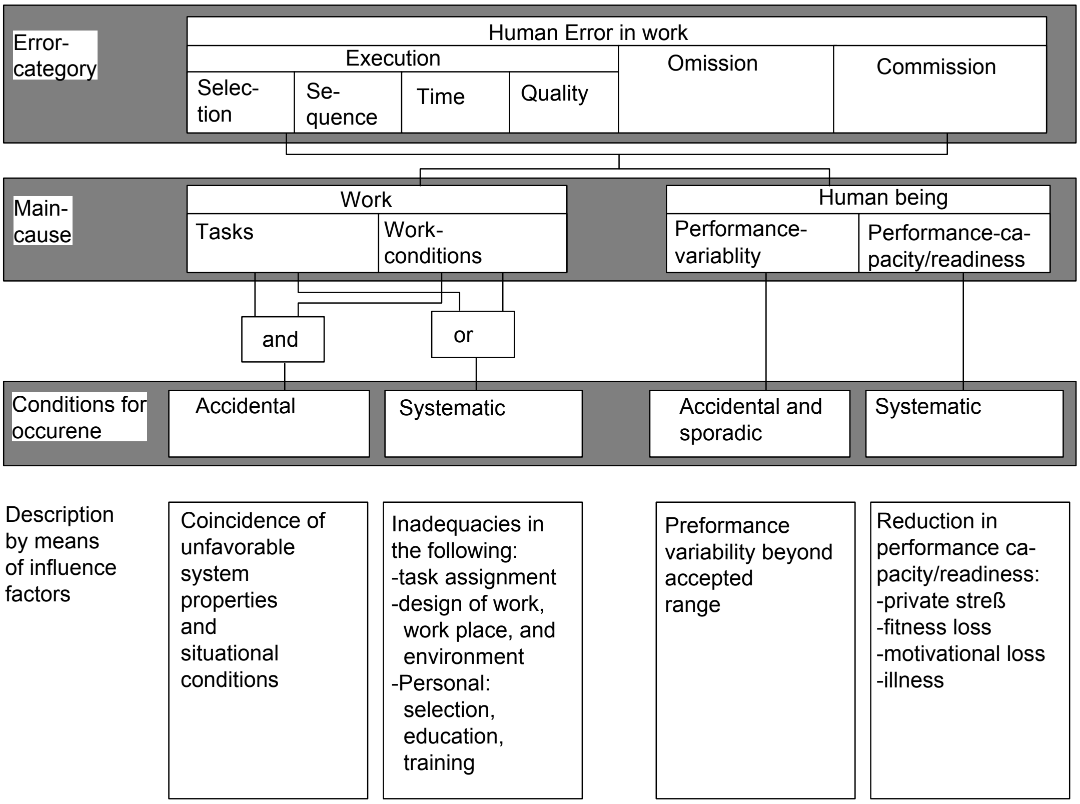

Figure 6 Subdivision by Seifert and Brauser

This approach clearly shows the way in which actional error models differ from causal error models: actional subdivisions emphasize possible improvements in the work system by subdividing the conditions for occurrence of an error in terms of improvable (systematic) or extensively not improvable (sporadic, accidental). Here, systematic error behavior can be described by means of various influencing factors; on the other hand, in case of sporadic or accidental error behavior, one could not cite any influencing factors.

- **Multi Causal Error Subdivision of Rasmussen**

Rasmussen (1986) illustrated the interrelationship between performance shaping factors and error types by means of an action diagram (Figure 7).

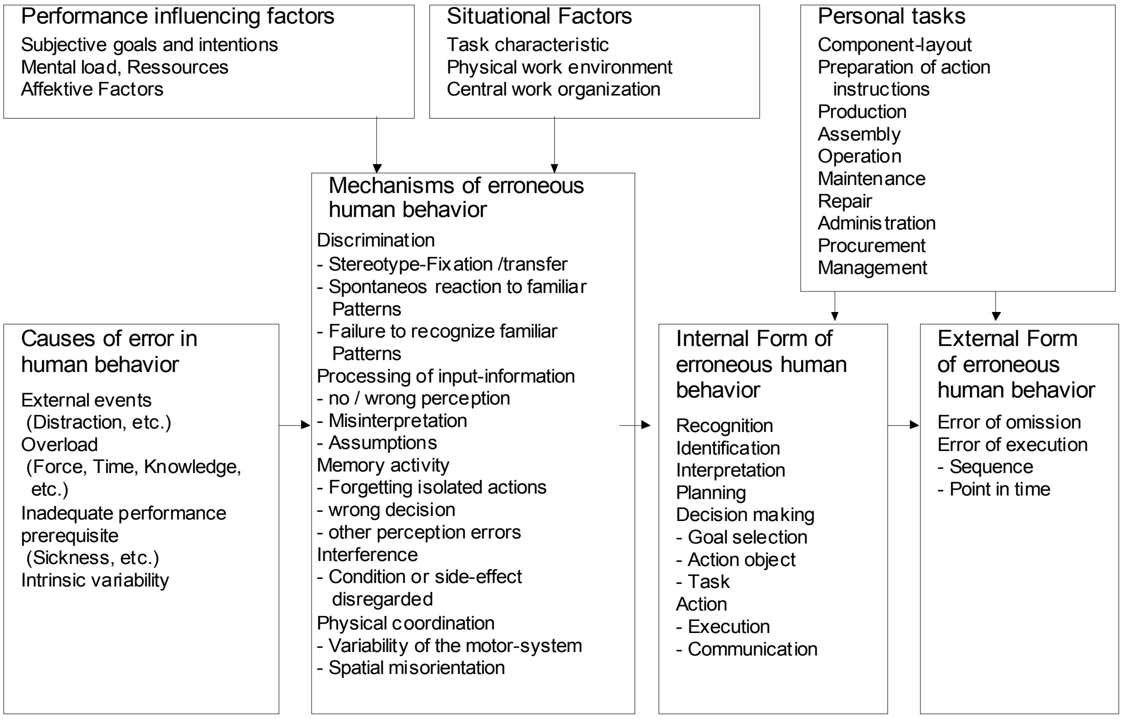

Figure 7 Multi-aspect of an Actional Consideration of Human Errors according to Rasmussen

Looking at this connection, within the load-cope model (see Bubb, 1992), Rasmussen distinguishes between „Performance Influencing Factors,“ and „Personal Tasks“ in terms of load and between „Causes of Human Error Behavior,“ „Mechanisms of Human Error Behavior,“ and „Internal Form of Error Behavior“ in terms of cope. The load factors are presented by vertical action arrows and relate to the environment and the situation. Cope factors are illustrated by horizontal action arrows and relate to the person. The load aspect thus images all of the external factors acting upon the individual; on the other hand, the cope side describes the possibilities of the human being in terms of coping with the load factors. Both factor groups cooperate to lead to the „External Form or Error Behavior.“

1.4 Approaches to a Model for the Analysis of Human Errors

In the last section, we presented various model ideas about human errors. To arrive at a model that is suitable for pinning down human errors in events, we will, in this section, discuss common features and differences between these error models, and, building on that, we will develop a behaviorism and cognitivism approach to the acquisition of human errors in events.

1.4.1 Discussion of Model Ideas

The consideration of various error models showed what points in describing an error are important. For example, in considering the causal error models and the error model of Swain and Guttmann, it is interesting to note that the basic procedure in causal attribution is the same in all models. Figure 8 illustrates this echeloned procedure.

In a first stage, we formalize the description in a model (of whatever nature it may be). All of the relevant observations that are chosen from the viewpoint of the selected model and that are part of the error event are described here. This is followed by a match-up of phenomenological error subdivisions (error taxonomies) to one part of this model in each case. In that way, we describe the errors that occurred in the error event. To determine the conditions under which the error event occurred, we list, in a third stage, the factors that influenced the error events in the form of performance shaping factors. The consideration of performance shaping factors less represents yet another step in the description of errors in that - along with error localization, by means of phenomenological description - the conditions are also named (for example, efficient design of two operating buttons). Naming performance shaping factors also makes it possible to work out improvements in the design of the technical system (for example, the influencing factor entitled „similar design of two operating buttons for the different subsystems“ indicates that the operating buttons should be designed differently). The approaches by Seifert and Brauser as well as the multi-aspect of Rasmussen, moreover, tried to depict the causal relationships between model, error types, and influencing factors. Figure 8 indicates these causal relations by means of connecting lines between description stages.

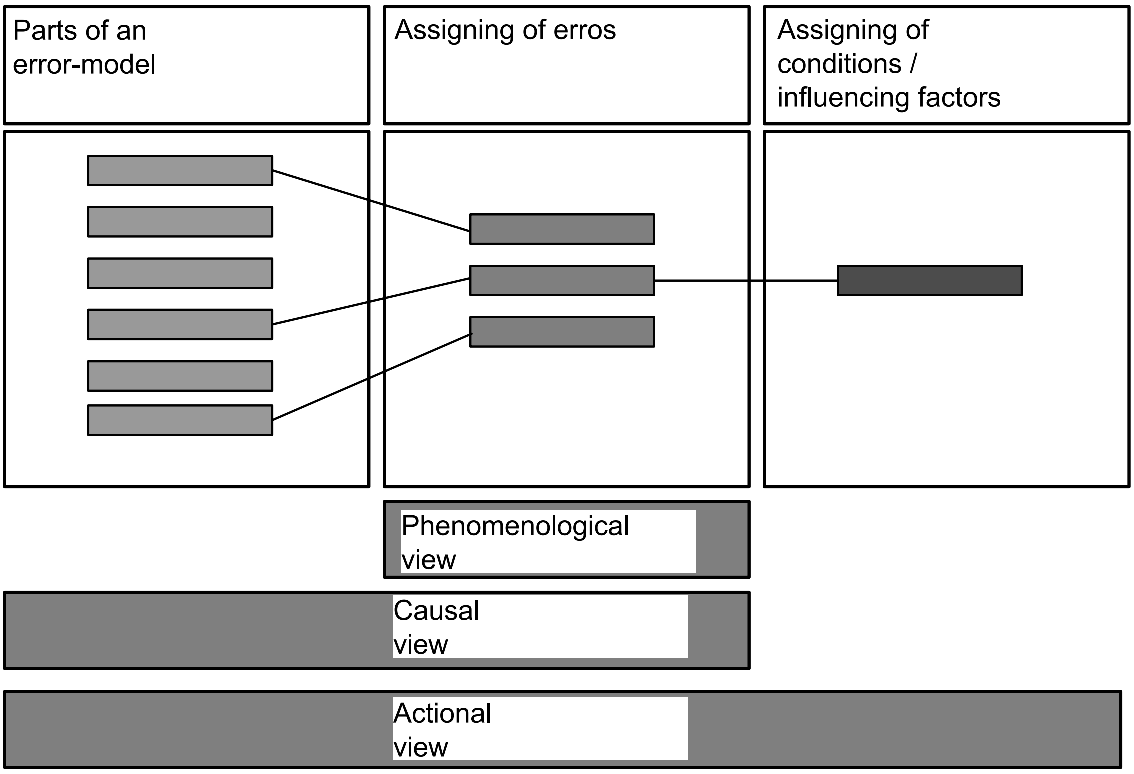

Figure 8 Echeloned Procedure in Error Description

The consideration of various error models, furthermore, shows that causal error models are confined to the human individual as an object of consideration, whereas actional error models consider man and his environment. Accordingly, causal error models can be labeled, rather, as cognitivism approaches and actional error models can be labeled, rather, as behaviorism approaches. In the prior sections, there was no indication as to which of these two approaches was better suited when it comes to acquiring human errors in events. The following points must be considered in making a decision in favor of a particular approach:

- In causal error subdivisions (of the cognitivism view), the individual represents the only possible cause when an error occurred. This results from the restriction of the object of consideration to the individual alone. This restriction does not make any sense when it comes to acquiring human errors in events, as was made clear in the discussion on the initially cited definitions for human error. For example, interrelations of system and operator are ruled out as possible error sources and are generally classified as „human failure.“ This means that the man-machine environment, in which the operator works, is ignored and error causes that are actually due to the flow of information in the working system, or due to technical factors, are projected upon the individual. This is why it is impossible, in a definition confined to the individual, to discover improvement measures within the technical system or to describe the interplay of technical and human factors.

- If one wishes to acquire human errors in events, then the cognitivism procedure leads to problems in practical implementability. The data that are required for these models cannot be acquired or are to be acquired only with difficulty from the events (see Bubb, 1992; p. 89). The cognitivism procedure is thus inferior to the behaviorism procedure in terms of implementability.

In the light of these considerations, it seems to make sense to select a behaviorism approach for error modeling that is supplemented by the cognitivism aspects.

1.4.2 A Behaviorism Approach to Error Modeling

The continued developments of the error models in work science show the direction in which error description models must develop so as to permit behaviorism (and thus also actional) considerations: the environment of the individual must be included in the error model. This central aspect of the environment of the individual, which is expressed particularly by the multi-aspect of Rasmussen, is described in an ideal fashion by the man-machine system. Figure 9 shows the general man-machine system (see Bubb, 1992).

In the Man-machine system [MMS], an action can be subdivided according to the viewpoints of task assignment or goal, information conversion by the individual (including perception and motor action or activity), information conversion by means of the technical system or the machine (including control or operating elements or work resource and system magnitude), system output or action result and feedback or action monitoring. Within the man-machine system, the acting operator is entrusted with a task assignment. By processing the task and by means of the feedback of the current system state, the operator triggers an action upon an operating element of a technical system. The action, in turn, has consequences for the behavior of the system magnitude that is reported back to the operator. The entire system is embedded in environmental conditions that can influence both, the information processing stages (for example, perception, motor system) and by the information processing paths (for example, feedback).

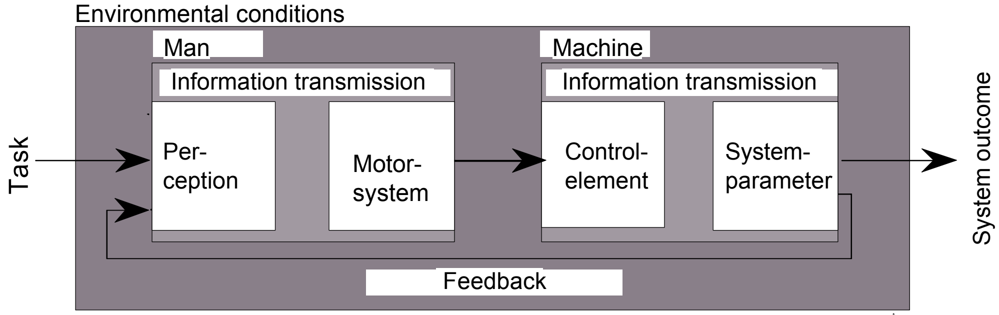

Figure 9 The Basic Diagram of the Man-Machine System

This model makes it possible to depict all of the actional factors discussed so far. The failure to use information or the use of false information (see Hacker) is depicted by the connections between task assignment and feedback to the individual. The subdivision by Swain is almost identical to the „man“ subsystem of the man-machine system and its direct connections. The subdivision of Brauser and Seifert in terms of task conditions (corresponding to task assignment) and working conditions (corresponding to the action feedback loop) can be found in the man-machine system just as much as the multi-aspect of Rasmussen (for example, the situational factors of Rasmussen are depicted in the task assignment and in environmental conditions of the man-machine system). Furthermore, the man-machine system is in a position, beyond the multi-aspect of Rasmussen, to depict the reciprocal interaction between the technical system (the machine) and the individual as operator because both of them are considered as a whole system.

Until now, the man-machine system, however, has been a pure description model for human actions in working systems (see DIN [German Industrial Standard] 4003). The considerations on past error models, such as they are compiled in Figure 8, showed how an error model can be developed from the approach of the man-machine system. The echeloned procedure illustrated there is independent of the chosen error model; therefore, this procedure must logically also apply to the model of the man-machine system. To broaden the man-machine system into an error model, one must thus mention the following with respect to every stage of the man-machine system:

1. A phenomenological error description by means of an error taxonomy.
2. A causal error description by means of the identification of essential weak points in the information flow of the Man-machine system.
3. An actional error description by means of a taxonomy for conditions or influencing factors.
4. Illustration of the interrelationship between error types and influencing factors by means of their joint appearance in events.

Summarizing, the man-machine system is an ideal point of departure for an acquisition and evaluation of human actions and events from the viewpoint of the definition of a human error, presented in this work, and from the angle of the discussions on the question of culpability. One thing that has been left open so far is just exactly how one can consider, within the man-machine system, the model ideas regarding human information processing.

1.4.3 A Cognitivism Approach to Error Modeling

There are two models that are currently in the lead in the area of cognitive errors: the model of Rasmussen (1986) and the follow-up model by Reason (1990), both of which were described earlier. We will first of all present the problem inherent in these models and we will then develop a model idea for the purpose of treating cognitive errors in this study.

Within the approaches of Rasmussen and Reason, the subdivision into skill-based, rule-based, knowledge-based behavior constitutes a central assumption. From the earlier description of the models, it emerged that the transition between these phases in both models depends on the degree to which the individual is practiced and exercised vis-à-vis retrieving adequate reaction patterns within certain situations. If a situation is less familiar, then one must chose a correspondingly higher behavior level in order to be able to react properly in keeping with the situation. The mechanism, by means of which one can choose the various behavior levels, is similar in both models, and is basically comparable to Holst's Reafference Principle (see Bubb, 1992; p. 32) or the concept of cognitive dissonance (Festinger, 1957):

In the Rasmussen approach, the various behavior levels are triggered by the previously described strategies of top-down and bottom-up search. If the use of the search strategies does not yield an adequate behavior pattern on a lower level, then one moves to the next higher level. The higher the behavioral level, the less conscious attention is required: on the skill-level, information processing procedures take place in a completely unconscious fashion. On the rule-based level, conscious attention is required in the selection of rules which then again can be implemented without any attention. On the knowledge-based, the processing procedures take place exclusively under conscious control.

In the Reason approach, this mechanism of transition between behavior levels was further formalized. Skill-based behavior prevails in Reason if existing skills apply faultlessly on the situation. The rule-based level is occupied when deviations of the situation from practiced ways of behavior are observed and when known rules to master the situation can be applied. The knowledge-based level is required if the deviation of the situation from the learned form of behavior is so great that no fitting rules can be found. The Reason approach thus represents a formalization of the Rasmussen approach because he defines the transition between the levels on the basis of the possibilities of the levels (for example, the rule-based level is occupied when fitting rules are present). Rasmussen, on the other hand, merely states that the level is always raised when no adequate behavior pattern was found in the application of the search strategies.

In the Rasmussen and Reason models, one can thus identify two basically different aspects that are critical when it comes to a choice of the behavioral level. That includes, first of all, familiarity with the external situation, and, besides, the mechanism that controls the type of conscious situation processing. Both aspects can be so described in the terminology of the load-cope model (see Bubb, 1992; p. 20) that the external situation will lead to cognitive load which stresses the apparatus of internal processing in a cognitive fashion. Both aspects will now be described in greater detail.

The aspect of cognitive cope relates to the mechanism by means of which the various behavior levels are triggered. The discussion, conducted with regard to the models of Rasmussen and Reason, made it clear that - in considering cognitive cope - one must in particular consider the phenomenon of conscious processing and automation of forms of behavior.

The philosophical considerations concerning human error discussed earlier showed which factors are important in this connection. The subdivisions performed there are known via cognitive psychology all the way to software ergonomics, such as, for example, in the Goal Operations Methods and Selection Rules Model (GOMS) of Kieras and Polson (1985). This system consists of goal (goal definition), Operations (Selection of Operations), Methods (Selection of Operators), and Selection Rules (Rules for the Selection of Operators). The GOMS Model is used primarily to determine the complexity of paths and times of indirection in operating software products. Within the model, the goals are first of all subdivided down to terminal sub-goals. For each terminal sub-goal, one can them indicate operations, methods, and rules that contribute to goal attainment. Overall, we can thus identify three central factors in cognitive cope: the determination of the goal (Goal), the knowledge needed to attain the goal (Operations), as well as the processing necessary for the attainment of the goal (Methods and Selection Rules). Research on attention control moreover shows how attention and information processes work together and what cognitive errors one may expect. This gives us the following subdivision.

1. Processing: To focus attention of a certain piece of information, we first of all need a mismatch between an expected and an actually occurring situation that leads to an orientation reaction (see Schandry, 1981, p. 56). Focusing attention on the mismatch leads to a conscious acquisition of the actual/required deviation. This conscious processing function is required to find a properly situation-oriented selection of action alternatives to compensate for the mismatch (unconscious processing would not facilitate any properly situation-oriented selection of action alternatives). The deviation between what is and what should be in this case is not tied to a certain abstraction level of existing knowledge in the form of skills, rules, or analogies (and it is thus not tied to the behavior levels according to Rasmussen). Possible cognitive errors here reside in the inadequate processing of information to detect the mismatch.

2. Information: The person tries again to adjust the determined is/should be deviation or dissonance via efforts to achieve consonance (Festinger, 1957). Certain capture information, so-called „cues," are required to make a selection of the corresponding action alternatives. The cues provide points of departure for a search for possible ways of compensation (see Sanders, 1975). They can be supplied either from the outside or they can reside in the knowledge of the person. Possible cognitive errors reside in no information or inadequate information pertaining to possible action alternatives or in the absence of pertinent cues that lead to triggering cognitive dissonance. In case of inadequate information, cognitive errors are characterized in that the individual is aware that there is a deviation from normal behavior but the latter cannot be specified any further.

3. Goal determination: The possible ways to compensation that are found via cues are picked out by means of similarity matching or via the criterion of frequency (frequency gambling) as a solution to the particular current situation (see Reason, 1990). The solution that was found (in other words, the goal of the action) is applied to the situation with the available information as well as existing rules or strategies, either closed loop or open loop (see Schmidt, 1975). Possible cognitive errors here reside in goal reduction by means of an incomplete similarity matching or due to the dominance of a false solution. In keeping with the later phase in problem solution, cognitive errors here are characterized by full awareness of the problem and by increased cognitive dissonance.

To classify the aspect of cognitive load, it seems to make sense to use the level model of Rasmussen and to combine it with the aspect of attention control as cognitive cope. Table 6 illustrates this relationship. The table shows a total of 9 fields for the classification of cognitive errors. This relationship is established in a similar form also by Freese (in Zapf et al., 1989). There, the constructs of memory psychology - situational feedback, memory, and goal selection, were used merely to subdivide the cognitive cope and these constructs basically correspond to the concepts used in the table: situational feedback corresponds to processing, memory corresponds to information, and goal selection corresponds to goal reduction. It is interesting to note here that errors of habit cannot be found on the skill-based level but only on the rule-based level. Errors of habit thus constitute a slip during the selection of rules. This means that this subdivision also considers the phenomenon -

already discussed in connection with the model of Rasmussen - to the effect that habits are important on every processing stage leading to the materialization of errors.

Table 6 Broadening the model of Rasmussen by adding the attention control factor

Cognitive cope Degree of attention ***Cognitive Load Behavior Level***	***Processing***	***Information***	***Goal Reduction***
Skill-based (for example, daily routine action)	Unconscious slip	Slip regarding problem	Slip regarding problem solution
Rule-based (for example, regular action)	Recognition error violation (routine violation)	Error of omission rule-based error (Rule-based mistake)	Error of habit attention error (attention failure)
Knowledge-based (for example, irregular action)	Error of judgement (Exceptional violation)	Memory failure	Thinking error (knowledge-based mistake)

The connection described in the table, of course, does represent a useful expansion of the Rasmussen approach; the differentiation illustrated there, however, appears to be unsuitable when it comes to the acquisition of cognitive errors. An essential point of criticism here is the following: the behavioral levels (1) are not discrete but rather represent a continuum, and (2), they depend on the degree of practice achieved by the person and are thus specific both to the person and are specific in terms of the situation of the individual person (e.g., Wickens, 1984). Moieni et al. (1994) were also unable empirically to prove the behavioral levels of Rasmussen. Instead, they found subdivisions aligned along technical system characteristics. The behavioral levels of Rasmussen thus are unsuitable when it comes to describing the quality of the external situation unambiguously and independently of the persons.

One must therefore pick another approach in order to describe the aspect of cognitive load independently of the degree of practice of the person. Here, the important thing is to describe the characteristic properties of the situation unambiguously and independently of the person. The man-machine system was chosen as the behaviorism model for the acquisition of human errors; therefore, to describe the load aspect, we can fall back on the system ergonomics classification according to Bubb (1992). Table 7 illustrates the system ergonomics classification and presents a description of the subdivision. System ergonomics is built on the approach of the man-machine system and represents a classification, based on the external situation, that is independent of the degree of practice of the person. It furthermore facilitates a clear classification of the characteristic properties of the situation (see also Billows, 1993).

Table 7 System ergonomics classification to model cognitive load

System ergonomics subdivision	***Configuration***	***Descriptions***
Task contents		
Operating Type	Simultaneous	Simultaneous activation of several operating elements is required
	Sequential	Activation must be done in a specific sequence
Dimensionality	Multi-dimensional	The technical system specify several alterable degrees of freedom (or parameters)
	One-dimensional	The technical system specifies only one alterable degree of freedom (or parameters)
Control Type	Dynamic	The task goal is continually changed within a narrow time frame (for example, tracking task).
	Static	The task goal is unchanged in terms of time
Task Layout		
Type of Presentation	Compensation task	The difference between task assignment and task accomplishment is presented. The individual can only recognize the deviations.
	Follow-up task	The individual must himself or herself recognize the difference between task assignment and task accomplishment.
Type of Task	Monitive	The individual performs a supervisory activity, absorbs information only to decide as to the system state.
	Active	The individual participates actively in process monitoring in that he or she constantly absorbs, interrelates, and processes information.
Compatibility		
Compatibility	Internal	Connection or obviousness between information items on the input side of the individual and the individuals internal ideas.
	External	Connection of information items on the input side of the individual among each other (reality, displays, operating elements)
Feedback		
Feedback		The individual gets information in some way about the execution of action (sense of touch, displays, or noises, etc.)

The above considerations can be used to propose the following procedure for the purpose of acquiring cognitive errors within the behaviorism approach of the man-machine system as a whole; this procedure makes it possible to obtain initial information about procedures of information processing that will constitute the basis of human error behavior.

1. Description of a human error in the behaviorism approach of the man-machine system according to the echeloned procedure illustrated in Figure 8.

2. System ergonomics classification of the description in the man-machine system for the sorting of cognitive load.

3. Classification of description in man-machine system with the cognitive cope factors of processing, information, and goal reduction.

1.4.4 Further procedure

This chapter represents approaches to describe human error. A theoretical approach to the analysis of human errors was developed from a consideration of the various error models. As a result, it was possible to work out theoretical foundations as to how human errors should be investigated. In order also to consider the practical requirements, we will, in the following chapter, investigate methods for the qualitative and quantitative evaluation of human reliability and methods for the acquisition of operating experience.

2 Process for assessing Human Reliability

In this chapter, we will assemble the practical requirements that must be met by a process to acquire human errors based on operating experience. These requirements will be used for the evaluation of the theoretical approach worked out in the preceding chapter.

In addition to theoretical questions regarding human error, as shown in the last chapter, we always face the problem - particularly in actual practice in industrial establishments with a hazard potential - of evaluating this potential of possible error in order to obtain statements as to (1) how high the overall risk of damage within a technical system is, (2) what scope the human error assumes, for example, in relation to technical errors, or what technical or human factor has the highest significance, and (3) what the possibilities are to reduce the risk. The central concept in judging a technical system here is the risk. It is defined as follows (among others, Hauptmanns et al., 1987):

$$\text{Risk} = \text{Anticipated damage frequency} * \text{Anticipated damage scope} \qquad (1)$$

The scope of damages given here in any scale that quantifies the consequences as regards persons and the environment (for example, lethal does, contaminated surface or space, monetary units). The concept of risk cannot be separated from the concepts of safety, reliability, and availability (or productivity). The concept of safety relates to the scope of damage; the concepts of reliability and availability relate to the frequency of damage. There are two general ways to proceed in judging the risk of technical systems: prospective judgement and retrospective judgement.

Prospective judgement performs an evaluation on the basis of potential errors in the technical system. Prospective judgement can also be described as a deductive method. It can be performed either deterministically or probabilistically. In the case of deterministic judgement, one analyzes qualitatively as to which failures are possible and whether there are any possibilities to bring the trouble under control (see, for example, HAZOP Method described in Bartels et al., 1990). In probabilistic judgement, one must additionally consider the probability that a system might fail. A recognized method of probabilistic judgement is the probabilistic safety analysis that is supplemented, for the judgement of human reliability, by human reliability analysis (see DRS-B, 1990). Probabilistic Prospective methods require data on the likelihood of failure of failure and are thus more data-intensive than deterministic methods.

Retrospective judgement makes an evaluation based on actual events. The judgement here is performed either purely qualitatively or quantitatively, with simple frequency analysis methods. Typical sources of retrospective judgement are events that actually occurred in operating experience or investigations on simulators. Retrospective judgement involves inductive methods. They seek to find the possible causes and improve on possibilities for the observed cases in the light of available operating experience.

In retrospective methods, specific situational information items are collected and tightly outlined statements are obtained about the materialization of an event. To make sure that this method can also supply data for prospective probabilistic methods, it must be possible to combine the various specific situational information items. The goal of this study can thus also be restated in the form of the following question: How must a retrospective method be fashioned so that it will facilitate both a specific analysis of the situational data of an event and supply data for probabilistic prospective methods? To answer this question, we will, in the following chapters, investigate the various methods of prospective and retrospective judgement of human errors in an effort to find out what the requirements are regarding the assessment of human errors.

2.1 Assessment of Human Reliability in Probabilistic Safety Analyses (PSA)

An essential task of PSA is to describe significant contributions of risk and possible remedies in quantitative terms. As PSA studies show in the area of power plants, the individual plays a by no means minor role with regard to the risks involved in the technical system. Using some manual measures in the German Risk Study for Nuclear Power Plants, which are to be evaluated, we find the operator measures are involved in the result of the reliability analysis up to 70% (DRS-B, 1990). Whether a quantitative judgement of the human influence is at all necessary is something that is often disputed rather in a controversial setting because human performance capacity can be recorded in numbers only to a limited degree.

The fact that quantitative data for error judgements are available by means of a probabilistic safety analysis also become significant for purely qualitative questions when decisions must be made between various safety precautions or measures within a big industrial setting. The quantification of significant risk contributions thus turns into approaches to optimization measures that must be worked on urgently from the safety angle. Thus, PSA also represents an instrument of qualitatively improving a technical setting in the most effective manner possible. This applies particularly for the case where precautions in the area of personnel must be weighed against automation measures or other technical precautions. This is furthermore always necessary when one must compare the risks inherent in various technical systems (for example, comparing Eastern European Power Plants to Western European Power Plants). The quantitative assessment can also express the contributions of the individual to the risk inherent in a technical system.

2.1.1 Method Used in PSA

The procedure employed in a PSA consists of various steps involving the formalized description of the technical system and the intervention of the individual. The differing description stages represent the basic instruction for describing the risk inherent in the technical system. The following steps for description stages that are built upon each other can be distinguished from the angle of human reliability:

• Definition of triggering event	(IE - Initiating Event)
• Preparation of Event Sequences	(OET - Operation Event Tree)
• Preparation of Error Tree	(OET - Operation Error Tree)
• Determination of Error Probabilities for human actions with the help of a Human Reliability Analysis Method [HRA]	(HEP - Human Error Probabilities)

In the following, we will briefly describe how the risk inherent in a technical system is calculated as a part of the steps.

- **Definition of Initiating Event**

In the first step, we define an initiating event and we determine the frequency per year with which this event is to be anticipated (for example, anticipated frequency of a steam generator tube rupture in a pressurized water reactor, per year).

- **Preparation of Event Sequences**

In the following step, we run through possible trouble in the form of courses of events. These event sequences are built up systematically in that one first of all asks about a possible failure of a system („What would happen if?“), followed by the question as to possible remedial action possibilities to bring the trouble under control („What is possible then?“). Figure 10 illustrates a typical event sequence.

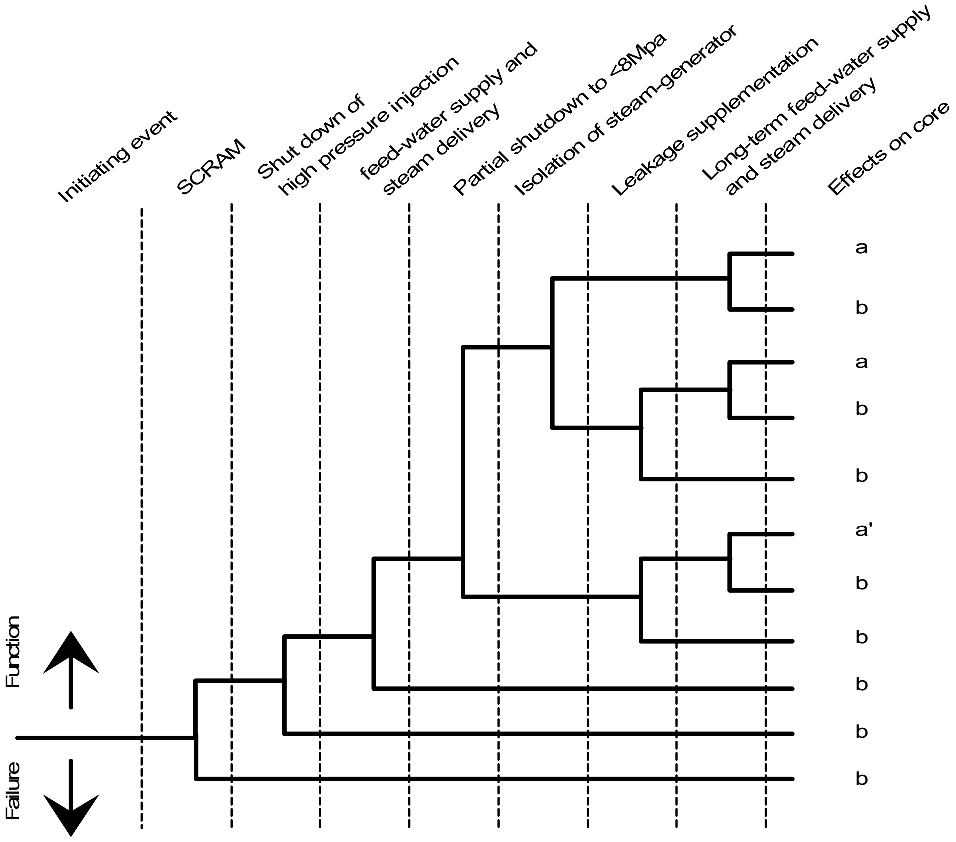

Figure 10 Event sequence diagram for a steam generator tube rupture (according to DRS-B, 1990)

The figure shows the course of a steam generator tube rupture in a pressurized water reactor. On the left side, we have the assumed initiating event. If it materializes, than it can be put under control by certain system functions. The system functions as such are available with a certain probability p (function) and can fail with a probability of q=1 (failure). Overall, we then get the expected frequency of a sequence within the run by means of the product of the expected frequency of the initiating event and the probability of the availability or failure of system functions that are required to bring the situation under control. At the end of the event sequence, we can identify various glasses of system states, for example, (a) trouble under control, (a^1) trouble controlled with damage to systems or (b) trouble cannot be brought under control with core melt.

- **Preparing Error Trees**

To consider the complex interrelationships of technical systems that backup the system functions, in the probabilistic safety analysis we construct an error tree for each system function and this tree is used to calculate the availability of the system function. If, for example, one assumes that the „leakage supplementation“ system function is ensured by turning on a pump X, than this situation can be illustrated by an error tree of pump X. The error tree then contains all details that can contribute to the availability or failure of pump X (Figure 11).

In the error tree, we first of all define the System Function as so-called Top Event. Starting with the Top Event, the partial functions, that can contribute to faulty behavior of the System Function, can be tied in with the Top Event by means of logical interconnections (AND, OR). When two Sub-functions are redundant with respect to each other, they are AND-tied up (for example, if the feed function is not insured, when the automatic unit does not start the pump, and the operator, as a redundant factor for the automatic unit, when the pump does not start). If both sub-functions are equally necessary to perform the function, then they are OR-tied up (for example, the automatic unit can fail because it did not get an order to start or because it, itself, is in trouble). Complex error trees may again be necessary to model each sub-function. This continues until such time as the possibilities of failure have been modeled with sufficient detail. So-called Basic Events (rounded boxes in the figure) are given at the lowest level of an error tree. The Basic Events cuts that will suffice to cause the system function to fail (which, in other words, in the error tree would cause a failure of the Top Event) are referred to as (minimal cuts).

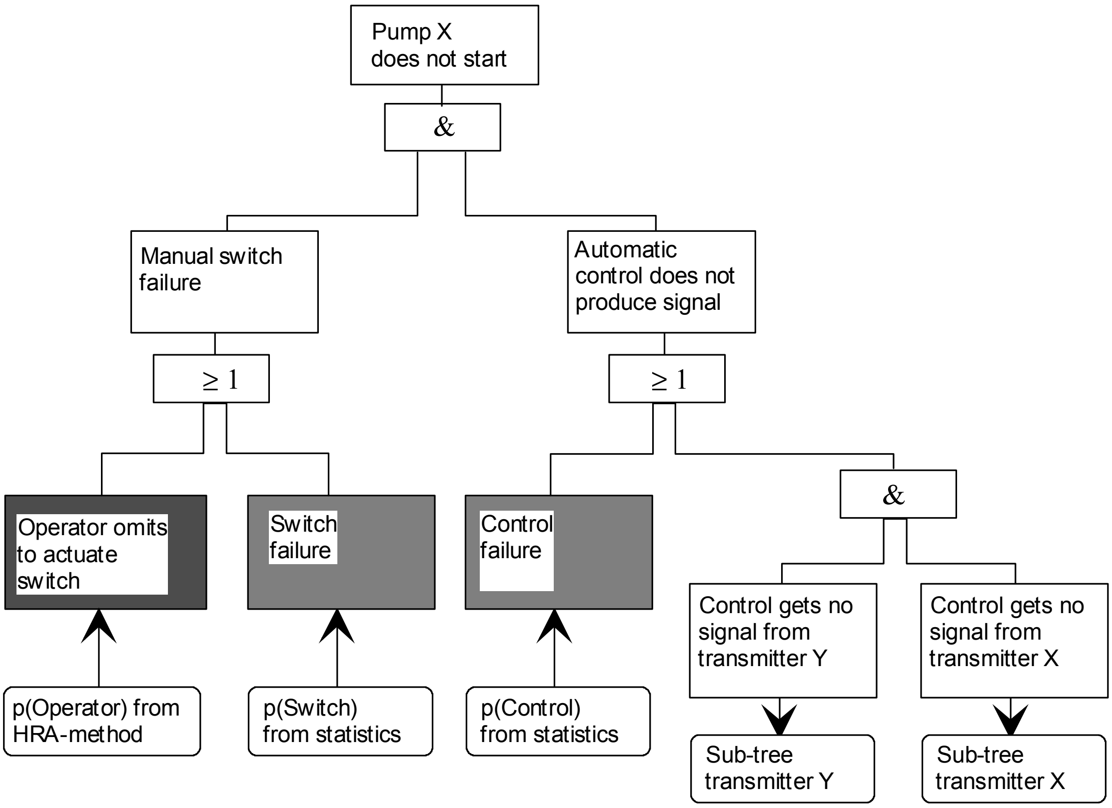

Figure 11 Simple hypothetical Error Tree with human and technical Basic Events („≥1“ corresponding to OR, „&“ corresponding to AND)

With the help of this method, one can build up a logic tree of all factors that can lead to the error in the system function. The probability of the failure of the system function is determined within the error tree in keeping with the rules of probability calculation. One proceeds as follows in a heavily simplified manner: when two events are OR-tied, then the probabilities are added up; when they are AND-tied, they are multiplied.

In contrast to the illustration of an event sequence, in which paths are given for success and failure, the individual junctions in error trees are tied to logic samples. The formal content of both approaches, however, is the same; both can be converted into each other. Depending on the nature and complexity and of the error sequence to be investigated, it is either comprehensive to use event sequence diagrams with small error trees or, instead, small event sequence diagrams with comprehensive error trees.

The Error Trees represent the step during which technical and human errors flow together to come up with the total result of probabilistic safety analysis. For further clarification, the basic technical events in Figure 11 are hachured singly and human basic events are hachured doubly. The failure probability of the component is given to calculate the reliability of a technical basic event. To determine the failure probability of a basic event with an operator action, we need error probabilities for this action.

- **Determination of Error Probabilities for Human Actions**

To blend human actions into a probabilistic safety analysis, we need to indicate the probabilities of a human error on the level of the basic events. The probabilities are designated as HEP and are defined as follows (see Bubb, 1992):

$$HEP_i = \frac{\text{Number of erroneously performed tasks of Type } i}{\text{Number of all tasks of Type } i} \tag{2}$$

These error probabilities are determined in that certain HEP methods are used within a standardized procedure.

2.1.2 Procedure in Human Reliability Analysis [HRA]

To get error probabilities (Human Error Probability [HEP]) about human actions, we must take two steps in judging human reliability: in the first step, we gather the qualitative data about the situation to be judged. In the second step, we quantitatively evaluate the situation with the help of an HRA. For this judgement procedure, the International Atomic Energy Agency [IAEA] proposed a method that is called the Systematic Human Action Reliability Procedure [SHARP]; it determines how one is to proceed in a probabilistic safety analysis in acquiring and evaluating human reliability (IAEA-499, 1987; Hannaman & Spurgin, 1984b).

The SHARP was developed by Hannaman and Spurgin (1984b). It offers the possibility of tying human reliability into a Probabilistic Safety Analysis [PSA] and it also makes it possible to systematize and standardize the procedure of data collection for a HEP. It is a procedural instruction for a systematic task analysis and consideration of influencing factors (Performance Shaping Factors [PSF]) and it is not to be confused with the HRA Method that can be used within the SHARP in order to get HEP data. The SHARP subdivides the process of blending into the 7 stages according to Figure 12.

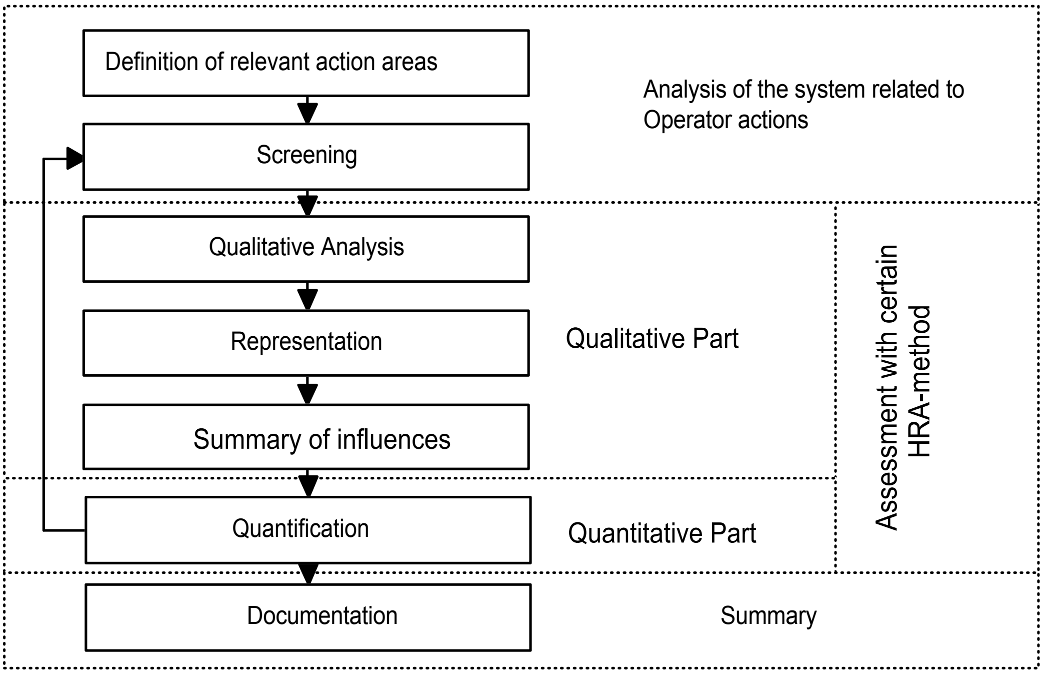

Figure 12 Analysis steps in SHARP

If it turns out, after quantification, that additional manual measures are significant for the result of the PSA, then one must perform a renewed evaluation, starting with screening. The procedure is continued in an iterative manner until no further operator actions are to be evaluated.

In the following we will briefly describe the various steps of SHARP with a view to the essential information items that are required here.

- **Definition of Relevant Action Types**

This step is used to identify those human actions for which a HRA is required. Here, we distinguish among five different types of human actions (Types 1-5). These five types can be subdivided into three action Types (A, B, C) according to IAEA-50 (1992) or IAEA-538 (1990).

- Action Type A/Type 1 - Personal actions during proper operation of system: this type comprises all actions by power plant personnel that took place prior to the occurrence of trouble but that led to so-called latent errors in the technical system (for example, wrong valve positions after maintenance of a fitting).

- Action Type B/Type 2 - Personal actions that led to an initiating event: this type combines all actions of personnel that directly led to trouble in routine operations, so-called active errors (for example, primary circuit leakage as result of improper operation).

- Action Type C - Personal actions after trouble has occurred: Type C includes all actions of personnel that were undertaken after trouble has developed in order to cope with the trouble (for example, turning the emergency cooling system on). Recovery actions are particularly important within this action Type. From this viewpoint, action Type C can be further subdivided into types 3 to 5:

Type 3:	Personal actions that are to be performed on the basis of fixed rules and that have favorable effects on the continuation of the incident.
Type 4:	Personal actions that influence the course of trouble unfavorably.
Type 5:	Personal actions that are to be performed on the basis of available knowledge and that, in case of correct diagnosis and perfect execution, have favorable effects on bringing the trouble under control.

At this point we might note that the subdivision of action Type C in the literature on the subject is partly handled in a mixed manner. IAEA-50 (1992) for example lists only erroneous executions of planned personnel actions under type C4. In Hirschberg (1990), on the other hand, type C4 covers all erroneously performed personal actions. A comparison of these different classification possibilities on a whole makes it obvious to conclude that a breakdown according to Table 8 would meaningfully summarize all possibilities in that type C4 is once again subdivided as to whether an action is planned or unplanned.

Human actions from Type 1, as a rule, are contained in the failure rates of the technical components and are directly included in the determination of the failure probability of a technical component, in other words, from the viewpoint of human reliability, they are indirectly contained in the error probability of a basic technical event. Human actions from Type B as a rule are contained in the frequencies of the initiating events.

Table 8 Subdivision of action Type C

Bases of action ***Effects on the development of trouble***	***Planned***	***Unplanned***
Favorable	Type C3	Type C5
Unfavorable	Type C4	Type C6

In some cases, it may be that human actions in Type A are not contained in the failure probabilities of the technical components, or that human actions from Type B are not contained in the frequencies of the initiating events. Typically, this is the case when the failure probability of a basic event was determined with the help of a material test or if the frequency of an initiating event was determined by an error tree. In these cases, one must perform HRA Investigations also for these two action types, as described below or action Type C. For human actions in Type C, we need the following steps of the SHARP to determine the probabilities of a human error.

- **Screening of Action Types**

Not all actions taken by personnel are equally important in terms of the safety of a technical system; therefore, the relevant actions must be filtered out by means of a so-called screening. In order to identify those actions that lead to significant contributions in case of a particular trouble considered, one first of all, during the first phase of screening (qualitative judgement), determines those actions that could cause an impairment of system availability and that accordingly must be considered in the error tree. In the second phase of rough quantitative estimation (quantitative course), these actions are then provided with pessimistic error probabilities (for example, 0.5 or 1) and a first screening calculation of the probabilistic safety analysis is performed. In a subsequent third phase, we make a fine estimate (quantitative fine course). Here, we identify those actions that, during the continuation of HRA, are contemplated in greater detail, in that we determine their contribution to system availability from the screening calculation. Whether the human action is part of a minimum cut of a system availability or whether it is categorized as significant in an importance calculation are measures for this amount. The phases of screening require data on human actions in different degrees of resolution, which are called Rough Analysis, Detail Analysis, and Sensitivity Analysis.

By means of these first two steps of the SHARP (Definition and Screening), we have now determined those human actions that must be investigated and quantified with the help of an HRA Procedure. For this quantification, we have available a series of HRA Methods that will be presented in the next section. The following steps of the SHARP are closely tied to the selected HRA Method; therefore, these steps will be described here only in general terms.

- **Qualitative Analysis**

A task analysis is first of all performed for purposes of qualitative analysis. The type and degree of detail of the task analysis here depends primarily on the selected HRA Method. The degree of detail in the task analysis also depends on the degree of analysis or on the degree of detail of the error tree of a PSA, because the tree already represents a task analysis that is already oriented by the technical system.

- **Representation**

After we have identified relevant actions, that is, actions that are important in the failure of a system, by means of screening, and after we have performed a task analysis for these actions in another step, we represent the results of the task analysis in a formal approach prescribed by the selected HRA Method in order to determine the error probabilities. The THERP method here calls for, for instance, an HRA event tree (Human Error Event Tree). The Human Cognitive Reliability Model [HCR] performs a representation in a so-called time reliability curve. Both methods will be explained in greater detail in the next section.

- **Summary of Influences**

According to the selected HRA Method, one must combine shaping factors that modify the error probability and they must be tied into the formalism of representation.

- **Quantification**

According to the selected HRA Method, we now determine quantitative statements in the form of error probabilities (HEP) about the investigated human action.

- **Documentation**

In conclusion, the procedural steps connected with judgement are documented for purposes of testing and replicability.

2.2 Method for Evaluating Human Reliability

Different HRA Methods can be used within the SHARP to determine an error probability for a basic event. These methods will be described briefly below. In conclusion, the HRA Methods are discussed with a view to determining which requirements those methods established in terms of a systematic analysis of events with a view to aspects of human reliability.

2.2.1 Human Reliability Analysis Methods

The literature on the subject documents a wealth of HRA Methods that can be used for the quantification of human actions. Summaries can be found among others in Swain (1989), Berg and Schott (1992), Reason (1990). An overview of more recent methods, moreover, can be found in Reer (1995) or Gerdes (1993). Further details regarding the information needs of different HRA Methods can also be found in IAEA-538 (1990). All methods require data for the evaluation of human actions. The concept of „data“ here includes both qualitative data on error conditions and shaping factors as well as so-called reliability parameters (HEP - Human Error Probabilities) for purposes of quantification. Not all methods are equally significant; therefore, in this section, to determine the requirements for an event analysis, we will present only five essential HRA Methods:[3]

THERP	(Technique for Human Error Rate Prediction)
ASEP	(Accident Sequence Evaluation Program)
HCR	(Human Cognitive Reliability Model)
PHRA	(Probabilistic Human Reliability Analysis)
SLIM	(Success Likelihood Index Method)

There are two reasons to back up this selection: (1) An investigation by Werner et al. (1992), showed that, in most PSA investigations worldwide, looking at the wealth of existing methods, it was primarily the THERP Method (with Accident Sequence Evaluation Program), Human Cognitive Reliability, Probabilistic Human Reliability Analysis, and Success Likelihood Index Method that were used. (2) This selection represents a representative cross-section as to which sources are typically used in HRA procedures for data concerning human reliability. Generally, there are four sources on which the data in HRA procedures can be based: estimates by experts, simulator studies, experiments, as well as operational experience. In the SLIM, the data on human reliability are based on the estimates of experts; in the HCR and in the PHRA, the data are based on simulator studies; in the technique for THERP (with ASEP), according to Swain (1992), they are based mainly on - though only personal evaluated - operational experience and experiments.

- **THERP - Technique for Human Error Rate Prediction**

THERP (Technique for Human Error Rate Prediction) is the most widespread method for judging personal actions (Swain & Guttmann, 1983). The method is described here somewhat more precisely because, in Chapter 5, we have a comparison of the data of this method with the data concerning human reliability that were obtained from operational experience.

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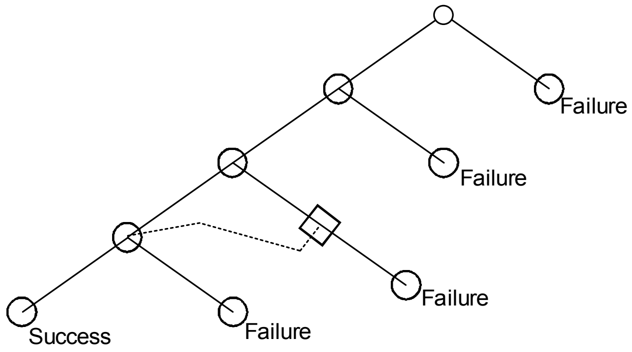
[3] Note that this work was accomplished in 1996. Newer developments like the ones now being established in the OECD-PWG5 Task 97-2 or the MOSAIC-Group are not included in this study. See for these developments the literature mentioned in the preface to this study and listed on page 276.

In this method, the individual is considered as system component and is treated in a manner similar to the technical components. In order to take into account here the greater variability of human behavior, as compared to technical components, we need a detailed task analysis to judge human reliability. This analysis is broken down into the following steps:

1. Determination of system functions which require personal actions.
2. Task analysis concerning human actions which can impair system functions.
3. Estimation of probabilities of human error in these actions.
4. Identification of weak points and derivation of recommendations for improvements to reduce the error probabilities in a new evaluation.

Within THERP, the so-called HRA action tree represents the procedure used in estimating probabilities. Reichart (1992) referred to it also as Probability Tree Diagram [PTD]. Figure 13 shows a HRA Action Tree according to Swain and Guttmann (1983). The HRA Action Tree represents a combination of necessary subtasks of personnel which were determined by means of a task analysis. In order to be able to give error probabilities (marked with capital letters in the Figure) and success probabilities (marked with lower case letters in the figure) for sub-tasks, we must, in addition to the activity (for example, „recognition of a message“ or „switching a pump“) also know the essential Performance Shaping Factors [PSF] that pertain to these actions. To determine them, considering the shaping factors already illustrated in Chapter 1 (Table 5), we perform a site inspection during which the PSF that are significant for the sub-tasks are investigated.

The THERP provides voluminous tables for the subsequent determination of the error probabilities of a sub-action. This table compendium is given in Appendix 5. According to specific instructions, we look for entries within the table compendium that correspond to the sub-action to be evaluated (see Appendix 5). This value is then taken over into the HRA Action Tree to determine the probability of a human error. In some cases, we must calculate the way a subtask is influenced by PSF also with the help of correction factors pertaining to the error probabilities (for example, in the stress model).



$$P_{Total\text{-}Failure} = A +(a*B) +(a*b*C*D) +(a*b*C*d*E) +(a*b*c*E)$$

Actions	*HEP-Probabiities from Tables*
A/a: control-room operator omits to order the following tasks	A=0.01 (0.005-0.05)
B/b: Shift-personal omits the check of switch MU-13	B=0.01 (0.005-0.05)
C/c: Shift-personal omits the check or opening of pressurizer valves	C=0.01 (0.005-0.05)
D/d: Recovery by Shift-suvervisor	D=0.09 (0.009-0.9)
E/e: Shift personal omits to lock pressurizer compartments	E=0.01 (0.005-0.05)

Figure 13 Action Tree and Error Probabilities according to Swain & Guttmann (1983)

Finally, the HRA Action Tree is systematically examined for the possibility of so-called recovery factors and conditions of dependence between sub-tasks (in the figure, this would be junction D). Recovery factors are possibilities of correcting a mistake that has been made (for example, the possibility that the shift leader might discover and correct an error made by an operator). Sub-tasks are subject to certain degrees of dependence when the success or failure of a previously performed sub-task directly influences the next following sub-task (for example, there is complete dependence between operator and shift leader when both together are busy solving a problem). The dependencies are graduated in a 5-stage scale, extending from independent up to fully dependent and are accounted for with the error of probabilities by means of correction formulas. Information is required on the following areas to carry out the THERP Method:

- Detailed description of task,
- Parameters of man-machine interface (for example, displays, operating elements),
- Description of shaping factors: Stress, Work station design, Ergonomic design of work equipment, Requirement for written or verbal procedures, Equipment and experience of personnel, Organizational factors (for example, management and administration),
- The time of available for diagnosis,

- Factors used in successful task accomplishment (including recovery factors),
- Dependencies of the various tasks.

The THERP was and is being used in many PSA studies. The procedure was used intensively in Germany and the United States for PSA likewise; its advantages and disadvantages therefore have already been discussed in many places (Swain, 1989; Reichart, 1985; Reer & Mertens, 1993; Hollnagel, 1992; DRS-B, 1990; Fujita, 1992). Although the THERP procedure performs a detailed task analysis and evaluation, the main criticisms that have been leveled against the method note that it is not sufficiently close to reality. The reason for this criticism resides in the methodological procedure of the method and in the evaluation of underlying data about human reliability.

Concerning the methodological procedure as such, there is, furthermore, the problem that not enough aid is offered for a definition of the task parts and the task breakdown. Sub-tasks again can contain other sub-tasks so that we run into the problem of „explosion of the HRA Action Tree“ (see Reer & Mertens, 1993). One must furthermore model human error in the HRA Action Trees just as the failure of a technical component, something that represents an inadequate simplification of human variability and complexity (see Heslinga & Arnold, 1993). This simplification, among other things, is indicated in that one can only model dependencies between two successive sub-tasks (see Berg & Schott, 1992).

Concerning quantification, the advantage of the procedure - performing a detailed investigation of the task - turns out to be a disadvantage: the data material available for THERP does not meet the information need that is actually demanded in a HRA investigation. To some extent, the data material, which is supplied through THERP, is not realistic in terms of the situation that must be evaluated in an HRA Investigation so that leeway in interpretation lead to uncertainties in evaluation. Also, the data partly come from differing technical areas so that they cannot be directly applied to the technical system that is to be evaluated or they are based on estimates by experts. These uncertainties can currently be smoothed out only by high uncertainty factors (see Reer & Mertens, 1993; DRS-B, 1990; Berg & Schott, 1992; Reichart, 1992).

A typical example of this inadequacy of data is the time dependence of error probability of a human action. Time dependence is considered in THERP as a direct parameter only in the so-called diagnosis model. In all other cases, time dependence is modeled only by adaptation of the stress level (Reichart, 1992; Hollnagel, 1992). THERP, furthermore, performs a logarithmic standard distribution of human errors. However, the validity of this assumption - that was made by Swain & Guttmann (1983) on the basis of plausibility considerations - has not been confirmed thus far (see also Reer, 1988).

- **ASEP - Accident Sequence Evaluation Program**

The ASEP method is an abbreviated and slightly modified version of THERP (Swain, 1987). It can be performed very much faster than THERP but it is more conservative (more pessimistic). The method is used for making a rough estimate of error probabilities inherent in personal actions. The method is subdivided into the following steps:

1. Screening: Rough task analysis and evaluation of activities prior to materialization of trouble. In the task analysis, among other things, one distinguishes as to whether an activity is to be performed on site or in the control stand, and whether written aids are available.

2. Nominal analysis: Determination of available time and evaluation of error probability according to a time-reliability model for activities after the trouble has materialized. The time-reliability model here establishes a direct relationship between the time available to accomplish the activity, on the one hand, and an error probability, on the other hand.

3. Dependence analysis: Determination of dependencies between various task parts are similar to those found in THERP.

4. Recovery Analysis: Determination of possible measures to correct errors, similar to those used in the THERP Method.

For this purpose, the accident sequence evaluation program needs the following information about the tasks that are required before and after initiating event.

For actions prior to the initiating event (Action Types A and B):

- Rough description of task, along the lines of information concerning the technical system
- Description of the type of error to be evaluated
- Written procedures
- Possible recovery factors
- Dependence of individual tasks

For tasks after initiating event developed (Action Type C):

- The time available to make a correct diagnosis and to perform those actions that are necessary to return the system to a safer state (T_m)
- The time needed for performing the actions correctly (T_a)
- The time window for accomplishing the task ($T_d = T_m - T_a$)

The ASEP diffuses the problem of the THERP Procedure that would necessitate a detailed task analysis and to supply data of adequately accurate quality. This is why the ASEP can be carried out very much faster than THERP. Of course, this advantage is obtained at the detriment of the accuracy of the statement obtained. The ASEP provides very pessimistic data on the reliability of human actions and accordingly would primarily be a screening method that can be used prior to the THERP procedure in order to further reduce the number of actions to be evaluated with the help of THERP. This is suggested by Swain (1989).

- **HCR - Human Cognitive Reliability Model**

Experimental error research was able to demonstrate that error rates vary with the available time and the experience of the person (see Wickens, 1984). The error rate drops along with the available time and also with the number of practice runs of a person for a certain task. This is also known in psychological literature as „Fitts' Law“ (Fitts, 1954). Because of the opposing effects of these magnitudes (error rate as compared to available time or practice runs), this relationship is also called the Speed-Accuracy Trade-Off. This relationship was picked up by Hannaman and Spurgin (1984a) in the Human Cognitive Reliability Model (HCR).

The HCR Model is a method for determining probabilities for human errors after trouble has occurred in that the available time window is considered. In a time-reliability curve, furthermore, the probability of an erroneous action is considered to be a function of a „normalized time period“. The „normalized time“ here represents the ration between the total available time and the time required to perform the correct action. The probabilities of an error in a given normalized time were determined from simulator experiments with operating personnel. The determined probabilities, furthermore, can be modified by the indication of practice levels and PSF in that the time needed to accomplish the task is stretched out artificially when the experience of the personnel is at a low level, when the stress level is high, or when the ergonomic quality of the man-machine interface or the procedures is inadequate.

Furthermore, different curves indicate the three practice levels in terms of skill-based, rule-based, and knowledge-based (see the error model of Rasmussen concerning the definition and discussion of the practice levels in Chapter 1). Using the indication of practice levels, one can employ the HCR Model to judge cognitive tasks in that the behavior on the skill-based level is given a low error rate, while behavior on the rule-based level is assigned a medium error rate, whereas behavior on the knowledge-based level is assigned a high error rate.

The procedure accordingly calls for information about the following sub-areas to determine HEPs:

- The available time and the time needed by personnel to accomplish a task.
- The cognitive stress on personnel, broken down into skill-based, rule-based, and knowledge-based.
- The experience of the personnel, the stress level and the ergonomic quality of the man-machine interface or the procedures.

The main point of criticism leveled at the method certainly is this: the dependencies of the error probabilities of available and needed time are illustrated inadequately (Reer &

Mertens, 1993). The normalized time only reproduces relationships between the available time and the needed time. The absolute level of the time reserved (for example, hours, minutes, or seconds) is not taken into consideration. The error probability of a task that lasts one second and for which two seconds are available, according to the HCR Model is identical to the error probability of a task that lasts 100 minutes and for which 200 minutes are available. Bands of uncertainty, that consider the absolute time reserve, are not specified in the distributions. This point of criticism is further reinforced by the fact that even the differing distributions of skill-based, rule-based, and knowledge-based behavior forms are carried out on the basis of a normalized time (see Fujita, 1992).

The discussion of the model of Rasmussen in Chapter 1 already made clear that, furthermore, the assumption - of subdividing cognitive processes of the individual during trouble control are to be subdivided via a breakdown into skill-based, rule-based, and knowledge-based behavior - is problematical. The mechanism of attention allocation, described in Chapter 1, implies that the process of task accomplishment takes place not only on one behavior level and that the levels should rather be viewed as a continuum.

A third essential weak point of the procedure is represented by the fact that the modeling of the situation is rough since it involves only three different PSF with a maximum of 5 different configurations (Swain, 1989, page 7-7). The underlying situation thus is not given commensurate consideration if one keeps in mind, for example, how complex action courses can be over a span of one hour (see Fujita, 1992).

In spite of the serious weak points of the HCR Model procedure, the method is often used for evaluating complex situations because the method does offer the definite advantage of quickly arriving at error probabilities on the basis of just a few parameters and being able to consider cognitive errors (for example, in diagnosis situations).

- **PHRA - Probabilistic Human Reliability Analysis**

It was intensively promoted and developed by the EDF (French Electric Power Company) on the basis of the advantages inherent in the HCR Model Procedure. In promoting the further development of the HCR Model Procedure, the EDF pursued the goal of eliminating the main points of criticism leveled against the HCR Model Procedure, the uncommensurateness for specific situations, and the problem of the normalized time (see also Worledge et al., 1988). The process, developed by the EDF, will hereinafter be referred to as PHRA (see Mosneron-Dupin et al., 1990). The PHRA Procedure was developed in France for the purpose of developing human actions in the EPS 900 Study and the EPS 1300 Study that built on the former. For further information see for example Wurst (1993) or Reer (1995).

As part of the procedure, a distinction is made between routine operation and operation after initiating event. Four classes of situations were differentiated for routine operation: alarms, tests, administrative checks, and periodic tests. Error probabilities are calculated for these classes with the help of simple evaluation instructions. Next, 200 simulator experiments were performed to evaluation the reliability of human actions after trouble has materialized. Various time-reliability curves for varying the complex trouble situations were determined from the experiments. In making the evaluation, error probabilities are determined from the time-reliability curves. But no normalized time is used for evaluation and the modification of the situation to be judged is accomplished not on the basis of the behavior levels mentioned by Rasmussen but rather with the help of certain situation types that were pre-determined in the experiment. Figure 14, according to Mosneron-Dupin (1994), shows the results of the experiments.

In the figure, P1 and P1' represent curves for simple diagnosis tasks involved in typical trouble cases; P3 indicates difficult diagnosis tasks with contradictory information; and P2 is a mixed form of both conditions.

In keeping with the similarity to the HCR Procedure, the PHRA requires the following information:

- The time for diagnosis (it is equal to the available time minus the time needed by personnel to remedy the trouble);
- Description of the complexity of the situation to be able to identify the corresponding curve from the time-reliability model.

A point of criticism on the PHRA Method that is frequently mentioned argues that the underlying data for the experiments and thus the method of data procurement are not generally accessible. Furthermore, it is difficult to use the data for other situations than those that constitute the basis of the curves and this must be judged by subjective estimate. At this time we also do not know whether these diagnosis curves can be transposed to German conditions.

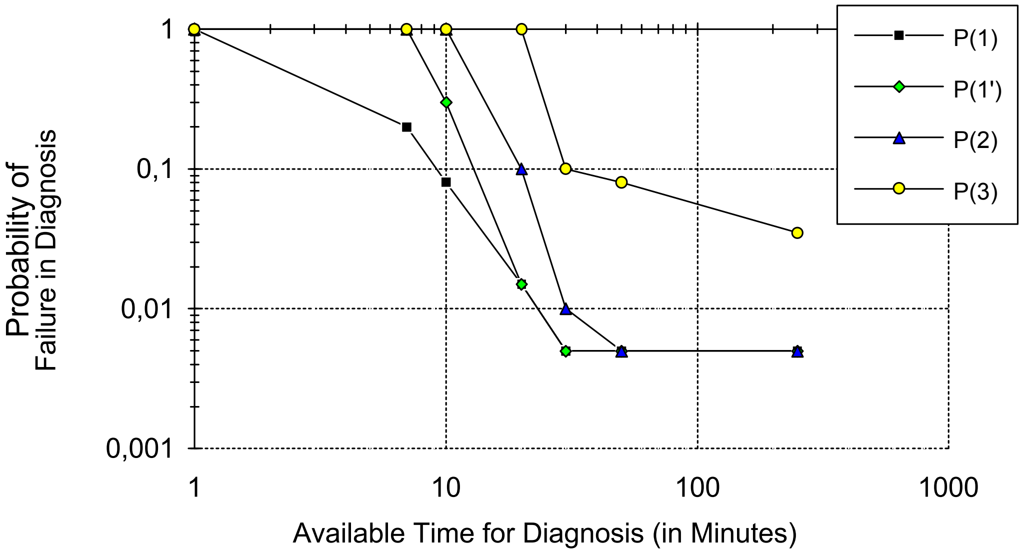


Figure 14 Time-reliability curves from the simulator experiments conducted by EDF

- **SLIM - Success Likelihood Index Method**

The SLIM Procedure determines error probabilities on the basis of estimates by experts (Edwards et al., 1977). In this method, the experts must estimate the reliability of human actions on the basis of a number of factors (PSF). With the help of estimates by experts, the SLIM seeks to get around the problem represented by the fact that data on human error behavior are often unavailable or do not adequately fit in with the situation that is to be evaluated. On the other hand, this introduces inaccuracies in the data as a result of the process of estimation which depend considerably on the experts who perform these estimations.

In SLIM, an action complex is first of all broken down into individual tasks. Then the PSF - that can influence the successful accomplishments of the tasks - are graded by experts according to their importance to the action complex. Here, one must distinguish between the factors that influence training, procedures, feedback, risk perception, and time pressure. An index (SLI - Success Likelihood Index) is then determined with the help of the estimates made by the experts. The SLI represents an orderly sequence of individual tasks with a view to the reliability of the individual. To be able to transpose this orderly sequence into a probability value for a human error, the SLI of the individual tasks is calibrated by means of two so-called anchor tasks for which one has estimates of experts or known HEP values. A psychological scaling method, building on the „law of comparative judgement“ according to Thurstone (1927) is used for calibration. Embrey et al. (1984), refined the procedure with the name SLIM-MAUD (MAUD for Multi Attribute Utility Decomposition) in order to reduce the inaccuracies in the estimates prepared by the experts.

The following items of information are needed for the SLIM in order to determine probability values based on the estimates of the experts:

- A detailed description of the particular case whose error probability is to be estimated.
- A description of the PSF and the reciprocal interaction of various PSF.
- Graduation of the importance of these PSF with relation to the task to be performed by the operator.
- At least two anchor tasks that can be used to determine the calibration values for the other tasks. The anchor tasks must be similar.

The main point of criticism leveled against the SLIM has to do with the method of data procurement, in other words, estimates prepared by experts. These expert estimate procedures do of course represent the simplest possibility of determining probabilities; but they are always tainted with additional uncertainties in the data because estimates by experts are always subjective. The uncertainties are boosted by virtue of the fact that the qualification of the experts, who are to provide the estimate, is not specified (Swain, 1989; Reichart, 1985). Another factor of uncertainty is the small number of PSF which makes it more difficult for the experts to get an accurate picture of the shaping factors that are at work in the situation to be evaluated (see Swain, 1989). Therefore one can expect only results that offer little consistency (see Berg & Schott, 1992). That is also documented by investigations conducted by Comer et al., (1984). They investigated various estimation methods, including direct numerical estimation (DNE) and paired comparison (PC) for their usability in the determination of probabilities. Overall, it is stated there that expert estimation procedures do of course supply consistent results but, in terms of the accuracy of the derived HEP data, they represent an unsatisfactory solution. Another point of criticism which is also documented by the investigations conducted by Comer, is the calibration of the estimated value with so-called anchor tasks. The SLIM, for instance, prescribes only two anchor tasks so that the HEP values depend heavily on the associated anchor tasks and so that one cannot determine any uncertainties in calibration. Furthermore, the theoretical foundations of scaling by means of anchor tasks are rather questionable (Swain, 1989; Bubb, 1992) and no aids are given for the determination of the error probabilities of the anchor tasks, nor is there any help for the determination of the similarity between the two anchor tasks (see Swain, 1989).

2.2.2 Discussion of HRA Methods

The above section showed what kind of specific information items are needed for various HRA methods or what parameters are employed by the differing HRA procedures in order to get the HEP values. The latter must be supplied by a method for analyzing events, if meaningful information is to be obtained from practical operational experience for PSA.

We will now look at some general procedural aspects involved in methods for assessing human reliability in a PSA in order to figure out what we can expect from an evaluation of actual operating experience for the problems of HRA. For this purpose, we discuss the HRA methods related to various classification possibilities. In overall terms there are the following possibilities of classifying HRA procedures:

1. With regard to the depth of detail into holistic and decompositional methods.
2. Regarding the general procedure on the basis of key parameters for the purpose of evaluation in terms of error related, performance shaping factor related, and time-related methods.
3. With respect to data quality.

- **Depth of Detailing**

With regard to the degree of detailing of their quantitative evaluation, HRA methods can be broken down into decompositional and holistic procedures (see Heslinga & Arnold, 1993; Gerdes. 1993; Zimolong, 1992). Decompositional procedures perform a quantitative evaluation of the reliability of human actions by breaking a situation down into sub-situations all the way to a certain degree of resolution. They evaluate the sub-situations and from that draw conclusions as to the reliability of the overall situation. The THERP method is a typical decompositional procedure. Holistic methods perform a quantitative evaluation of a situation in its totality without breaking the overall situation down. The HCR Method is a typical procedure here.

Regarding the holistic procedures, one must note, particularly in terms of the methodological aspects involved, that they provide only a rough image of the reality prevailing in the system if no task analysis is performed (Fujita, 1992) because a satisfactory image of the real situation in the system (the so-called „face validity") can be obtained only by means of a detailed task analysis (Swain, 1989). This criticism applies particularly to those methods that base their evaluation on time-reliability curves. Basically, this evaluation will include only the times available to personnel. Other aspects (for example, complexity of situation, number of work functions to be performed) are not considered sufficiently.

From the psychological angle, decompositional procedures are reproached for being unsatisfactory when it comes to a quantification of human errors because they model a human error via an HRA Action Tree and thus treat it like a component failure, something that represents a simplified assumption as to the complexity of a human action (see Heslinga & Arnold, 1993).

As for the acquisition of human errors from practical operational experience, we may conclude from this that a method for the acquisition of human errors from events must supply both <u>detailed information</u> for decompositional procedures as well as <u>general information</u> for holistic procedures.

- **General Procedure**

The subdivision based on key parameters classifies the HRA methods according to their basic procedure in the course of evaluation. They can be subdivided into error-related methods (THERP and ASEP), time-related methods (HCR and PHRA) as well as PSF related methods (SLIM) (see Reer, 1995).

Error-related and time-related methods are guided by specifications that are preset by the system. These preset specifications must be considered in any acquisition of human errors arising from practical operational experience. Here one must in particular investigate the distribution assumptions underlying the methods (standard logarithmic distribution and logarithmic-linear time reliability curve). As for methods related to PSF, that are currently being further developed in various directions (for example, HEART by Williams, 1986 or INTENT by Gertman et al., 1992) it must be remarked that the quantity and structuring of PSF is by no means determined methodologically and depends heavily on the expert who is supposed to judge the situation (see Embrey et al., 1984). This way of proceeding is accordingly inadequate until such time as a method has been found for structuring PSF. Furthermore, at this point we do not know the magnitude of the effect of individual PSF, nor can we make any statements about the reciprocal interactions of different PSF (see Hollnagel, 1992); this means that the HEP values that are generated in these methods as a result of estimates by experts cannot be checked out.

Looking at this point of criticism, one can certainly see a strong point in a systematic analysis of actual operational experience. When the identification of PSF is determined by a methodological procedure, then practical operational experience is in a position to determine both realistic PSF and interrelationships between different PSF, plus the magnitude of this interrelationship.

- **Data Level**

In judging the various methods, one must furthermore consider the quality of the data which these methods used for quantification. Here are the various possibilities: procedures involving estimates by experts, experiments, simulator studies, or an empirical acquisition of data from practical operational experience. Procedures involving estimates by experts constitute the simplest possibility for obtaining data on human reliability. In the case of simulator studies, one performs operational runs and trouble cases within a simulator - that are to be specified in advance - and one qualitatively or quantitatively analyzes and evaluates the behavior of the operators in bringing the trouble under control. Experiments supply data, obtained in the laboratory, with standardized and defined marginal conditions. Looking at practical operational experience, finally, realistic data material is available in the form of events. The advantages and disadvantages of the various data sources can be discussed on the basis of the data level of the data as such. In general, we differentiate between absolute scale, relative scale, and ordinal scale (see also Bubb, 1992);

Methods involving absolute scale level are in a position to supply genuine HEP values within limits of 0 to 1. Methods working with relative scales can only provide statements about the interval („when $HEP_1=0$ and $HEP_2=0.2$, then event 1 is twice as likely to occur as event 2"). Methods involving ordinal scales can set up only priorities, such as, for example, event 1 is more likely than event 2. Each HRA method must supply data on the absolute scale level in order to be able to be employed in a PSA. Upon closer examination of the various methods, however, we find that these methods accomplish this only very rarely.

Experiments and simulator studies represent the only possibility of supplying data on the relative scale level and thus yielding at least a statistical estimation value for data on the absolute scale level. But here, in particular, we encounter the problem of the transposability of the probabilities obtained to the situation that is to be judged. The THERP method according to Swain (1992) is at least partly based on experimental data; therefore it represents to an (albeit unknown) extent, a method on the absolute scale level. The PHRA method can also be placed in this category because it rests on simulator studies.

Methods involving estimates by experts typically provide data on the ordinal scale level. These methods employ scaling procedures in order to „raise" the data level (see Fischer, 1974). But both the mathematical setup of the scaling method and its underlying prerequisites must be plausible and must be capable of being tested. A typical example is SLIM that generates estimates on the absolute scale level from data on the ordinal scale level using the absolute scale level of the anchor tasks for the calibration of ordinal scale estimates by experts for the individual tasks.

Regardless of whether it is holistic or decompositional or whether it is oriented by PSF or error types, each HRA method needs data to determine the probability of a human error; therefore, the underlying data are exposed to particular criticism. This criticism is all the more intensive, the lower the data level of the method is. Data often are insufficiently accurate or they are not realistic enough (see Fujita, 1992; Reer & Mertens, 1993). This uncertainty in data is further increased by the fact that HRA methods so far are hardly being subjected to a systematic investigation of the validity (for compilations and additional discussions in ACSNI, 1991; Zimolong, 1990; Zimolong, 1992).

In addition to the inaccuracies in available data, the methods likewise are not in a position to supply data for more recent problem fields. For example, the incompleteness of the methods (for instance, in the area of the organizational effects or cognitive errors) can lead to a miss-estimation of the total risk (see Bley et al., 1992; Reer & Mertens, 1993). Cognitive errors are given only insufficient consideration but are important, particularly for estimating human reliability in future technical systems (for example, computerized control rooms) (Reichart, 1992; Reer & Mertens, 1993) and, along with organizational aspects, they are significant in terms of internal system measures (AM - Accident Management).

The data foundations constitute a main problem in the HRA methods; this is why attention must be focused on this problem. Both the validation of existing data sources and the evaluation of cognitive and organizational errors should be possible with the help of the data derived from practical operational experience. A method for analyzing data derived from practical operational experience, furthermore, must be flexible enough in order to cover differing ways of proceeding equally (error related, PSF related, or time related).

2.3 Methods for Analyzing Practical Operational Experience

In the two preceding sections, we described the requirements for a method to be used in the acquisition of human errors from the viewpoint of the process of prospective judgement. The requirements there are aimed at a rather quantitative evaluation of human reliability. In this chapter, we now wish to present retrospective methods that are used rather for the qualitative analysis of events. The following retrospective methods can be distinguished in this context: ergonomic evaluation systems, methods for analyzing events, and systems for event reporting.

2.3.1 Ergonomic Evaluation Systems

Various methods have been developed to evaluate the work environment of individuals. They are used for a qualitative analysis of the shaping factors upon human reliability and they are thus basically important in analyzing events as well. We can distinguish the following groups here:

- Checklists for ergonomic evaluation: This group comprises methods that perform a qualitative ergonomic evaluation of work systems. The best known, among others, are the activity evaluation system [in German: Taetigkeits Bewertungs System] by Hacker et al., (1983); the work analysis questionnaire by Frieling and Hoyos (1978); the ergonomic investigation method for activity analysis by Rohmert and Landau (1978), the ergonomic data bank system by Jastrzebska Fraczek and Schmidtke (1992), as well as various ergonomic checklists, such as, the checklist for the design of display systems, the guidelines for procedural design in SR2055 (1995), devised by Eggerdinger et al., (1986) or checklists from American or Japanese literature (see O'Hara, 1994 or Fujita, 1992).

- Taxonomies for the description of events: This group contains methods that are used for the classification of events. These methods are being used both by operators (for example, French Electric Power Company in France [EDF] or the RWE (Rhinish-Westphalian Electric Power Utilities] in Germany, and by supervisory or regulatory authorities (for example, the Human Action Classification System in the United States, prepared in the Nuclear Regulatory Commission by Barriere et al., 1994). Wilpert et al. (1994) present an overview of some of these methods. Appendix 2 contains some of the taxonomies mentioned here that are used in the databank system developed in this study (Appendix 1).

Summarizing, we may say that ergonomic evaluation systems are optimized toward certain problem statements and cover only some portions of ergonomic problems (for example, motivation, personnel management, ergonomic design of work stations). But they furthermore show that - when it comes to a complete analysis of human influences and the conditions leading to human errors - one must basically supply a broad spectrum of ergonomic knowledge which is used within these evaluation systems (cognition, organization, communication, etc.).

Taxonomies for ergonomic evaluation or for the description of events, furthermore, consist of fixed descriptors and are unsuitable for a detailed investigation because they do not represent the variability of the information items to be observed in the events and because they cannot describe the interrelationships involved in error origin. Therefore, looking at these methods overall, the connection is lost to the individual aspects of the error situation.

There is furthermore a great interpretational leeway in the application of the taxonomies in cases where one cannot apply any predefined descriptor to the event to be described. This results in inaccuracies in event description so that simple taxonomies are of only limited use when it comes to detailed describing of events. This is further accentuated by the fact that events possess an enormous variability and complexity and that each event has its own specific constellation of errors and conditions.

2.3.2 Methods for Analyzing Events

On account of the restricted usability of simple taxonomies for analyzing events, two procedures for analyzing the causes of events were generated in studies conducted by the International Atomic Energy Agency [IAEA] and by the Nuclear Regulatory Commission [NRC]; these methods are presented in this section. They are the Assessment of Safety Significant Events Team [ASSET] and the Human System Method [HSYS].

- **The ASSET Method**

ASSET is a method that was developed by the IAEA to analyze human errors in nuclear power plants (see IAEA-632, 1991). The central assumption underlying the ASSET Method is this: trouble events (ranging from an accident all the way to a temporary breakdown in operations) are caused by latent weaknesses. The latent weaknesses are referred to as direct causes that emerge within the event in the error chain. They are based on root causes as conditions which, for example, can reside in deficient maintenance, quality control, or operations monitoring and that cause the latent weak points. ASSET has a series of points that correspond to other analysis methods (such as, for example, MORT in Johnson, 1980) which are employed to analyze organizational safety barriers (on that score, see, for instance, Becker et al., 1995). The procedure employed in the ASSET Method is as follows (see Deutschmann, 1994):

1. Analysis of events (What happened?): To analyze the event, it is further broken down into individual occurrences.

2. Analysis of the direct cause (Why did it happen?): The occurrence type is determined here for each identified occurrence. The occurrence type here can involve work equipment, instructions, or procedures, or the personnel and represents the direct cause for the occurrence.

3. Analysis of the root cause (Why was it not prevented?): For each occurrence type, we look for the latent weak point that was the root cause of the occurrence. Here, the ASSET Method offers, as possible latent weak points: deficiencies in maintenance, quality controls, or operational monitoring.

4. Initiation of corrective measures (What must be done?): Corrective measures are proposed for each event. The corrective measures should encompass equipment, instructions, and personnel and should include short-term and long-term measures.

To go through these steps, the ASSET offers standard forms and flow charts that help in analyzing the causes of the events. The procedure used by the ASSET thus confirm the echeloned procedure toward error description as depicted in Figure 8 (1). The effectiveness of improvement measures must be considered from the angle of retrospective analysis, in addition to the procedure illustrated in that chapter.

A careful look at the possible root causes shows that ASSET reduces the causes of human errors to the management of the enterprise. For example, faulty procedures can come about according to ASSET only due to deficient quality assurance or operation of procedures. No consideration is given in this method to errors that, along with these factors, can be traced back to complex reciprocal interrelationships between the user of the procedure and the specific properties of the situation. In conclusion, looking at discussions on culpability, the method thus represents a rather one-sided procedure for cause analysis. Furthermore, it cannot be expanded by additional findings concerning interrelationships in the origin of the error that may have been obtained from the events.

- **The Human System Method [HSYS]**

The HSYS was developed by Harbour and Hill (1991) for purposes of cause analysis in the United States. The starting point of the method is an error model similar to the one devised by Reason (1976) that was presented in Chapter 1. It subdivides human errors on the first level on the basis of the processing stages according to Sternberg (1969). An error tree of possible causes is built up on the basis of this psychological model. Factors for error origin are differentiated all the way to terminal factors in sequentially subordinate levels. Higher situated junction points here represent causes of lower situated junction points. Figure 15 shows a segment of the hierarchy used in the human system. As one can see from the illustration, factors that can be checked, such as, for example, skill qualification, training, work place design, are mentioned at the lowest level of the hierarchy for the purpose of determining the cause. These factors are classified as inadequate when they influenced an action within an event. In analogy to the error tree technique, one can derive action mechanisms by looking at the next higher level.

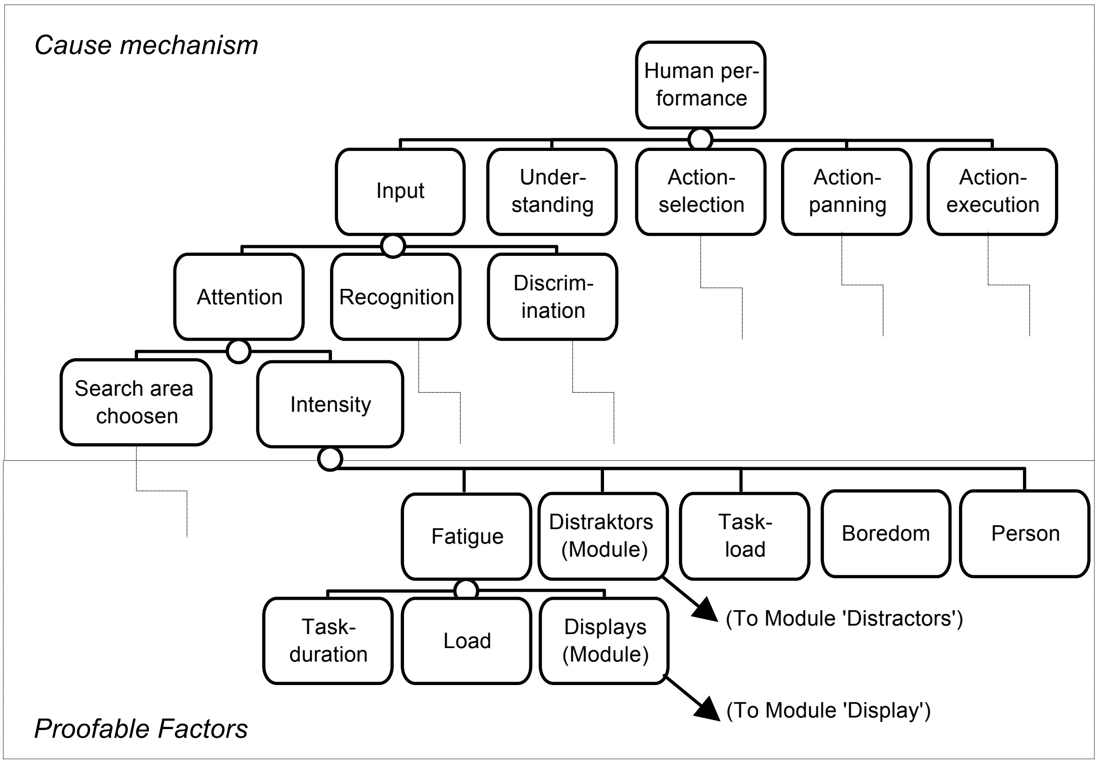


Figure 15 Segment of the Hierarchy in Human System

Regarding the underlying theoretical model, it should be noted that the subdivision of processing stages according to Sternberg, as performed there, does not agree with the currently discussed state of properties of human information processing. As noted in Chapter 1, this becomes clear solely by virtue of the fact that the model of Reason (1976) - that falls back on these processing stages - does not take into consideration certain effects of practice and certain effects of habits in human information processing. The effects of habits mean that a sequential processing can no longer be assumed (see Chapter 1). This means that human behavior is incorrectly modeled already by the basic structure of the HSYS.

In addition, the model also has some formal weak points. The error tree built up in the model is not organized strictly along hierarchical lines; analyses can produce multiple solutions. In case of identical information on the lowest level, the model, for example, leads to error causes both in the input stage and during the stage of action selection. Furthermore, the hierarchy in the human system originated on the basis of theoretical considerations and does not represent any interrelationships that are to be found or were found in an empirical fashion. Nor can it be expanded by these considerations.

While, within an event, errors related to the testable factors were identified, the HSYS Method, however, does permit a determination of superordinate shaping factors in that the hierarchy is tracked bottom-up. Once a shaping factor has been identified, one can identify other action determining factors in that the hierarchy is now analyzed top-down. In that way, one can image interactions of several shaping factors that were involved in the erroneous event.

2.3.3 Event Reporting Systems

In addition to the methods so far illustrated with regard to the retrospective judgement of human reliability, there are various systems used in event reporting which are used particularly for more extensive documentation and evaluation within databanks. They can be subdivided into three classes: data acquisition forms, databank systems, and event descriptions.

- **Data Acquisition Forms**

In data acquisition forms, events are described by classifying them in predetermined categories. They are used to prevent an overview of a certain event. Customarily used data acquisition forms are notice forms for defect reports on technical components. All of these data acquisition forms share one thing in common: an event is recorded by checking off certain categories (about 30). Wilpert et al. (1994) propose a data acquisition sheet for human errors based on several category systems from literature on the subject.

The fixed categories on the data acquisition forms merely facilitate a rigid description of the events in the pre-determined categories. To be able nevertheless to image events that do not fit into the previously devised scheme, we have residual categories where freely stated data may be put down. An event cannot be described in detail with the help of the data acquisition forms because of the restricted number of categories. Errors that are based on the operator or on interactions between the operator and the technical system or on reciprocal interactions, cannot be described with these means. Also lost in these methods is the interactive connection between information, actions, and errors relating to specific events plus shaping factors.

- **Databank Systems**

Databanks are used to collect event descriptions in order subsequently to facilitate an across-the-board case analysis (for example, determination of the effectiveness of improvement measures, transposition of error causes to other systems). They are thus used for both national and international exchange of information between various systems and system types. Databank systems are also sources of detailed analyses of an event and supply information on systematic errors or human influence. They furthermore supply data for which prospective judgement procedures currently do not contain any data, such as, for example, problems when the system is not operated at full power.

Databanks of practical significance in the nuclear power industry, worldwide, are the Nuclear Computerized Library for Assessing Reactor Reliability [NUCLARR] databank, described in Reece et al., 1994; the Incident Reporting System [IRS], presented in IAEA-

632, 1991; and, nationally, the Special Occurrences Databank; see Kotthoff & Voswinkel, 1981. There are other databanks for the purpose of collecting events, for example, in Germany, in the United States, or France, that were not accessible during this study.

The NUCLARR was developed by the NRC in order to meet the data requirement arising during the judgement of human actions in nuclear power plants. Error probabilities of human actions (HEP) from various sources (experiments, simulator tests, bibliography data, practical operational experience) are collected in the NUCLARR. Information on the tasks of the operators, errors and erroneous operation, according to which error probabilities are determined, are also documented so that the data can be properly used. Table 9 shows the structure of a data set in the NUCLARR (translated from Reece et al., 1994).

Table 9 Structure of a Data set in the NUCLARR (according to Reece et al., 1994)

Producer	***Personnel***	***Task Description***	***HEP Data***	***PSF's***	***Information***
(Producer of system)	for instance: Control station personnel, maintenance	(brief description of tasks and errors in one sentence)	Median Mean Value Error factor Upper limit Lower limit	Available time Action time Experience Feedback report Procedures Equipment Stress Surveillance Monitoring Training	(Administrative Information)

The incident reporting system contains events from nuclear power plants that are subjected to mandatory reporting worldwide. The system was introduced in 1980 for member states of the Organization for Economic Cooperation and Development [OECD] to ensure international exchange of experiences on events in nuclear systems. In 1983, the IAEA took this system over for countries not belonging to the OECD (the former East Block, some countries in Asia, and South America). Basically, the IRS has a structure similar to that of the special occurrences [system] [BEVOR] of the Society for System and Reactor Safety, Inc [GRS].

The Special Occurrences Databank was built up by the GRS for the purpose of documenting domestic events within Germany that are subject to mandatory reporting. The BEVOR has several data fields for standardized data (such as, system, system type, date and other administrative information) and a free text part for the description of the event;

this part is subdivided into several chapters (see Table 10). The databank was designed for the purpose of providing replicable documentation for individual events.

Table 10 Categories of the BEVOR

General Data in Fixed Data fields	***Brief description in text form with respect to the chapters***
Procedure number	Heading
Date	Description of event
System/System Type	Identification
Safety marking (for example, RESA)	Effect
Gravity of event	Cause
System involved, component	Remedial action
Key concepts for event identification	Precautions

The databanks differ from the data acquisition forms in that there is more than just a category subdivision of events. Additional data fields here facilitate a brief description of the event, supplying additional information concerning the error within the event. This facilitates a more detailed analysis of human intervention during the event. The size of the field for event description varies greatly from a field with 254 symbols in the NUCLARR all the way to any length of free text in the BEVOR. Conversely, it should be noted that fixed data fields are advantageous when it comes to a standardized and frequency analysis evaluation of the data. In that way, one can distinguish essentially two types of event acquisition: standardized acquisition by the indication of descriptors or free description of the event in the form of text. The method of giving concepts leads to more consistent, more easily evaluated data than does the textual form. The textual form is to be preferred when there is a demand for more detailed data on the course of the event, a description of interrelationships, or a reconstruction of the procedure.

If one investigates the content of various messaging facilities with a view to human errors, then data acquisition forms are suitable only for a general classification of human error actions. For more detailed analyses, when they consider only the databank systems and the event descriptions, the NUCLARR soon runs into limitations when it comes to providing a detailed look at an event on the basis of inadequate task description. The BEVOR and the IRS depict events already in such a way that at least a rough analysis of human errors is possible.

- **Event Descriptions**

Event descriptions are used to get a precise idea as to the errors during the event and to initiate specifically target-oriented precautions against possible repetitions. The event descriptions differ from the methods described so far in that the event is described in them only in the form of text. Summarizing, they involve a subdivision according to Table 11.

Table 11 Summary of Subdivisions of Event Descriptions

Data related to a system
- Identification number
- Source
- Date
- Duration
- Failure times, time sequence of event
- System state before and after trouble (for example, turn-off, power operation)

Data on course of event
- Error designation (heading)
- Summary of event (classification of gravity of event according to International Nuclear Event Scale, Error cause)

Description of course of event according to the following characteristics
- Technical system involved
- Situation (rounds, recurring tests)
- Participating personnel (persons or groups of persons) and their communication
- Recognizable symptoms (successful or unsuccessful recognition of the signaling of process magnitudes at the control stand or on site)
- Actions carried out (Direct, Planned, Preventive actions, switching operations, procedure).
- Observable errors and interrelationships of errors.
- Causes and shaping factors (machine: design, wear and tear, material flaw, human individual: lack of attention, misinterpretation, neglect)
- Complexity of error (concatenation of technical and human errors)
- Coping with event state

Evaluation of Event
- Evaluation from safety engineering angle (reactor shutdown, radioactivity release, safety stages)
- Evaluation from ergonomic viewpoint
- Precautions, measures against repetition
- Transposability of event or other systems

Compared to the methods described so far, information in the event descriptions is very detailed. The following event descriptions are used in Germany, among others. Forwarding news [in German: Weiterleitungs-Nachrichten], comments by the technical monitoring administration and the Reactor Safety Commission [RSK]. Event descriptions are not standardized and depend on the course of the event. In particular, they are in a position to illustrate interrelationships and, for this purpose, feature a chapter subdivision similar to the one that is used in the BEVOR. As a rule, they are subdivided into the description of the event, identification, effect, and remedial action as well as cause, safety engineering or across the board system significance and precautions.

As one can see from the table, event descriptions constitute in particular reciprocal interactions or interrelationships of the technical system with the persons. One can furthermore clearly see that there are mostly several persons cooperating in events and that the identifiability of the symptom plays an important role for possible human intervention.

2.4 Requirements for a Model to Judge Human Reliability on the Basis of Practical Operational Experience

In the preceding sections of this chapter, we compiled requirements for a model used in the acquisition of human errors that result form the process of prospective judgement of human reliability and of retrospective analysis of human influence. We must distinguish three main aspects in order to consolidate them into a requirements profile for a method for analyzing events involving human influence:

- Requirements for the information be acquired;
- Requirements for the structure of the data to be supplied and their analysis;
- Requirements for the anticipated information gain resulting from analysis.

2.4.1 Requirements for the Information to be Acquired

In the preceding sections of this chapter, we mentioned various types of information that the different HRA methods require as evaluation parameters in order to judge human actions. The latter must be obtained from events. They can be summarized as follows according to Table 12.

In the table, information regarding a prospective assessment assigned with "P" and those for retrospective assessment are assigned with "R". The table shows how similar prospective and retrospective assessment is regarding the information requirements. This is obvious since both attempt to reduce human failures and therefore finally intend to optimize the technical system from the human point of view. It is interesting to note that retrospective methods usually do not ask for the time budget and that prospective usually do not focus on finding best improvements.

Table 12 Requirements for information to be acquired

Area	*Requirements*
Data pertaining to situation	
P	The time available in the disturbance situation in order to initiate and execute correct actions (the latter are predetermined by the technical marginal conditions of the system)
P, R	Direct, planned, or preventive actions (for example, recurring testing or ad hoc action)
Data concerning task assignment and activities:	
P	The time needed for diagnosis and correct action execution resulting from the task assignment.
P, R	The tasks of the operators that result from the requirements of the system plus a description of the actions or subtasks.
Data on the person:	
P, R	Qualification of the person who is to do the job (for example, control panel personnel, maintenance personnel).
P, R	The degree of cognitive stress as well as shaping factors (for example, experience, stress factors, perception and action abilities and fatigue).
P, R	The type of error (omission, commission)
Data on perception, operation, and feedback:	
P, R	The man-machine interface and the work resources as well as their ergonomic layout
P, R	The identifiability of the current system state through available information systems
Data on organization and communication:	
P, R	The available procedures or work instructions (for example, operations handbook).
P, R	Interactions between several persons (under certain circumstances, at different locations).
Data on environment:	
P, R	Shaping factors from the environment (for example, noise, gasses, illumination, etc.)
Data on the technical system:	
P, R	The components of the technical system that were defective or that were needed to bring the trouble under control.
Data on system output:	
P, R	The effect on the system and the environment that is significant in terms of radiology for safety engineering.
R	Preventive measures against repetitions.

2.4.2 Requirements for the Structure of the Data to be Supplied and their Analysis.

The information must be present in a certain manner and form so that it may be useable for the judgement process. The requirements may be summarized as follows:

- Qualitative data on human reliability: An essential requirement for the data to be supplied is the complete and comprehensive consideration of the error types and the shaping factors that took effect during an action. This means that a data acquisition method must consider comprehensive ergonomic and organizational knowledge relating to the possible shaping factors. Pertinent support in the identification of errors and PSF's must be insured when analyzing practical operational experience.

- Quantitative data on human reliability: To use data for a probabilistic analysis of human actions, one needs data on probabilities of human errors along with qualitative statements. Error rates or error frequencies do not suffice for a PSA.

- Degree of information detailing: The information required to evaluate human reliability (see Table 12) must be adapted to the degree of detailing of the analysis. This calls for differing detailing, for example, in the case of holistic as against decompositional methods or in screening considerations (rough analysis and detail analysis). It must be possible to give and analyze information on differing stages of detailing.

- Methodology for analyzing information collected: The method of analysis must be capable of discovering similarities in the cases in order to facilitate a corresponding statistical analysis. The similarities here can relate, among other things, to the key parameters of the HRA Methods (error related, time related, or PSF related); they can also relate to the action types that are distinguished in a PSA (the action types A, B, C) or they can pertain to measure taken by way of precaution. For this purpose, an event description must be so flexible that the variability of possible events as well as interrelationships in complex events can be displayed.

2.4.3 Requirements for the Anticipated Knowledge Gain from Analysis of Practical Operational Experience

The requirements compiled in the last sections also point to the significance of the validation of existing data material or the supplementation of unavailable but needed data material. The following were mentioned specifically:

- Validation of data material and of assumptions that can be made in HRA: practical operational experience is to be used in testing or validating the realism of the data material that is used for the evaluation of human reliability. That includes both central distribution assumptions (the logarithmic standard distribution of the THERP method and the logarithmic/linear interconnection between time and reliability), as well as a validation of the numerical data on reliability (the human error probabilities values). Furthermore, one must validate the statement on the accuracy of the HEP values or the uncertainty spread.

- Realistic illustration of the complexity of the error situation and of the variability inherent in human actions: In order to model the complexity of the situation in a realistic fashion, one must display the minifold interrelationships or reciprocal interactions between situational conditions, shaping factors, and possibilities of human intervention. For this purpose, one must above all obtain statements concerning the interrelationships of the various tasks and of the conditions for human error (PSF’s). That also includes statements on the safety engineering usefulness or on the effectiveness of precautionary measures and recovery factors.

- Supplementation of the unavailable but needed data material for current evaluation problems within HRA: Recent technical developments (such as, for example, the computerized control rooms) and requirements for a probabilistic evaluation of aspects that are relevant in terms of safety but that have not been considered so far (for example, non-full power states and accident management) demand statements on cognitive and organizational influence factors. Here it should be possible to come up at least with qualitative statements on possible shaping factors by analyzing practical operational experience. It is also necessary to figure out to what extent probabilistic evaluations have so far been realistically covering human intervention, for example, in terms of investigating the aspect of damage enlarging factors (among other things, errors of commission).

3 A General Model for Analyzing Human Errors in Events

In the preceding chapter, we developed requirements and questions from the angle of the HRA Methods; we will now respond to these requirements and questions by analyzing events coming to us from practical operational experience. The simple question in this chapter is how this plurality of requirements and expectations must be converted methodologically. For this purpose, we develop a description model from past considerations; this model is an imposition to acquire and analyze those information items from events that are required for a judgement of human reliability.

3.1 Foundations of the Description Model

First of all, it is necessary to build up a generic description model. It must be generic, in other words, generally valid, for the simple reason that it must be applicable to all observable events. Furthermore, the model must be in a position to collect all information items on human errors from the events in such a form and manner as is necessary for an analysis with a view to the discussed requirements.

3.1.1 Generic Description Model for Analyzing Events

In Chapter 1, we used various error models that are known from the literature in order to develop a point of departure for a model that can be used for the acquisition of human errors based on practical operational experience. For this purpose, we selected the man-machine system that is customary in ergonomics and we explained how it can be further developed into an error model. The man-machine system was chosen because it traces possible error causes back to the man, his working environment as well as the flow of information and interactions and because it does not boil it down solely to the individual. In addition we discussed how this model can consider cognitive factors by the load/cope approach. The investigation of the requirements for methods used in analyzing human actions (HRA Methods) and of methods for event analysis in Chapter 2 showed what kind of information must be gathered from practical operational experience in order to be useful for an evaluation of the human reliability in a HRA. The common points that were identified in the various HRA Methods were compiled in Table 12 (Chapter 2).

If one looks at these results, then the man-machine system must be expanded by the following fundamental components in order to combine the practical changes in HRA Methods and methods for acquiring practical operational experience with the description approach from Chapter 1 to get a description model:

- Separation of system state and feedback: The actual system state is, as a rule, not reported back to the operator. The state of the system is communicated to him only indirectly (for example, via displays). The operator can judge the system state only by means of symptoms. The operator coordinates the symptoms with his knowledge about the system and carries out a corresponding action.
- Supplementation of order issue and order dispatch: It is required to include interpersonal or organizational psychology aspects because events come about mostly through several persons (see example from Table 1, in Chapter 1, and the ASSET Method for event analysis in Chapter 2). To be able to depict these aspects, one may expand the man-machine system by the „order issue“ and „order dispatch“ components. With the help of this expansion it is possible to depict interpersonal factors such as they always occur in complex error events.
- Supplementation in the situational context: The situational context must contain data on the time window so that it may be used for time-reliability considerations. The time data are important in estimating the time available for a decision (in particular, for type C actions after trouble has occurred, see Chapter 2).

If one combines these fundamental aspects with the approach of the man-machine system, then one gets an expanded man-machine system (Figure 16). Information elements are labeled in the figure with Arabic numerals whereas information flow is labeled with letters. The expanded man-machine system can be described according to the following viewpoints (see also Bubb, 1992): A task (1) is performed (1-a-3) by operator (4), for instance by receiving an order issue, an order form, or a procedure (1*). After the acquisition of the task and the current system state, the operator initiates his action on the operating element of a system (5-c-6). The action in turn has consequences in terms of the behavior of the system magnitude (e-10). The system magnitude depends on the system behavior of the machine (7) which, among other things, is characterized by the dynamics of the process and the degree of automation of the technical system. The operator cannot directly influence the system behavior. Furthermore, he gets feedback only indirectly via system behavior symptoms (9-d-3). As a rule, the symptoms are fed back visually or in an auditory fashion via a display. If the task has been accomplished or if the operator has failed, then the operator can make a feedback report to the task assignor concerning accomplishment or failure to accomplish (5-b-2). The entire man-machine system is influenced by situational factors (among other things, time window) and by environmental factors (for example, noise).

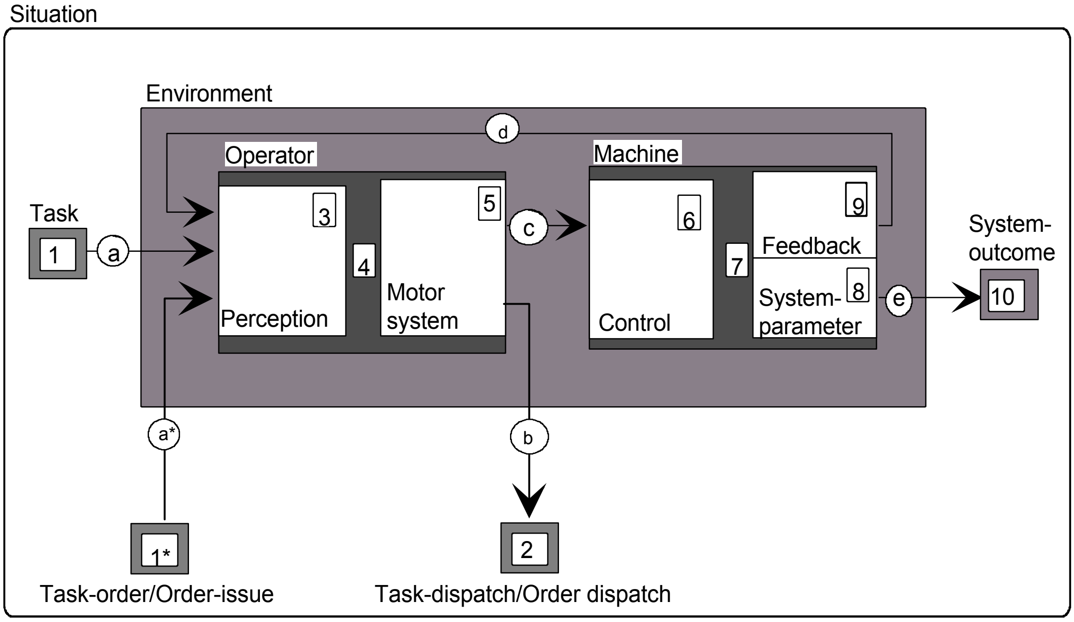


Figure 16 The Man-Machine System as Generic Element in the Acquisition of Human Actions[4]

The man-machine system is a classical ergonomic model; it is therefore particularly in a position to display ergonomic and organizational factors. In order to depict information going beyond that, information that could also be of significance in connection with the events, it was supplemented by adding the communication aspect (for example, order issue and order dispatch) and by adding situational information (for example, time window for an action). Below, we will show how the consideration of the aspect of communication

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[4] In other translations or papers in English language, the item "task order" was used synonymous to "order issue", the same holds for "task dispatch" and "order dispatch". The reader should treat the terms as synonymous in this translation.

in addition makes it possible to describe complex events, in which several persons are involved, by interconnecting several man-machine systems. The expanded man-machine system thus, first of all, assembles a structured set of instructions to collect information relevant to the event. Additionally, it is the basic building block for an event description and, for this reason, it will below be referred to as a generic man-machine system. Aspects that are combined with the man-machine system were also graded in IAEA-538 (1990) as being significant for the acquisition for information items for HRA.

The information elements and information flow must be considered in the man-machine system so that an event may be described. An error at the system output of the man-machine system may come about here through one or several weak points within the man-machine system. The system output represents the replication magnitude and thus the consequences deriving from errors within the man-machine system. The system output thus represents the characteristic value that points to errors within the man-machine system (see definition in Chapter 1).[5] In order to investigate and understand this error, the following questions must be asked with relation to each component of the man-machine system and according to the echeloned procedure, as developed in Figure 8 (Chapter 1):

- What objective information is available? (For instance: What was the task assigned to the operator?)
- What error was made? (For example, omission)
- What error-promoting conditions prevailed? (For example, time pressure)

- **Objective Information**

An object-oriented error description can take place within the generic man-machine model; that is, in the man-machine model we first of all collect the information items pertaining to

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[5] It should be pointed out clearly that the MMS assigns the error in the system outcome by no means to the human involved in the man machine system. It may be for instance that the human is convinced to do the correct action because of a wrong task-design, bad feedback or misunderstanding task orders. Such weak-point allocation is therefore particular important for dealing with errors of commission and to understand the context of the human action or decision.

an event that were actually observed during the event. Table 13 shows the possible examples related to the components or classes of the generic man-machine system.

Table 13 Description of Components in Man-machine System [MMS]

MMS Components	***Designation***	***Description***
Situation		In what situation did the event take place? All general data that are important to the observed erroneous action. Example: During inspection, recurring testing, 10 minutes after event occurred.
Task	1-a-3	What was the task of the person? All tasks that are assigned to a person. The tasks are described with the help of process engineering concepts. Example: Check coolant pressure in tank xy.
Person	3-4-5	What person was involved in the event? The person who participates in task accomplishment. Example: Electrician to perform task, operator to watch.
Activity	5-c-6	What was to be done? All activities required to accomplish a task. Example: Coolant pressure set, Switch activated.
Feedback	9-d-3	What means of information reported the state of the system to the person; How did the person note the error? All objects or systems that report the system magnitude back to the person. Example: Read pressure value of display screen.
Order Issue	1*-a*-3	What organizational aids were available to the person? All persons or objects (procedures, telephone call) by means of which the task was assigned to the person. Example: Follow written directive xy.
Order Dispatch	5-b-2	What organizational tasks was the person to accomplish, to whom did the person have to report about the work? All persons or objects who were informed of task accomplishment. Example: Fill out work permit form.
System	8-e-10	What sub-system, what system component was involved? All technical systems upon which task accomplishment had an effect or on which damage occurred. Example: Pressure rose in tank xy.
Environment		At what sites did the event take place? Premises in which the person was to accomplish the task. Example: Control panel, on the spot.

- **Errors Made**

Once the objective information had been acquired, then, in a next step, one can identify the weak points within the man-machine system, in that observable errors were listed for each component of the man-machine system (for example, whether the operator failed to read off the pressure value on the display screen or whether the coolant pressure was set at an excessively high value). Generally, one can use the error taxonomy of Swain and Guttmann (1983) for each individual component of the man-machine system (Table 14).

Table 14 General Taxonomy for Error Identification within the MMS (along the lines of Swain & Guttmann, 1983, pp. 3-7)

Taxonomy	***MMS Component to which the taxonomy applies***
Error of omission Omitted	Task Order Issue Feedback report Person
Error of execution (select) wrong (set) faulty Time Error Too early Too late Qualitative error Too little Too much	Person Activity Order dispatch System

Errors of commission must be placed in the information output side of the individual (the operating crew) and errors of omission must be placed on the information input side (the task assignment).

- **Error Promoting Conditions**

Once it was possible to identify an error in a component of the MMS, then, according to the echeloned procedure, as described in Figure 8 (Chapter 1), one can indicate the error conditions (i.e., PSFs). For this purpose, PSF can be matched up with the various components of the MMS. This was shown by way of example in Figure 17 for some PSF taken from the literature on the subject. Appendix 2 shows the match up of additional pertinent PSF with the MMS components. The identified error conditions not only represent causes in terms of conditions necessary for the errors, as discussed in Chapter 1; they also make it possible to find approaches to improve impossibilities and to the prevention of future errors, as will be shown below.

Environment		Situation		Order Issue-Dispatch
Temperature Air Quality Radiation Cleanliness	Illumination Noise Vibration	Working hours Breaks Shift system Test situation	Remuneration-system Group Structure Organizational structure	Means of communication Design of procedures Task demanded by management

Task			Feedback	
Complexity Difficulty Dimension Precision	Risk Time Pressure	Significance Usefulness	Surface Inconsistency Design Compatibility	Repetition frequency Aids Warnings

Person		Activity	System
Stress Attention Motivation Experience Working methods Training Personality Intelligence Skill Emotion Knowledge Physical Factors Fatigue Hunger/Thirst Insufficiently challenged	Information load in connection with interpretation and decision Memory load (short-term memory, long-term memory), cognitive load, calculating, skill-based, rule-based, knowledge based) Personal consequences	Selection Handling skill Accessibility Monotony Relationship between control and display Dynamics of order control	Reliability Maintenance intervals Suddenness of occurrence Degree of alternation Concatenation Intermeshing

Figure 17 Association of Error Promoting Conditions from Literature mapped on the MMS-Components

3.1.2 Expansion of Generic MMS to Work Systems

A close look at events shows that most of them occurred due to the cooperation of several persons in different places. The cooperation of several persons here can be referred to as a work system and can be modeled by the two MMS components which are: order issue and order dispatch. The generic MMS can thus depict events that are characterized by a complex event and error chain. To make this clear, Figure 18 first of all shows a simple work system with a hierarchical organization, such as it is often encountered.

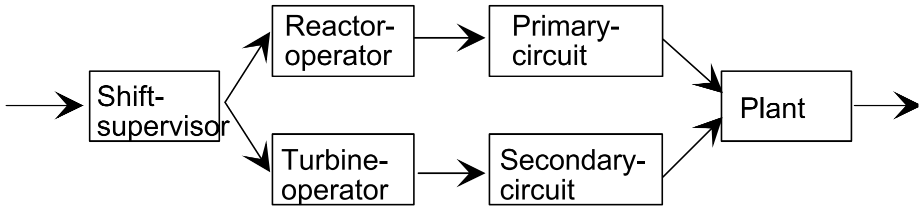


Figure 18 A Simple Work System

If one now looks at the individual sub-paths of the illustration as individual MMS, then one gets a description of the work system as illustrated in Figure 19.

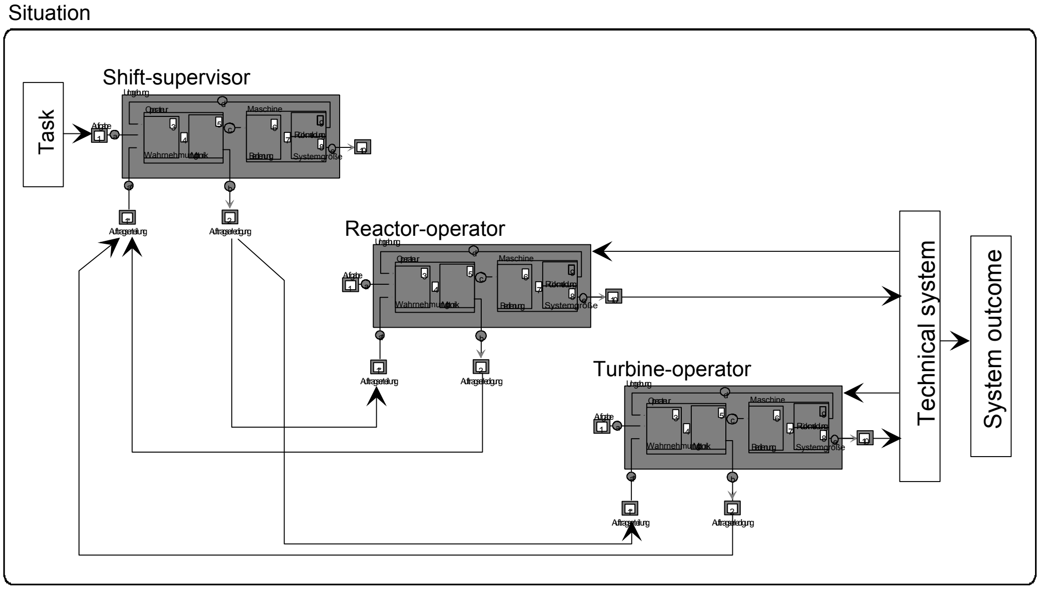


Figure 19 Description of Complex Events in the Work System

As the figure clearly shows, a complex work system can be described by saying that individual MMS are used in order to sub-divide the overall complex of the occurrence into various sub-systems. On the whole, we thus get a network of different sub-systems that are connected to each other via the task assignment and task accomplishment.

3.2 Analysis of Events

The preceding section presented a generic model for the description of human errors. In this section we want to expand the procedure presented there into a complete procedure for the analysis of events. In chapters 1 and 2 we already touched on the steps involved in the acquisition and analysis of events drawn from practical operational experience with respect to human error actions. We must distinguish the following steps within which the generic MMS is required as a description model:

1. Event identification
2. Breakdown of course of action

3. Analysis of action course and of weak points
4. Analysis of cognitive load and cope
5. Analysis of measures aimed at system optimization

3.2.1 Event Identification

In analyzing events, one first of all encounters the difficulty of separating events that were caused by human factors and by technical factors. A demarcation is required in order to be able to identify those cases where it becomes necessary to investigate human errors. As point of departure for identification, one can use the error definition already proposed in Chapter 1. If one applies it to the generic MMS, then one must investigate all events in which one can identify an error in the information flow within a MMS.

According to this definition, occurring events can thus be sub-divided into those that are caused by human factors and those that are caused by technical factors; here we investigate whether (1) information is or is not available on a MMS, (2) information can or cannot be found on weak points in the MMS system. Both criteria can be identified in that one searches events for words that supply hints as to these two possibilities. In case 1, we must try to find out whether objective information is available on a MMS (for example, the concept of „instruction," „testing," „operating handbook"). In case 2 we must try to find out whether there are any hints as to an error within a component of the MMS (for example, the words „falsely recognized"). Appendix 6 is a compilation of the concepts that were used in this study as predictors for event identification. In an event, one can furthermore differentiate whether the technical system worked flawlessly or faulty. This generally results in the possibilities that are compiled in Table 15.

Table 15 presents a sub-division into trouble caused technically during operation and trouble deriving from errors in the MMS. We can distinguish the following cases:

- A technical event (T): Operational procedures or trouble taken place without action of (or caused by) the individual (cases 1 and 2). They are discovered and sometimes corrected.

- A Human Factor Relevant Event (HR): Operational routine for trouble during which the individual successfully intervenes in happenings in some way (Cases 3 and 4). They will hereafter be referred to as Human Factor Relevant Events.

- A Human Factor Event (HF): Trouble where a MMS is the originator (Case 5) or where a MMS system performed a fault intervention in an already fault technical system (Case 6). They will hereafter be referred to as Human Factor Events.

Table 15 States in Operational Routine

Behavior [obtained] from technical system ***MMS System***	***Faultless***	***Faulty***
No information on MMS	1 - Routine operation within automated system	2 - Technical event that intercepts the automated system
No weak point in MMS	3 - Routine operation with manual measures	4 - Individual handles trouble in accordance with regulations
Weak point in MMS	5 - Triggering event initiated by MMS	6 - Event initiated by MMS after occurrence of trouble

Although HF events are analyzed in this study by way of focal points, one should keep in mind that human factor relevant events are also very important to the judgement of human reliability because HF relevant events (HR-events) reflect the capacity of the individual in terms of acting correctly and faultlessly even in partly very complex situations with stringent requirements. HF events on the other hand relate only the fault behavior within an event chain and thus to the difficulty of mastering a situation. It must also be mentioned that actions, that correspond to Cases 1 and 3, basically can be acquired only incompletely because they do not provide any occasion for an event report. On the other hand, Cases 2, 4, 5 and 6 can always be acquired if they are within a certain reporting threshold. The level of the reporting threshold here depends on which organization gets the report of the event (operator, utility, supervisory authority).

3.2.2 Breaking an Event Down for Analyses

When a HF event was identified, then one must work out the MMS that are significant for the error chain or, in other words, one must build up the work system to be observed in the event. For this purpose, one can assemble generic MMS in building block fashion to get a complex course of events in that they are interrelated with each other by means of the

MMS components called „order issue“ and „order dispatch“. An event here can be broken down into different individual MMS according to the following viewpoints:

- Phases in the course of event: The phases in the course of event are particularly important in understanding the error chain. Action Types A, B, and C, were presented in Chapter 2. They can be used to describe the phases of the event and to sub-divide an event into situation-related units of meaning. Type A actions are all actions that occur prior to trouble; type B includes actions that are event-triggering actions of the operators; type C actions are all actions after the occurrence of trouble.

- Persons involved: Another striking sub-division of events into individual MMS is always possible by the participating persons because they mostly have to accomplish differing sub-tasks. Participating persons can be sub-divided according to the enterprise operating sectors which they can be matched up with along the lines of DIN [German Industrial Standard] 31051, DIN 32541, DIN 55350 and KTA [Nuclear Technical Association] 3501:

    Production: Production comprises the generation and new generation of a required state and thus relates to the engineering design and construction of the system. Errors during production mostly lead to latent failures.
    Repair: This comprises all work relating to maintenance, inspection, and repair. Maintenance activities can lead to a result in the system immediately (active error) or later (latent error).
    Utilization: Utilization comprises the properly intended use of a unit of consideration or activities intended to compensate for a deficiency. Errors in utilization can (1) trigger an event or (2) alter the course of trouble in an already defective system state.

- Place of action: The place where a person is active is an additional characteristic for making a sub-division of the MMS. Typical sub-divisions are on the spot, control room or local control stand.

The entire error situation is characterized by all information items with the total course of event. Looking at it overall, the error situation involved in complex events can be depicted as a combination of different MMS. Figure 20 shows the sequence of a hypothetical example (see also Appendix 3).

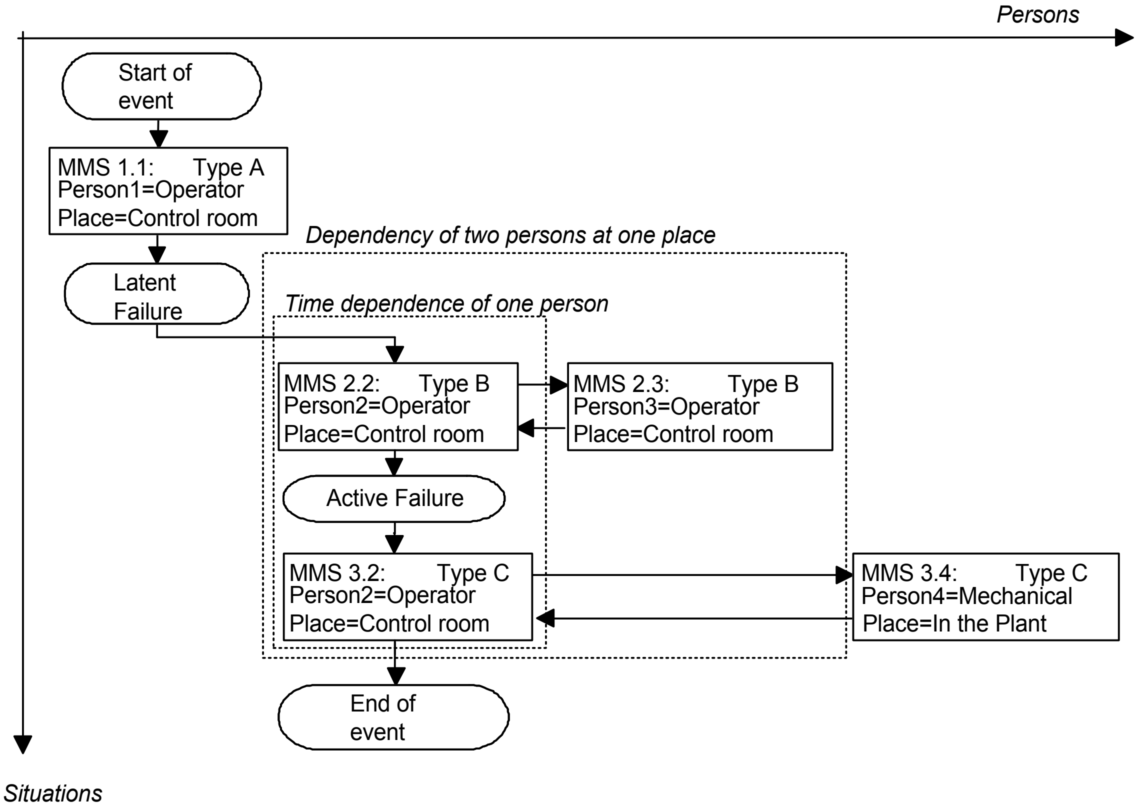


Figure 20 Event Breakdown and Examples of Dependencies between Various MMS

The event breakdown shown in the figure represents a task analysis that combines the flowchart technique, as described by Bubb (1993) with a timeline analysis according to Meister (1985). Persons, places, and events phases are factors according to which one can sub-divide an event. The illustration furthermore has the advantage that the event subdivision can also be used to depict dependencies between different MMS. Dependencies must be considered among other things for probabilistic safety analyses (for example, dependencies of persons or effectiveness of the „4 eyes principle“). The figure shows two possible dependencies by way of example which we will go into in greater detail later.

3.2.3 Analysis of Course of Action

After the event has been broken down into individual MMS, a detailed analysis is made of the individual MMS, as was presented above during the description of the generic MMS. This procedure will now be arranged in a formal manner. As for formalization, it must be determined how the errors and error conditions are to be described. Here, Figure 21 first of all illustrates the general definition of an error as a deviation of the actual value from the required state beyond a tolerance threshold (see Bubb, 1992).

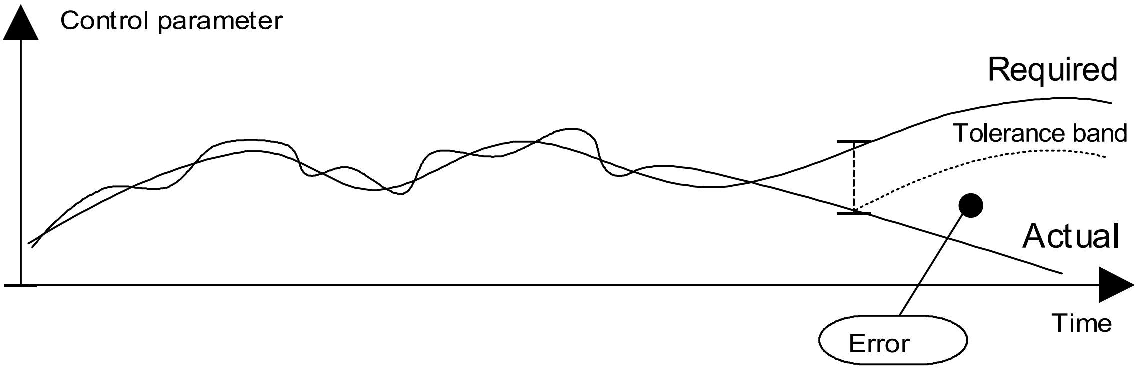
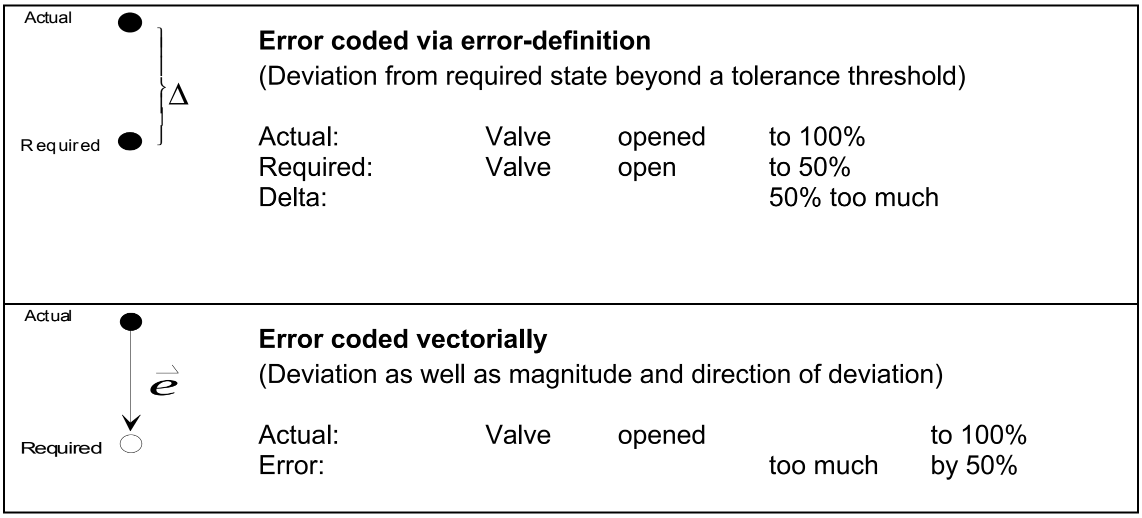


Figure 21 Illustration of the General Definition of an Error

An erroneous deviation can be described in two ways: by means of the determining concepts of error definition or by means of a vectorial notation. Figure 22 compares the two possibilities of description. We may well say that the vectorial notation contains the same information as the notation on error definition; but it saves the trouble of doing the description.

For a more efficient description, we chose an acquisition scheme that employs the vectorial notation. According to Figure 22, the notation consists of three stages: the indication of an object („valve“), the indication of an action („open it“), and the indication of an error („too much“). Detail information can be supplemented in another column as attribute or as element of the object or of the indication („by 50%“).

The attribute or element column is also used to perform an event description on any desired detailing level. Generic term or sub-generic term structures - such as they are required for a detailed analysis of the events - can be reproduced in this manner and form. Typical examples are „valve - motor powered valve“ or „instruction - operations handbook.“ To be able to depict error conditions (PSF) also, these description stages can be supplemented by a fifth stage. The element column can then be used for a detailed description of the properties or error conditions also for the PSF. As described earlier in Chapter 2, this is particularly important for event analysis because a broad spectrum of ergonomic knowledge may be relevant, on any level of detailing, for the analysis of the event and should then be supplied accordingly for analysis.



Error coded via error-definition

(Deviation from required state beyond a tolerance threshold)

Actual:	Valve	opened	to 100%
Required:	Valve	open	to 50%
Delta:			50% too much

Error coded vectorially

(Deviation as well as magnitude and direction of deviation)

Actual:	Valve	opened		to 100%
Error:			too much	by 50%

Figure 22 Description of Errors as Actual-Required Deviation or in Vectorial Notation

A semantic analysis of an event, as illustrated in Table 16, is performed by means of this procedure. The table shows an excerpt from the description table for the MMS components „task,“ „person,“ „activity,“ and „feedback report.“ Using the example of „open the valve,“ we demonstrate how an error description can be done. Appendix 3 shows how a complex real event can be depicted in the description table.

Specifically, the lines in the table can be explained as follows. On line 0, we find all prior information items on another component of the MMS. A new unit of meaning begins in line 1 with the sentence start indication („sentence 1"). Units of meaning (i.e. sentences) must be formed in order to depict and unambiguous match-up of objects, actions, errors, and shaping factors in the data structure (in analogy to the period in natural language). In the unit of meaning, we first of all build up the object structure (generic term: valve, sub-generic term: Type X). Both are connected with the MMS component „task.“ Line 2 presents a verb giving the description of an action that is being performed on the object called „valve“ and this is followed by an error localization. The error here is depicted in the above presented vectorial notation. Once it was possible to identify an error, then, in another step, one can look for shaping factors that caused this error. The table, by way of example, gave the shaping factor „time pressure“ for the error of omission. This means that, for instance, lines 1 and 2 describe the circumstance that the opening of the valve of Type X was neglected due to time pressure. One MMS also can include several error types plus several shaping factors; in the table, an error of omission and a setting error, with the shaping factors „labeling“ and with the sub-factor „insufficient legibility“ as well as „time pressure“ were observed.

Table 16 Illustration of Possibilities of Error Description on the Basis of a Hypothetical Example

Line	*Component*	*Sentence*	*Object*	*Action (verbal)*	*Indication (error)*	*Property (PSF)*	*Element (Sub-generic term)*
0	:						
1	Task	Sentence 1	Valve				Type X
2	„	„	„	Open	Omit	Time Pressure	High
3	Person	Sentence 2	Control station personnel				
4	Activity	Sentence 3	Valve				Regulator
5	„	„	„	Opened			
6	„	„	Regulator	Set	Too much		
7	„	„	„			Labeling	Legibility
8	„	„	„			Labeling	Insufficient
9	„	„	„			Legibility	Poor
10	Feedback report	Sentence 4	Message				Position-indication
11	„	„	Position-indication	recognize			
12	„	Sentence 5	Display				Pressure gauge
13	„	„	Pressure gauge	Read off			
14	:						

Lines 4 and 6 as well as 7 and 9 also show how the concepts in the columns (object, action, indication, property, element) can be differentiated up to any desired degree of resolution in that a sub-generic term is indicated in the element column of the generic term, while the sub-generic term in a subsequent line of the same sentence is again picked up in the object or property column. Overall, hypothetical sentence 1 in the table thus contains the same information as a flow text having the following shape: the opening of valve type

X was omitted due to time pressure. Furthermore, during opening, another valve of the regulator was set too high. When the error was investigated, it turned out that the label lettering was difficult to read.

The description table is structured in an implicative manner. This means that an action may be indicated only when an object was indicated. The same applies to the indication of an error that requires the indication of an action. Error conditions, finally, can be indicated only when an error was identified. Looking at it overall, the table structure here is built up from left to right. In the description table, every empty table box represents a question that must be answered by analyzing the event.

To make sure that all relevant factors are identified during acquisition and that an event will be examined to find out whether these factors played a role in the event, one must supply a complex taxonomy to answer the questions that were asked in the tabular structure. Taxonomies are also required in order to ensure the analyzability of the event by means of a uniform language used for acquisition, analysis, and judgement of cases. Here one can differentiate situation-describing concepts (object and action taxonomies), the error describing concepts (error taxonomies) and the cause or the concepts that describe performance influence factors (causal taxonomies). These taxonomies must also be capable of being broadened by new concepts in order to be able to consider the variability of the events. On account of structured procedures, one may consider all mentioned types of taxonomies within the generic MMS in that the following taxonomies are supplied in a manner sub-divided over the MMS components and the description stages:

- An object taxonomy for the object column
- An action taxonomy for the action column
- An error taxonomy for the indications column
- A cause taxonomy for the property column

The taxonomies can furthermore be sub-divided with relation to the MMS components (for example, causes related to the task for the activity, etc.). Taxonomies that are to be found in the literature were distributed over the components of the MMS (Appendix 2). By structuring the PSF according to the MMS components, the description makes it possible to consider all types of taxonomies and thus a wide range of possible shaping factors. As further pointed out by comparison of the various sources, the concepts that are used in the taxonomies are strongly tied to the goal of the line of questioning in the course of the causal analysis. Mostly cognitive, organizational, and system ergonomics error causes are being investigated in western industrial countries (for example, Bubb, 1992; Cacciabue, 1992; Embrey, 1992; Modarres et al., 1992; Fujita. 1992). They are particularly oriented toward current investigations and lines of questions (for example, non-full-load states, maintenance errors). On the other hand, classical ergonomic error conditions prevail in Eastern European taxonomies (see GosAtomNadzor, 1992).

3.2.4 Analysis of Cognitive Load and Cope

In Chapter 1, using the system ergonomics approach, we found a taxonomy to describe cognitive load. Furthermore, we set up a simple taxonomy to describe cognitive cope. Cognitive cope is modeled in the description model by means of individual error conditions or shaping factors that are matched up with the MMS component „person.“ These factors were worked out in Chapter 1: Information or Knowledge, Processing, and goal Reduction.

We use the system ergonomics taxonomy to describe the cognitive load that prevails within a MMS. The cognitive load is associated with a MMS and is given separately for each identified MMS within the description of the event. When system ergonomics is applied to the individual MMS of the event, then one can proceed according to conventional practices that are illustrated in Table 17. Cognitively more heavily loading system ergonomics configurations are marked in the table with „(+)“.

In contrast to the system ergonomics sub-division made in Table 7 (Chapter 1), Table 17 no longer shows the cognitively loading factor „feedback“ because it is already explicitly contained in the structure of the generic MMS.

Table 17 Rules for System Ergonomics Classification of Cognitive Load[6]

System Ergonomics Aspect	***Configuration (Load)***	***MMS Characteristic***
Operation Type	Simultaneous(+)	The sentence is used to describe the tasks and activities are units that have to be processed independently of each other. (cognitive activity: coordinate)
	Sequential	The sentence is to describe the task and activities are built upon each other. (cognitive activity: follow)
Dimensionality	Multi-dimensional(+)	Several system parameters are mentioned in the MMS. (cognitive activity: imagine)
	One-dimensional	A form of system behavior is mentioned in the MMS. (cognitive activity: expect)
Control Type	Dynamic(+)	Task and feedback in the MMS form a closed loop with a limited time window. (cognitive activity: track)
	Static	Task and feedback report in the MMS represents an open loop without time limitation. (cognitive activity: operate)
Presentation Type	Compensation(+)	The deviation from the goal stage (task) and the actual state (feedback) is now presented. (cognitive activity: identify)
	Sequence, pursuit	Goal state (task) and actual state (feedback) are presented to the individual next to each other. (cognitive activity: recognize)
Task Type	Monitive(+)	No activity is mentioned in the MMS. (cognitive activity: observe)
	Active	Activities are mentioned in the MMS. (cognitive activity: perform)
Compatibility	Internal(+)	The connection between information items on the input side of the individual must be established by the person himself or herself. (cognitive activity: associate)
	External	The connection between information items on the input side of the individual is established by the external illustration. (cognitive activity: match)

3.2.5 Aspects Regarding System Optimization

The investigations on the procedures of event analysis (Chapter 2), in particular those for the ASSET Method, in addition to the procedure addressed so far, made it clear that an estimation of the effectiveness of the precautionary measures will be required. In order to consider this aspect likewise, precautions taken in a final step of event analysis or improvement measures performed, can be included in the description model in that they are

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[6] As described in Sträter & Bubb (1998), the system ergonomics list of cognitive activities provides a methodological link between cognitive activities, task parameters and cognitive load. The cognitive activities are quite similar to the ones proposed in Hollnagel (1998) along with offering the analyst a decision scheme if only task parameters can be identified in an event or assessment problem (which is often the case).

appended to the description table. The precautions can also be described with the help of the object-action-indication-property-element description stages. Typical improvements are shown in Table 18. Here, again, several precautions relating to one event may be mentioned since sentences are used.

Table 18 Description of Improvements in the Description Model

Com-ponent	***Sentence***	***Object***	***Action (Verbal)***	***Indication (Error)***	***Property (PSF)***	***Element (Sub-generic term)***
Precau-tion	Sentence 1	Personal	train			
„	Sentence 2	Valve				Labeling
„	„	Labeling	improve			

3.3 Error Type and Error Conditions in the Description Model

In the preceding section we showed how one is to proceed in order to analyze an event with the generic MMS. According to an old basic principle in physics - to the effect that a new model or procedure must have at least the same explanatory value as the preceding models and must be able to explain the same observations - this section will summarize the performances and possibilities of the description model. The latter should correspond to those of the error models and evaluation procedures that were addressed in Chapters 1 and 2. In this section, we will answer three questions in this context:

1. What error types and error conditions can be derived from the description model?
2. How do they correspond to the error types of the models mentioned in the literature on the subject?
3. How can one use the description model to evaluate human actions?

3.3.1 Error Descriptions within the Model

The error descriptions to be differentiated are based on the idea that there will be a faulty system output in the MMS and thus an observable error in the work system whenever a weak point can be observed within the MMS that will lead to consequences at the system output. The error descriptions accordingly can be sub-divided into two types: (1) Error conditions that result from the information flow within the MMS (for example, wrong setting of a valve because there was no feedback). In this case we are dealing with a follow-on error from a weak point within the MMS that acts upon the individual. Such implications on the individual are possible by virtue of the task, the order issue, and the feedback. Indirect effects are operation, system as well as environment, organization and solution. These errors are depicted within the description table in that an error is entered in the „indication" column. (2) Error conditions that prevailed in an identified error (for example, poor arrangement of a procedure). The latter are depicted in the „properties" column within the description table. Error conditions are necessary conditions for a weak point in the MMS and point to ways of improving this component. Overall, we thus get various possibilities to describe errors within the description model. They can be labeled, according to the subdivision made in Chapter 1, as phenomenological, causal, and actional error descriptions:

- Phenomenological Error Descriptions (weak points in the MMS): These are all errors that can be identified within the individual components of the MMS.
- Causal Error Description (follow-on error in the MMS): These are all error conditions that are grounded inside the information flow within the MMS and that depict interactions between the various MMS components.
- Actional Error Description (PSF): These are all error conditions that can be indicated as properties within a MMS.

- **Phenomenological Error Description**

An error is always possible in a MMS when a MMS component is faulty. The following error states can be distinguished:

- Omission: Errors due to the failure to perform an action can occur only if a task is to be performed but is not accomplished. An omission must thus be associated with the input side of the individual in the MMS (task, order issue, feedback).
- Fault Action Commission: Errors due to a false action can occur only if an activity did not serve to accomplish an assigned task. Erroneous commission must thus be matched up with the output side of the individual in the MMS (activity, order dispatch).

- Human Error: A human error exists when all information within the other components of the MMS are available faultlessly.[7]
- Human mistake: A person has made a mistake when the fault human action is due to other components in the MMS.

In addition to these basic error types, one can derive the following additional error types from the basic error types:

- Error of Confusion: An error of confusion exists when, within a MMS, a task is neglected and when, in its place, another activity is performed falsely (for example, required: open valve A; actual: failed to open valve A and opening valve B is wrong).
- Sequence Error: A sequence error exists when, within a MMS, an activity is performed too early and when another activity is performed too late (for example, required: open valve A first, then open valve B; actual: valve B was opened too early and valve A was opened too late).

- **Causal Error Description**

Another possibility of error consists in the fact that the information flow within the MMS might be disturbed. Typical examples are errors in task assignment that lead to cognitive errors (for example, misunderstanding) or to action errors (for example, setting a value that is too high). These causal error descriptions result from the interrelationships between the components of the MMS or due to the information flow in the MMS. In Figure 16, all of them are labeled as arrows between the individual components of the MMS. The human error,

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[7] It is important to note that - according to Weimer - Human error and Human mistake is not meant in the sense as it is usually understood in English language, mainly influenced by the definition of Reason 1990 who assigns error to the skill-based level and mistakes to the rule-based or knowledge-based level (cf. Ch. 1). The German psychologist Weimer exhibited in 1931 the distinction between "Fehler - here translated with error" and "Irrtum - here translated with mistake": Weimer said: "Man befindet sich im Irrtum; einen Fehler begeht man - One is mistaken or one is making an error"; this means 'Fehler/error' is an active failure of the human whereas 'Irrtum/mistake' is accompanied by being convinced to do the right thing but this is wrong because of circumstances not considered during the action. This latter fact is now heavily rediscovered during the discussions of errors of commission (EOC) where the French Method MERMOS of EDF for instance avoids to speak about errors because one has to assume that the operators are convinced to do the correct and necessary things for the plant from their perspective - i.e. an 'Irrtum/mistake' in the sense of Weimer.

in a causal error description, is always to be viewed as a follow-up error after other errors in the MMS.

If, for example, a display is poorly grouped in functional terms, then this violation of ergonomic rules causes an error in the feedback which is expressed for the individual by virtue of the fact that the system state is poorly recognizable. The error thus relates to the feedback in the MMS. As a result of this causal PSF labeled „faulty feedback," we then, for instance, get an error of omission by the person (for instance, pump not started). This means that the human error is a follow-up error from the interrelationships in the MMS and it is not caused by the individual. Specifically, we get the following sub-divisions:

- Task Error. Task errors exist when there are errors in the task assignment (for example, imprecise assignment) or when there are errors in the content of the task (for example, poor organization of sub-task routine in terms of time). Task errors can also always be of a organizational nature (for instance, faulty order issue due to faulty written material).
- Execution Error. These are errors that were initiated by a faulty human action. In the MMS, „pure" errors of execution - that is to say, those that can be traced exclusively to the individual - exist only when one can observe exclusively errors of perception of the actual state, errors in information processing or action errors, without any other errors having been identified in the MMS. Errors of execution can also be of an organizational nature (for example, faulty order dispatch due to absence of means of communication).
- Ergonomic Error. Ergonomic errors are all those errors that result from defective design of work equipment (operation and feedback). They are characterized by errors in the design or arrangement of operating elements, errors in system feedback (for example, wrong reading in a display), or errors in signal transmission (or in feedback).
- System Ergonomics Errors. In addition, from the viewpoint of system ergonomics, errors may involve the design of the technical system. Factors that can lead to fault behavior in the individual, among other things, consist of the dynamics of the system, the compatibility between action and feedback, the dimensionality of the system, or the manner of operation. Typical examples of errors with system ergonomics meaning are couplings and meshing of the technical system in an error chain that result in the fact that a one-dimensional task, that is to be handled sequentially, is turned into a multi-

dimensional task that has to be handled simultaneously. This means that system ergonomics also considers the requirements for the individual that result from the dynamic behavior of a technical system.

- Errors in Certain Situational Conditions or Environments Conditions. Errors due to defective design of the environment are classical performance influencing factors (illumination, temperature, acoustics, etc.). By situational facts, we mean all those factors that can be of significance to the origin of the error chain from an across-the-board aspect (for instance, one and the same human intervention, such as, for example, opening valve A, is to be arranged differently under startup and turn-off conditions than in the case of full power operation).

The discovered weak points in the MMS are considered in a more differentiated fashion by virtue of the causal error description. As a result, one can find possible points of departure for improvements in the case of human errors by investigating the particular ergonomic significance of the component concerned in the MMS. The following example is intended to cast light upon this explanatory value of causal error description. If a signal - that acoustically and optically points to a disturbed operating state - is not recognized under conditions of noise, then, through the consideration of this event, we get the following weak points and improvement possibilities in the MMS, depending on whether the individual is considered as necessary (but not sufficient) condition:

- Perception (neglected) ⇨ Perception amplification: The improvement possibility that is most out-of-the-way for economic reasons is a training measure to alert the operator to the fact that, in certain situations and at regular intervals, he must check optical signaling.
- Inadequate Feedback (too little) ⇨ Display amplification: Signal transmission can be improved so that the signal can be heard.
- Disturbing Environmental Factors (too much) ⇨ Improvement of signal flow: Another thing to do would be to improve the signal flow in that disturbing environmental factors (disturbing sound sources) are insulated.

The example shows that possible improvement measures can be compiled early by considering the weak points in the MMS. The efficiency of the improvement measures, however, must be estimated on a case-by-case basis. In case of human errors, one might think of specifically target-oriented training measures; in case of defective ergonomic design of the feedback, one should perform structural measures. In the above example, of course, one can primarily think in terms of training measures when the ergonomic layout is defective. The efficiency, however, would be less than in the case of structural measures and the probability of a renewed occurrence of the error event would be greater.

Just what remedial measures should be taken can be determined by making a more precise analysis of the error behavior of the discovered weak points in the MMS. For this purpose, one must more accurately investigate the participating factors - that led to the erroneous behavior of the component in the MMS - by means of an actional error description.

- **Actional Error Description**

Error conditions (PSF) are given for an error in a component in the MMS in an actional error description. In the literature, these error conditions are mostly sub-divided into internal and external PSF (see Swain & Guttmann, 1983). According to Bubb (1992), this subdivision is identical to the load/cope concept because the external PSF are ascribed to the load, while the internal ones are ascribed to the coping possibilities of the individual. The subdivision into internal and external PSF can also be performed via the MMS components; the MMS, however, performs a more differentiated approach because the external PSF are subdivided in a manner related to the MMS components. This means that, regarding actional error conditions, the PSF illustrated in Figure 17 and Appendix 2 can be significant, something that applies particularly to the following:

- MMS component „task“: Complexity and time requirement of task (for instance, intertwining of various measures or dependencies between the effectiveness aspects of measures).
- MMS Component „operator“: Information processing by operator, which function is influenced by the knowledge of the operators concerning the system state and by the goals of possible measures.
- MMS Component „activity and operation“: Wide variety of measures to be performed and time requirement for these measures. Difficulty in carrying out the activities at the control stand or on the spot and ergonomic layout of the required aids.

- MMS Component „feedback“ and its perception: Messages and information to monitor introductory criteria and the effectiveness of a measure. Observability of system state or of disturbance image. Due to the disturbance picture, certain system magnitudes under certain circumstances could no longer be observed (for example, failure of filling level measurement due to failure of all signal transmitters).
- MMS Component „technical system“: System engineering dependencies of various safety systems and of systems that are used in the execution of a measure. Process dynamics and process behavior as well as the available time also play a role here.
- MMS Component „order issue and order dispatch“: Required organizational effort in the form of testing instructions, handbooks, phone communication, etc.

Along with the direct influence deriving from error conditions, a reciprocal interaction of various PSF may additionally be important in the search for improvement measures. The analysis of interactions makes it possible to analyze the action structure of the error chain on a broader basis (for example, poor designs of displays and poor arrangement of operating elements point to incompatibility of perception and activity). Interactions thus provide a more accurate picture of the situational information and the specific relationships among the shaping factors. They are important in order to understand the error chain that was significant in a very specific situation. Interactions also point to additional PSF that could not be observed directly so that the observed interactions of PSF can be interpreted as indicators for higher level shaping factors (for example, organizational shortcomings).

As for the significance of interactions between different PSF, one may use a sub-division by Bubb (1994) in directly acting PSF and indirectly acting PSF (Figure 23).

Directly acting PSF are those that are at work inside the immediate work environment of the acting individual. Indirectly acting PSF reflect interrelations between directly working PSF and thus reflect the management of the work process. In an event analysis, one can observe directly acting PSF by means of the ergonomic analysis in the MMS. In other words, they are entered in the property column of the description table. One may draw conclusions as to the indirectly acting PSF by analyzing the joint appearance or the interactions of directly acting PSF.

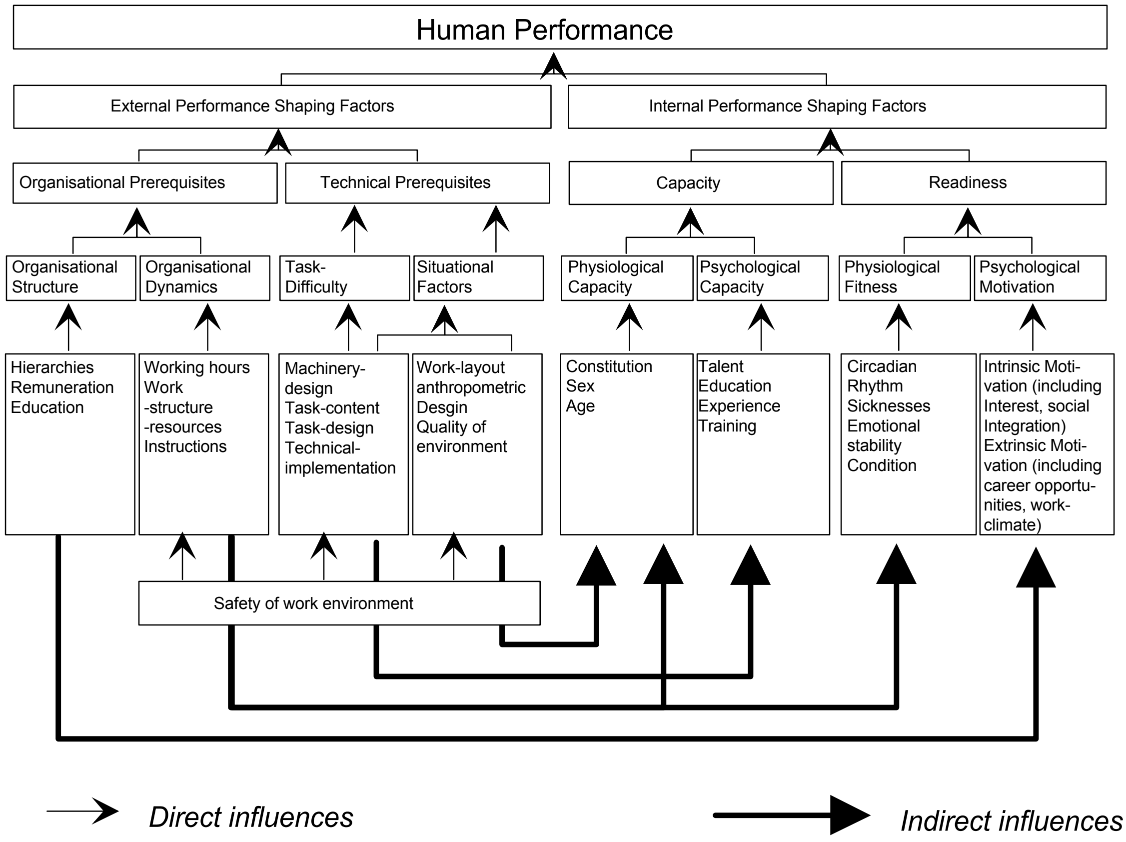

Figure 23 PSF that Act Directly and Indirectly on Human Performance (according to Bubb, 1994)

3.3.2 Error Models in the Description Model

The object of the description model is to ensure that information can be gathered for as many different error models and the HRA methods as possible. In the following, we will summarize which of the customary psychological error models can be imaged by the description model. For this purpose, we will tie in with the discussion of the error models at the end of Chapter 1. There, we worked out a solution for depicting cognitive process with relation to the cognitive error models that correspond to the causal error models. All cognitive error models that were mentioned in Chapter 1 thus are already considered in the description model through the analysis of cognitive load with the help of system ergonomics and of cognitive cope via the aspects of cognitive psychology. So far we have not investigated the extent to which actional error models or Hacker, Swain & Guttmann, Seifert and Brauser and of Rasmussen can be found again the description model.

- **Hacker**

As described earlier in Chapter 1, the model of Hacker (1986) is subdivided into missing or false information use. In the description model presented, missing information use is depicted by errors of omission on the task side. False information use is depicted by errors of execution. The cognitive processing stages - additionally listed in Hacker - which can lead to false information use (for instance, wrong design of action programs), are covered by the approach of cognitive load and cope.

- **Swain and Guttmann**

Swain & Guttmann (1983, pp. 4-10) assume a simple MMS for the identification of error-prone situations. It distinguishes the „main“ subsystem and its connections to feedback and operation (see Figure 5 in Chapter 1). This approach is almost identical to the MMS components of the description model. The description model expands the approach of Swain & Guttmann by some additional components and is thus in a position to provide a link between the PSF that were mentioned by Swain & Guttmann and that are described mostly separately from the MMS, on the one hand, and the description model, on the other hand (see Figure 17, compare to Table 5 from Chapter 1). As in Hacker, the cognitive processing stages mentioned by Swain & Guttmann are covered in the „man“ subsystem by means of the approach of cognitive load and cope.

- **Seifert and Brauser**

The error model of Seifert and Brauser (1987) is concentrated on the action mechanisms between PSF and error types. If one compares the model to the description model illustrated in this chapter, then one finds that the echeloned procedure of error description of objective information about error types leading to error conditions corresponds to the relationships in the error model of Seifert and Brauser. This means that all of the interrelationships touched on by Seifert and Brauser are depicted in the description model by the tabular structure with the object-action-indication-property-element description stages.

- **Rasmussen’s Multi-Aspect**

It was stated in Chapter 1 that the Multi-Aspect of Rasmussen (1986) can be viewed in the context of the load/cope model. The aspects on the load side here have a direct correspondence in the description model: the „personal tasks“ aspect corresponds to the input side of the individual in the MMS. The „situational factors“ aspect has a direct correspondence to the situation in the description model. The aspects of „PSF“ and „causes of human error behavior“ were already discussed intensively in this chapter and will be considered in the description model in a by far more differentiated fashion than is the case in the figure given by Rasmussen (1986). The aspects on the cope side („mechanisms of human erroneous behavior“ and „internal form of erroneous behavior“) again are covered by the approach of cognitive load and cope.

- **Reason**

As shown in Chapter 1, Reason makes a sub-division into intentional and unintentional errors. Both error types relate to the cognitive processes of the individual that take effect in an erroneous action. Intentional errors are made by the individual with intention, in other words, consciously; unintentional errors are made without intention, in other words, unconsciously. On account of the discussion in the first Chapter, as to the fact that cognitive dissonance is required to develop a conscious goal idea and thus an action intention, one can consider intentional errors in the description model as errors based on erroneous goal ideas (goal reduction) and one can consider unintentional errors as errors based on faulty information processing (processing).

3.3.3 Specific Aspects of the Description Model regarding HRA Methods and System Optimization

To be able to use the information obtained in the context of the description model in HRA or for purposes of system optimization, one must, in addition to the discussed error models, depict additional aspects that were touched on in Chapter 2. Here they are:

- Support for screening,
- Transferability of individual results,
- Illustration of action areas and action types,

- Analysis of latent and active errors,
- Effectiveness of recoveries,
- Dependencies between actions,
- Effectiveness of measures aimed at system optimization,
- Safety engineering significance or consequences of error.

All of these aspects are depicted within the description model by concept combinations. In the following we will show what these patterns look like.

- **Support for Screening**

A HRA evaluation as a rule extends from rough analyses to fine analyses (see Chapter 2). In the early phase of a PSA one must first of all find those actions that lead to significant contributions for the overall risk of the course of the event considered. To filter these actions out, one must make a rough estimate. In precision analysis one then evaluates only those actions that make an important contribution in rough analysis.

The description model is in a position to support these abstraction procedures. Rough analyses and precision analyses can be considered by virtue of the degree of abstraction of the inquiries for the recovery of data collected with the description model. If, for example, in the rough analysis, we want to evaluate how great the potential of an error of omission is, then one may look only for errors of omission. In precision analysis we are required, for instance, to find all events where a valve was not opened from the control stand.

The transferability of data runs counter to the degree of detailing during screening because data on human reliability, on the level of rough analysis, are basically more generally valid or better transferable then data on precision analyses.

- **Transferability of Individual Results**

In analyzing events to make an evaluation of human reliability, we always arrive at the question as to the extent to which collected results are at all comparable to each other in the first place. The problem of transferability of events here essentially consists in the fact that each event occurred in a very specific condition constellation that is not present in other events in that form. In order, nonetheless, to transfer events and thus to be able to compare events, they must agree regarding certain characteristics or marginal conditions. These characteristics or marginal conditions must be comparable to each other in some form from the ergonomic angle.

Because the MMS customary in ergonomics was chosen as the point of departure for the description model, we can also say that the transferability of various events is ensured because the model, by definition, is geared toward investigating different working systems for identical ergonomic marginal conditions (see Bubb, 1993).

Various data for ergonomic analysis may be combined in the description model by virtue of the structured form of the event illustration related to the components of the MMS and the description stages (object, action, indication, property, element). For instance, all errors of omission that came about due to the absence of feedback can be combined in that the word „neglected“ is used in the indication column of the MMS component „task“ and that, in the indication column, entitled „feedback“ the word „ missing“ is used. Due to agreement of these ergonomic marginal conditions, it is possible to transfer various events to a question statement (for instance, „How large is the share of omissions due to absent feedback?“), although the events need not be directly comparable regarding the technical component.

Transferability of events in the description model is thus ensured in that the MMS is the foundation of the generic description model. Within the generic description table, transferability becomes possible in that one looks for ergonomically relevant error patterns instead of specific aspects that were of significance in the event.

- **Description of Action Areas and Action Types**

The differentiation among action areas within the MMS is important in order to reproduce correctly the various possibilities of modeling human interventions in a PSA. In Chapter 2, we said that one must consider actions from Type A in the failure rates of the technical components, that one must consider actions from Type B in connection with the frequencies of occurrence and that actions from Type C must be considered in the basic events and the courses of events. In the generic description model, action Type A is depicted by task or activity errors within the MMS, although they do not lead to any observable erroneous system state (latent error). In these actions, in other words, the system is faulty but not the system output. Actions from Type B are depicted in the MMS by task or activity errors within the MMS where one can observe a faulty system state and, as a direct consequence, a faulty system output. Action from Type C are a direct reaction to the disturbed system output. They lead either to a flawless system output in the MMS, in other words, the improve the state (recoveries) or they again lead to a faulty system output in the MMS, in other words, they degrade the state. These actions thus can be recognized in the MMS in that the primary task of the operator is to correct a particular trouble. Figure 24 summarizes the entire situation.

- **Analysis of Latent and Active Errors**

In Chapter 1, we made a distinction between latent and active errors. Latent errors are of special importance because they are concealed (in other words, they are not observable to a certain extent and they are not directly observable) and thus can weaken system safety. They are observable only when the error is discovered or manifests itself by a failure of the components in response to a demand from the system.

The description model depicts latent errors in that there is a faulty system although it has not yet led to a false system output. Active errors, on the other hand, lead to a faulty system and to a false system output. During the discussion of action types, we already showed how both error types are depicted as error patterns within the MMS (Figure 24).

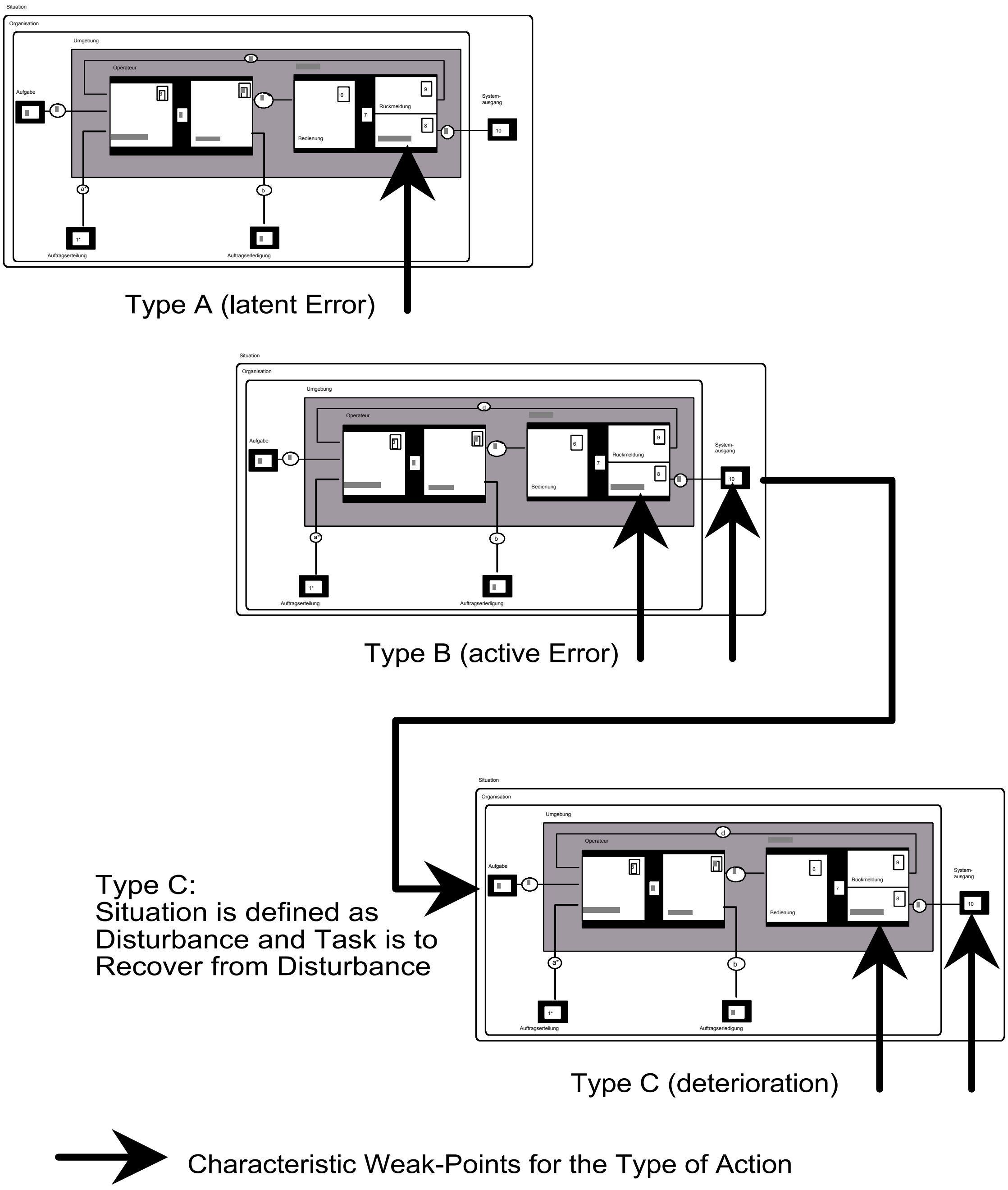

Figure 24 Characteristic Weak Points in the MMS to be used in Classifying Action Types A, B and C

- **Effectiveness of the Recoveries - Error Corrections**

We can distinguish the following types of recoveries:

1. Recoveries that are made by the person himself or herself or by another person already prior to the commission of the action.

2. Recoveries that are made by the person himself or herself or by another, directly after the faulty actions and that reverse the faulty action itself.
3. Recoveries that are performed after a faulty action and that consist of the start-up of substitute systems.

4. Error corrections that are performed after a faulty action and that correct the effects of a faulty action or a faulty technical system by repairing a technical component.

Recoveries are depicted in the description model in that an error of commission was successfully reversed by actions that are described in a subordinate MMS. But here one must keep in mind that Type 1 recoveries in practical operational experience are not observable as errors of commission. At best, one can draw conclusions regarding them in that two persons are in a state of dependence with each other (for example, by means of communication). It will be stated in the next point that this type of recoveries can thus be depicted through the consideration of dependencies. Type 4 recoveries are characterized in that the recovering measure consists of the repair of a technical component and not of switching measures as in Types 2 and 3. In Type 2, the corrective measure pertains to the same technical system as the faulty action, whereas in Type 3 it pertains to another technical system.

- **Dependencies between Actions**

The determination of dependencies is particularly important for estimating possibilities for error discovery in the HRA methods. Figure 20 regarding event breakdown clearly showed that the dependencies can be considered in the description model. Overall, the dependencies addressed there between persons, situations, and places can be differentiated according to Table 19. The sequence given there was prepared on the basis of plausibility considerations (equivalence of situations can be graded as very significant, equivalence of persons can be graded as significant, and equivalent of places can be graded as less significant). Hints regarding the validity of this subdivision and sequence can be found in investigations pertaining to the psychology of organization (see, for instance, Schuler, 1995; page 327).

Table 19 Presentation of Possible Dependencies in Description Model[8]

Number	*Situations*	*Persons*	*Places*	*Dependence*
1	Equivalent	Equivalent	Equivalent	Completely dependent because all characteristics are the same
2	Equivalent	Equivalent	Not equivalent	High, because the two decisive ones are equivalent
3	Not equivalent	Equivalent	Equivalent	Average, because only one of the decisive ones is equivalent
4	Equivalent	Not equivalent	Equivalent	Average, because only one of the decisive ones is equivalent
5	Not equivalent	Equivalent	Not equivalent	Minor, because only one characteristic agrees
6	Not equivalent	Not equivalent	Equivalent	Minor, because only one characteristic agrees
7	Equivalent	Not equivalent	Not equivalent	Minor, because only one characteristic agrees
8	Not equivalent	Not equivalent	Not equivalent	Completely independent because no characteristic agrees

- **Effectiveness of Measures Aimed at System Optimization**

Within the description model, one can also judge the effectiveness of measures aimed at system optimization in that the components of the MMS - for which weak points and PSF were identified - are compared to the measures that were taken (inadequate arrangement of feedback report would, for instance, be bound to have ergonomic measures and not lead to personnel training). Optimization measures must be in keeping with the typical properties of the MMS component that was identified as a weak point (see Table 20).

Table 20 Prediction of Optimum Effectiveness of System Optimization Measures

Weak Point found in MMS *Improvement of Information flow with regard to the following*	*Person* *- Person*	*Organization* *-Task* *(Task assignment)* *- Order Issue* *- Order Dispatch*	*Technique* *- System*	*Ergonomics* *- Task* *(Task content)* *- Activity* *- Feedback*
Person	¿			
Organization		¿		
Technique			¿	
Ergonomics				¿

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[8] This distinction is in accordance with the recently published dependency model published by Byers et al. (2000).

As shown in Table 20, there should generally be agreement between the weak points discovered in the MMS and the measures that were taken, if the measure is an adequate means for preventing similar errors and thus for the purpose of system optimization. It should be noted further that two aspects must be differentiated regarding the task: (1) The organizational aspect of the process of task assignment and (2) The ergonomic aspect that is based on the task content.

- **Safety Engineering Significance or Consequences of Error**

The Safety Engineering Significance of an event is determined by the technical systems that were damaged as part of the event or that did not respond correctly when a demand was placed upon them.

Both aspects are depicted in the description model in that the consequences of the error are always described as the system and system output in the MMS. Because this is also done in a manner subdivided into to the description stages of object-action-indication-property-element, an analysis of the Safety Engineering Significance is possible in that, for example, the object column of the „system“ MMS component is searched for components that are significant in terms of safety engineering.

3.4 Discussion

A semantic analysis method was developed in this chapter for the purpose of analyzing events. The method is in a position to inquire as to information that is required for different error models, HRA, or system optimization. This was demonstrated with the help of a discussion of error models and specific aspects of the hitherto used HRA methods.

Here it should be emphasized that the method avoids assigning culpability to a person in that the event is analyzed starting with the error situation and not starting with the participating persons. This feature of the description model was discussed earlier in Chapter 1 as being critical for event analysis. The chosen description model thus is also in line with the intention of the definition of a human error given in Chapter 1 because it describes the work system as completely as possible and does not approach it in a one-sided fashion. The echelon procedure furthermore facilitates a standard acquisition of events.

In conclusion, we will now summarize the performance features of the description model and address essential differences with respect to past methods of event analysis.

3.4.1 Performance Characteristics of the Description Model

Summarizing, we can highlight the following performance characteristics of the description model:

- By virtue of the acquisition of the information related to the components of the MMS, the description model proceeds in a situation-related fashion instead of focusing on the error of the individual during the analysis. It thus analyzes an event regardless of the question as to the culpability of a person in the event.
- By using the description stages (object-action-indication-property-element), the description model offers both great flexibility in event description, that takes the variability of events into account, and the possibility of a consistent and detailed analysis of events regarding human error.
- By forming sentences in the description stages, the effect interrelationship between errors and PSF is preserved and offers broader possibilities of analysis than do independent indications.
- With the help of an element column, the description model is in a position to consider process engineering and ergonomic knowledge in any degree of resolution.
- The description table that is put on by the description stages and the components of the MMS ensures better transferability of the collected data than is the case in simple taxonomies, because ergonomic marginal conditions become comparable.
- The procedure for event description thus represents both a scheme for the acquisition of relevant information and a way to analyze an event and thus ties event description and event analysis together.

- Error types and error models, such as they are known from literature, and such as they are used within the HRA methods or event analysis, can be depicted as concept patterns in the description model.

Many of the requirements presented at the end of Chapter 2 have already been put to practical use with the help of the performance characteristics listed here. One point that was not addressed was the extent to which the description model presented here differs from the event analysis methods used until now. Accordingly, at the end of this chapter, we want to discuss essential differences with respect to past methods used for event analysis.

3.4.2 Differences with Respect to Past Methods of Event Analysis

The method features a decisive difference when compared to the existing methods for analyzing and evaluating events that were presented in Chapter 2. The methods that were illustrated there describe and analyze an event in that one looks for one or more descriptors that characterize the course of the event in an optimum fashion. As a result, possible answers are heavily standardized and can be used easily.

The process presented in this chapter describes an event within standardized description stages and not by means of previously specified descriptors. Here, in other words, the procedure itself is analytical during event description as such: the description stages are determined, but the concepts used for description are hardly standardized. This means that the method offers possibilities similar to those of a free text; the many fold and differing aspects of various events however can be described uniformly by means of the chosen description structure within the determined context. As a result of this procedure, data however can no longer be analyzed with simple means (for example, frequency accounts of descriptors).

On the whole, both procedures are in a so-called trade-off relationship, that is to say, in the case of aspects, where one approach offers advantages, the other one has weak points. The trade-off relationship also pertains to the acquisition of information and to the analysis of information from the collected events. The essential aspects of trade-off which result with regard to the acquisition and analysis of the data are compiled in Figure 25. Generally, standardized methods with fixed descriptors offer advantages in terms of reliability, whereas open procedures offer advantages regarding validity.

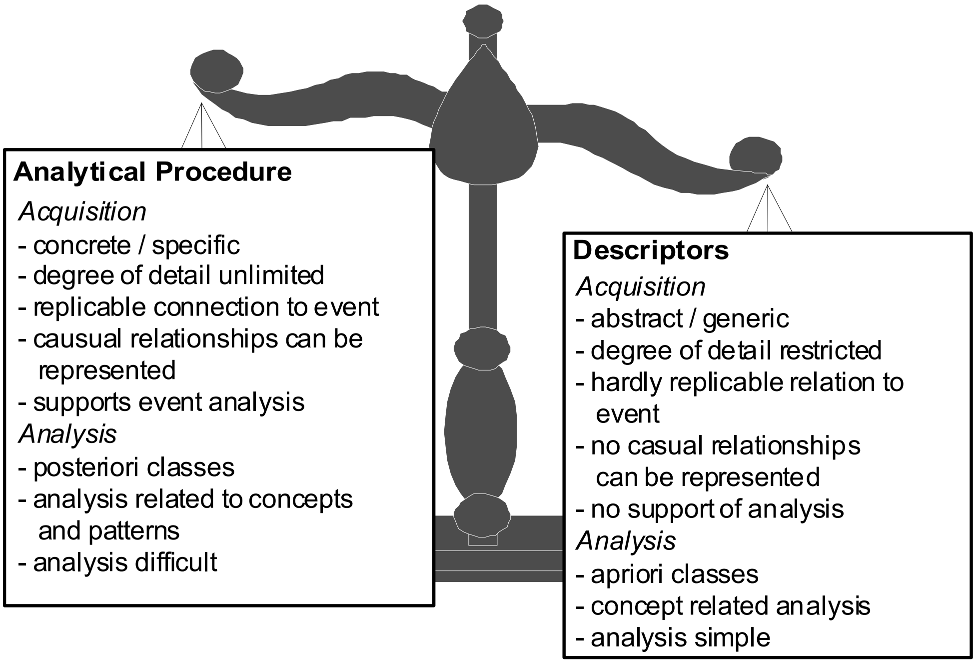

Figure 25 Trade-off between Analytical Procedure versus Descriptors

Descriptor-oriented methods appear to be superior to the analytical method developed here for the simple reason that the heavily standardized possible answers and the collected information is thus easily analyzable. This brings up the question as to why the description model is developed is required and why one does not chose a descriptor-oriented process here. We can distinguish the following efforts in answering this question in order to gain indications of human reliability from events and to take into consideration the many evaluation parameters for an evaluation of human reliability.

- Expenditure connected with description of course of event,
- Expenditure during analysis of events,
- Usefulness in answering questions that extend over several events,
- Effort connected with analysis of information.

- **Effort During Description of Course of Event**

Descriptor-oriented methods seem to be advantageous in making an event analysis for the simple reason that they do a better job in describing events because concepts are found that reproduce the essential characteristics of the event. As for the acquisition of information, descriptor oriented methods present one chief difficulty, and that is to find the most meaningful possible descriptors that (1) can be handled in a clear fashion and (2) can characterize the course of the event in an apt fashion. But this means that the possibilities of illustration inherent in the descriptor oriented methods are always restricted because each event has very specific characteristics that cannot be considered with the help of a fixed taxonomy and that are lost for subsequent analysis.

If one were to try to depict specific characteristics of an event by means of descriptor oriented methods, then one quickly reaches the limit of technical applicability. If, for example, one uses Table 14 as basis for error description, then, for complete description of all possible error types, that can be depicted within the MMS, we need at least n = (4*1) + (4*6) = 28 descriptors (4 possible faulty MMS components with one type of error on the input side of the person and 4 possible faulty MMS components with six error types on the output side). But here we cannot as yet distinguish any relationships (for example, errors on the input side and follow up errors on the output side of the person). The consideration of additional effects (for example, reciprocal interactions with technical components or type of faulty actions, such as „opened falsely“ or „closed falsely,“ etc.) would further increase the number of descriptors. In that way, one can easily see that descriptor-oriented methods when analyzing events on the detailed level quickly run into the limits of practical implementability.

With the descriptor-oriented approach it is thus basically impossible to acquire events that both consistent and detailed indications are possible about human errors. This advantage emerges particularly clearly when one is to investigate interrelationships between different aspects that played a role in the event, because interrelationships cannot be depicted by mutually independent descriptors. On the other hand, the description stages presented in this chapter (subdivided into object, action, indication, property, element) facilitate a language in the form of simple sentences (for example „fail to close valve due to insufficient labeling“). This means that the standard-language used in the description model, offers similar illustration possibilities and a similar information content as does the free text; each event can be described with its own specific features and their interrelationships (see Sträter, 1991).

- **Expenditure for Analyzing Events**

One is guided by the structured procedure also in event analysis (by observable information on errors related to PSF). This kind of support for analysis is impossible in this form with descriptor-oriented methods. Another advantage of standardized language is represented by the fact that the indications that are given in the description stages precisely correspond to the degree of detailing that is required for an analysis of operational experience with a view to data on human reliability in human reliability analyses (see Table 21).

Table 21 Difference between Descriptors and Standardized Language

Required level of detailing for use of information in a HRA (corresponds to the level of detailing of the description model)	***Description by means of a descriptor***
Operator neglects step in procedure	„Omitted measure“
Operator fails to inform shift leader by phone	„Faulty communication“

This means that the description effort of the method presented in this chapter is necessary in order to attain the degree of detailing that is required for an analysis of the events regarding different HRA methods. A completely filled out description table is a stop rule for ensuring that the analysis will be complete regarding a question asked as part of an HRA.

- **Usefulness in Answering Event-Overlapping Questions**

When it comes to analyzing information, descriptor-oriented methods enjoy a presumed advantage in that one need merely try to find out which descriptor played a role with what frequency in what event. But if one looks at the procedure as to how a descriptor is given for an event, then this advantage turns out to be an essential factor in a situation where descriptor-oriented methods lead to a greater effort in the analysis of events.

In event analysis, descriptor-oriented methods proceed in such a way that an analyzing person concentrates on the course of the event and then matches the event up with certain descriptors. As a result, the direct connection between the course of the event and the classification of the event is lost. This is because descriptors and event description are independent of each other. If another person wants to replicate the classification, that person is forced to work through the entire event all over again.

The same problem occurs when events are to be investigated according to aspects that were not described by a descriptor, as shown by the following example: The descriptor „neglected measure," mentioned in Table 21, cannot be used for the purpose of finding all cases where a procedural step was neglected. If this descriptor is used in a search for all neglected procedural steps, then it is necessary once again to search all events - where the descriptor „neglected measure" was given - in order to find whether the neglected measure was or was not shown as procedural step. This problem of descriptors basically is not changed either when one introduces an additional descriptor entitled „neglected procedural step" because the same problem occurs during the recovery of information in a slightly different question (for example, neglecting to open a valve).

A combination of two descriptors, of course, does restrict the search effort but still does not offer any clear solutions. If, for example, one were to search for all events where the descriptor „neglected measure" and the descriptor „procedure" were given, then the search area is of course restricted; for final clarification, as to whether a procedural step or some other measure were neglected, one must, however, once again investigate all discovered events because the two descriptors may have been given out independently of each other.

Looking at analysis with respect to human reliability, a descriptor-oriented procedure thus means that, for every aspect that is to be newly investigated, one must fall back on laborious individual analyses of the events. It was stated earlier that taxonomies for this reason are always oriented toward certain questions and thus always permit a unilateral and thus incomplete analysis of events. Descriptors thus do, of course, perform a reduction of information during the acquisition of events; but that happens at the expense of the effort connected with a detailed analysis.

Summarizing, we can say that descriptors always run into the limitation of meaningful applicability when the same data material must be analyzed with respect to many-fold aspects. They are thus not suitable for analyzing events connected with the analysis of human reliability because, in this case, one must consider a plurality of differing evaluation parameters (see Chapter 2). The description model developed in this chapter, on the other hand, ensures the replicability of the event description because an event is simultaneously acquired, analyzed, and documents in the description stages. This integration is possible because the analysis of events is built up starting with general questions on information that was observable during the event (object column, action column) and because only then is there a mention of error indications (indication column) and shaping factors (property column). That ensures that the effect interrelationship between actions, errors and shaping factors will be illustrated and that one determines what the PSF acted upon. The model is thus in a position to depict the specific situational interrelationships of errors.

- **Effort during Information Analysis**

The description model, however, demands a method for analyzing the collected data which is in a position to search for concept patterns in the events. In order to filter a specific aspect - that is important for a HRA investigation - out of the events (for example, neglect of a procedural effect), one does not look for the descriptor „procedural step neglected“ in the collected events, but rather one looks for the situation describing pattern as illustrated in Table 22.

Table 22 Situation Describing Pattern to Search for Events in which a Procedural Step was Neglected

Component	***Object***	***Action (Verbal)***	***Indication (Error)***	***Property (PSF)***	***Element (Sub-generic concept)***
Order Issue	Procedure				Procedural Step
„	„		neglected		

This means that the description model can be used meaningfully only if one can find a model for analysis which, in a similarly simple manner, permits analyses of concept patterns, such as is currently possible in frequency analyses of descriptors. Such an analysis model will be developed in the following chapter.

4 Model for Evaluation of Information from Events

The description model that was presented in the preceding chapter supplies data closely along the lines of natural language, in the form in simple sentences and is thus in a position to depict interactions to be observed in events as we have so far only seen with relation to the description of events in the form of text (for example, in Mosey, 1990). As observed in the last chapter, an evaluation model is necessary because the information contained in the description model cannot be analyzed with simple methods of frequency analysis. Here also lies a reason why such a complex method for event description and event analysis as was presented in the preceding chapter currently has not yet been put to any practical use, although it has a higher explanatory value when compared to simpler procedures. On the other hand, the information collected from the events can be used meaningfully only if, along with a high declaratory value, it can also be analyzed without any major effort and when general statements can be obtained. This means that a method that can analyze the description structure developed in the last chapter is inseparably connected with whether the analytical procedure presented there can at all be used in order to gain statements about human reliability.

But how can a plurality of events, gathered with the help of the description model, be analyzed so that qualitative and quantitative data on human reliability will become possible? The goal of this chapter is to answer this question. As indicated in Chapter 3, the evaluation of data that can be obtained by means of the description model is basically a methodological problem of processing the large number of possible relations between the concepts that are used within the description model to describe an event. To develop the analysis model we will first of all depict the desired evaluation aspects and the structure of the data obtained in the description model. Then we will address the problems of putting together the evaluation model with the help of simple databank algorithms; and we try to correct these problems with the help of methods taken from artificial intelligence. Building on that, we will finally develop and discuss an evaluation model.

4.1 Aspects of Evaluation

To convey an idea of the problem complex of event evaluation, Figure 26 shows an excerpt of a part of Table 16 from Chapter 3 as a semantic network. In evaluating events, we must now evaluate several such semantic networks of individual events as a whole. The problem connected with evaluation here is this: on account of the variability of event descriptions, the concepts that are used can appear in almost any random combination. For instance, in all collected events, the indication „omit“ can be associated with a valve or a switch or with the action „open“ or „close“ etc. Shaping factors can also be associated with several objects (for example, the arrangement of signal lamps, switches, valves, or the like can be inadequate). Furthermore, each concept can occur in any MMS (as initiator or in connection with error correction) and this can happen there in several MMS components (for example, „valve“ related to the task or related to „activity“).

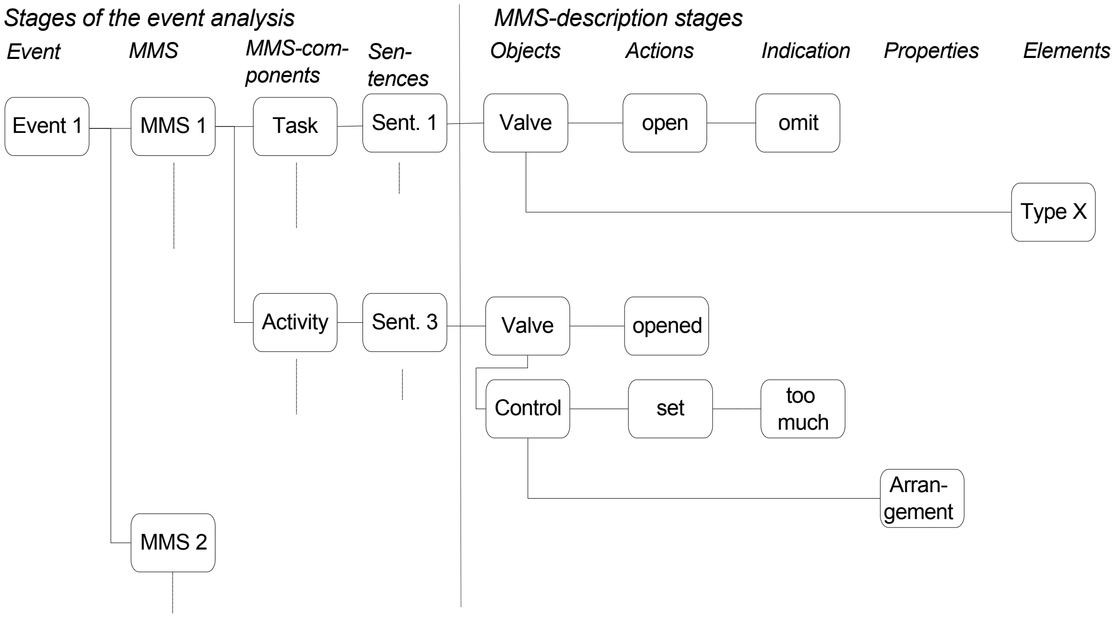

Figure 26 A Simple Example of a Data Structure Obtained with the help of the Description Model

One general problem is connected with analysis: the information from several collected events must be reduced so that they can be used for the desired analysis possibilities. Accordingly, in the following, we will compile the required analysis possibilities and we will explain them on the basis of the example given in Figure 26.

4.1.1 Required Analysis Possibilities

It was made clear in Chapter 2 how multi-layered the questions of HRA are. In order to be able satisfactorily to supply all of these questions with data, we find that a simple frequency analysis evaluation of the information of the description model is not sufficient; this point was noted at the end of Chapter 3. The main features that the analysis model should have may be summarized considering the results of the prior chapters according to Figure 27. Those aspects, that are to be selected according to the events, are described here as data keys or access keys; the process of data recovery is generally referred to as retrieval (see Wiederhold, 1981).

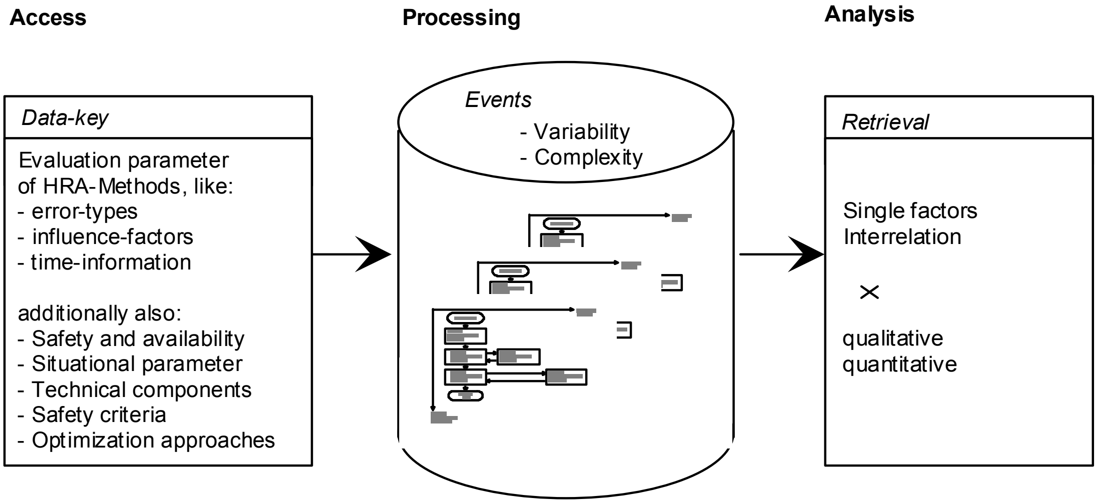

Figure 27 Required Analysis Possibilities from the Collected Events

- **Access to Collected Data**

The analysis method must allow different access possibilities to the data (so-called data keys in databank terminology). In Chapter 2, by way of example, we mentioned the evaluation approaches of the HRA methods (error types, shaping factors, and time) as required access possibilities. Other access possibilities must be given in addition for other questions. If, for instance, a valve of Type X is of significance in terms of safety engineering, then it must be possible to determine certain errors and shaping factors with relation to that valve. Ideally, therefore, every concept or every combination of concepts must be capable of being used as a data key for the analysis of the events. Meaningful event analysis must also be in a position to find events that are essentially alike, in other words, events that correspond to each other with respect to certain features or feature patterns (for instance, shaping factors in erroneous actions on valves). The analysis model must have the following properties because the event descriptions are endowed with a high degree of variability.

1. Class formation: Every concept, that is used to describe an event, must be capable of being analyzed as individual concept but also with relation to a class (for example, error types in case of a Type X valve or related to the class „valve“). This property is necessary so that the analysis method may be sufficiently flexible in order to analyze data on differing levels of detailing.
2. Variable access: Access to an event must always be possible via every class, every concept, or every combination of several classes or concepts (via a pattern of characteristics) (for example, frequencies of errors of omission should be determined for all valves or only for valves of Type X). Furthermore, it should be immaterial whether the frequency is determined on the basis of an error (for example, „omit“) of an object, „valve“ or of a shaping factor (for instance, „arrangement“).

- **Processing of Collected Data**

The variability and complexity of events harbors additional problems when it comes to the processing of data. The following must be possible when processing the collected data:

1. Ability to Learn: On the basis of the variability or wide variety of possible events, the process must be capable of being expanded by means of new concepts and classes and one must also be able to analyze the data that are related to these newly formed classes (for example, a Type X valve, so far has never been involved in any events, must be capable of being inserted in the hierarchy of concepts of already existing valves). This means that the analysis method would be in a position meaningfully to integrate new concepts into already existing ones, in other words, it would be capable of learning.

2. Determination of Similarity: All events that correspond to each other with regard to the pattern of characteristics of the inquiry must be found again by means of accessing inquiry (for example, all errors of omission on valves).
3. Random Degree of Detailing: Regardless of how detailed it is put, each inquiry must lead to a clear solution (for example, it must be possible to determine frequencies for general statements on erroneous actions on valves but also for errors of omission on Type X valves).
4. Combinations: It must be possible to provide a clear solution not only for individual concepts but for every combination of concepts or classes. This means, for instance, that cup quantities and combination quantities must delivery correct frequencies in spite of differing degrees of detailing (for example, the cup quantity from (valve$\cap$omitted)$\cap$(Type X$\cap$omitted) must not exceed the quantity „valve$\cap$omitted“ because this is a super-quantity of the first inquiry).

- **Analysis of Collected Data**

The analysis model should make it possible to identify influences among describing factors, error types and shaping factors, and to quantify their significance. There are two target directions here that are important in the evaluation of human reliability: (1) Quantitative predictions on error frequencies and the frequency of shaping factors in order to evaluate human reliability. (2) Qualitative data on shaping factors and their interrelations in order to determine possible influences deriving from different factors and to find improvement possibilities. For this purpose, the analysis method must be in a position to perform a data retrieval with regard to the following two aspects:

1. It must be possible to determine the frequency of occurrence for each concept, each class, or each combination of concepts and classes. This is necessary to form quantitative data. In other words, it must be possible to determine the frequency of any statement in order to be able to answer questions such as these: „How often did errors of omission occur on valves?“
2. Relations: For each concepts, class, or each combination of concepts and classes, it must be possible to establish any relationship to another concept or another class. This is required to determine qualitative data. In other words, it must be possible to determine every relation in order to be able to answer questions such as

these: „What shaping factors can be observed in connection with errors of omission on valves?“

4.1.2 The Data Structure of the Description Model

The analysis possibilities that were described in the preceding section must relate to the data structure of the description model. Accordingly, one first of all makes the following agreements concerning the description of the data structure of the description model.

- **Objects and Classes**

All descriptions of events consist of a number of concepts that have significance. A significant element (for example, a concept, an object, or a class) is in research on artificial intelligence generally referred to as an entity (see Shastri, 1988). The following style is determined for each entity:

Entity , if it does not contain any other sub-concepts *(3)*
[Entity] , if it does contain additional sub-concepts

This gives us the following for each MMS component or each description stage:

[MMS-component] Î {[Situation], [Task], [Person], [Activity],[Feedback],
[Order Issue], [Order Dispatch], [Environment],
[System]}

or

[Description stage] Î {[Object], [Action], [Indication], [Property], [Element]}

or, for the error taxonomy

[Indication] Î {omit, false, faulty, too much, too little, ...}

A certain element or a certain concept of a quantity of entities is indexed as follows:

$$[Entity]_i(4)$$

The allocation of an entity to a superordinate class is called instantiation and is performed by the operator „=“. The first indication in the above example thus reads as follows:

$$Indication_1 = omit$$

The frequency, with which an entity was observed, is given as follows:

$$h([Entity]) \qquad (5)$$

In the description structure, each entity is determined with relation to the MMS components and the stages of description. This situation is illustrated by two entities separated with the dot operator „.“. This, for instance, gives us the following instantiations for an error of omission in a task or the taxonomy for the designation of persons:

$$\begin{gathered} Task.Indication = omit \\ or \qquad (6) \\ [Person.Object]\ \hat{I}\ \{Control\ stand\ personnel,\ Control\ personnel,\ Manufacturers\ personnel,\ ...\} \end{gathered}$$

- **Statements and their Valence**

The analysis model is to help gain statements about human reliability from the collected events. All entities that are used in the events for purposes of description are thus combined into the basic quantity Ω.

Every statements A then consists of one or several entities $[E] \in \Omega$ that are tied in with logic operators Op. The following operators are chosen: AND tie-ins and OR tie-ins of two concepts should be possible as fundamental operations. But NOT statements should also be possible. They however are one-sided; that is, they perform an operation on a concept but they do not tie it in with any other one. In order to be able to tie such NOT statements in with others, we will in the following introduce the AND NOT tie-in. It ties a concept in with the complement of another concept, for example, the following statement applies to all valves outside the control stand: *A='[Object]*$_i$*= Valve AND NOT [Environment]j= Control stand).* On the basis of these considerations, the logic operators for the construction of statements are given by the following (see Ameling, 1990):

Op Î {AND, AND, NOT, OR} (7)

The following convention should be agreed regarding the formulation of the statements: when considered in terms of the theory of quantities, the first concept of a statement is always tied in with the basic quantity Ω. This circumstance is mostly neglected in the formulation of statements but will be considered in the following in order to be able to indicate an operator for the first concept of a statement (this convention also serves for the equal treatment of all elements of a statement and offers advantages regarding the analysis model to be presented as we continue this chapter). The quantity-theory expression A= Valve∩open∩omit thus and in logic notation corresponds to the expression A=Ω AND Valve AND open AND omit or, simplified, A = AND Valve AND open AND omit.

When several entities are combined to form a statement then OR-tied entities have equal standing and can be combined to one class (for instance, the statement A=AND „open“ OR „close“ OR „set“ can be combined into the class K= „activate“. But they can also stand explicitly next to each other. In this case, the OR-tied concepts relate to the previous AND NOT-tied concept and during the analysis, they must be treated like a class. For example, the statement A=AND „Valve“ AND „open“ OR „Close“ OR „set“ AND NOT „omit“ can be worked up as follows:

A = AND 'Valve'
(AND 'open' OR 'closed' OR 'set')
AND NOT 'omit'

Accordingly, the valence of a statement should be defined according to the number of AND or AND NOT-tied entities as follows:

Valence of a statement A = (8)
Number of all {AND; AND NOT}- tied entities [E]

If a statement B consists of several n-valence statements [A], then each statement B is designated as a sentence if the statement if composed as follows:

$$B = \quad AND\ [Object]_i\ AND\ [Action]_j\ AND\ [Indication]_k$$
$$AND\ [Property]_l\ AND\ [Element]_m \qquad (9)$$

Sentences can also be incomplete here. Thus, valid sentences are, for instance:

B_1 = *AND Valve AND open*

B_2 = *AND open AND omit AND time pressure*

etc.

A statement with several sentences is designated as a complex statement. The sentence valence of complex statement C is then analogous to the valence of a simple statement by virtue of the number of the {AND; AND NOT}-tied sentences [B] as follows:

Sentence valence of a complex statement C = *(10)*

Number of all {AND; AND NOT}-tied statements [B]

- **Relations and Combinations between Entities**

All entities that are used to describe an event are in a relationship with each other. In chapter 3, by way of example, we showed that the structure of the description table proceeds in an implicative manner, starting with the object column; in other words, only certain actions are considered in a specific object. Such an implication is illustrated formally as relation between two entities. Here are some generally applicable rules:

$$\text{Directed (1 to 2):} \quad [Entity_1] — g_{12}\ ®\ [Entity_2]$$
$$\text{Directed (2 to 1):} \quad [Entity_1]\ \neg\ g_{21} — [Entity_2] \qquad (11)$$
$$\text{Undirected:} \quad [Entity_1] — g_{12} — [Entity_2]$$

with:

g *Frequency with which relation occurs*

If, for example, the term ‘Valve’ was used, then one can consider only specific actions with a frequency of g>0 (for example, open, close). That means:

$$[Object] = Valve — g>0 \text{ ® } [Action]\ \hat{I}\ \{open, close, ...\}$$

Furthermore, one can define that a relation is always undirected when the following applies:

$$h([Entity_1] — g_{12} \text{ ® } [Entity_2])= h([Entity_1] \neg\ g_{21} — [Entity_2]) \qquad (12)$$

and thus

$$g_{12} = g_{21}$$

Exclusively undirected relations occur in the structure to describe events. This means that $g_{ij}=g_{ji}$ always applies. The frequency of a certain error in a certain shaping factor, for instance, is independent of whether this frequency is determined starting with the error or starting with the shaping factor. The direction thus only indicates starting as of which entity the relation is considered. To classify the possible relations of the description model, one can use a subdivision of data relations customary in data processing which is illustrated in Figure 28 (see also Wiederhold, 1981; Ebert, 1993; Gerster, 1972).

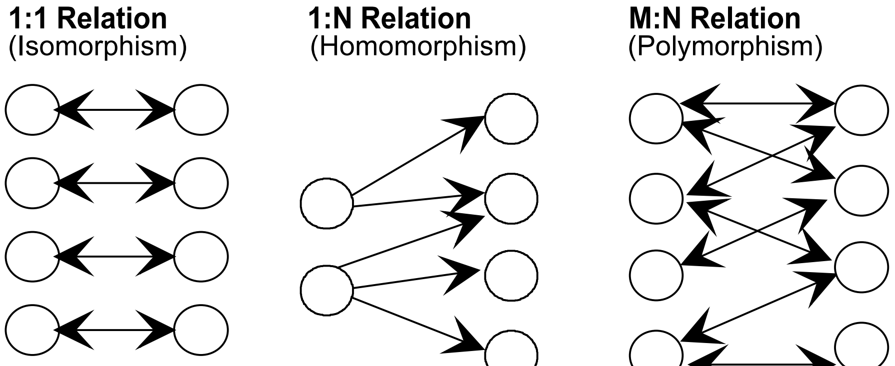

Figure 28 Possible Relations between Data

In words used in databank terminology - looking at the data structure of the event description - thus involves multiple M:N Relationships because, for instance, the concepts, that are used to describe objects, are in a M:N Relationship to concepts in the indication column (the error types). Thus we see that a valve can be open too wide or too little; but an electronic subassembly can also be supplied by an error during the setting with too much or too little voltage. The same applies to the other stages of description as well as to the stages of the events analysis (event, MMS, MMS components, sentences). Table 23 is a summary showing the possible relations between the entities of the description model.

Table 23 Relations in the Data Structure of Event Description

Relation	***Stages of Event Analysis***				***Stages in description of MMS components***				
	Event	***MMS***	***MMS component***	***Sentence***	***Object***	***Action***	***Indication***	***Property***	***Element***
Event									
MMS	M:N								
Compnent	M:N	M:N							
Sentence	1:N	1:N	1:N						
Object	M:N	M:N	M:N	M:N					
Action	M:N	M:N	M:N	M:N	M:N				
Indication	M:N	M:N	M:N	M:N	M:N	M:N			
Property	M:N	M:N	M:N	M:N	M:N	M:N	M:N		
Element	M:N	M:N	M:N	M:N	M:N	M:N	M:N	M:N	

The table clarifies the problem that was already discussed at the end of Chapter 3 where a conventional procedure was seen as problematic for the analysis of complex event descriptions: the analysis of all relations is performed sequentially in traditional inquiry language (for example, SQL - Structured Query Language) and can be implemented only with a considerable effort because they are designed for 1:N relations. On the basis of this restriction, however, every sequentially working data bank must organize the data in a so-called normal form in order to facilitate unambiguous recovery of data sets (see Ebert, 1993 or Wiederhold, 1981). The normal form, among other things, requires every data set to be unambiguous or free of redundancy. To illustrate frequencies and interrelationships, we need, in such query languages, several data structures (tables) that can be determined according to the following formula:

$$h = n(n-1) \qquad (13)$$

where:

h *Number of required tables*

n *Number of entities to be interrelated in N:M Relationship*

In order to be able to analyze frequencies and interrelationships of all information of the data structure illustrated in Table 23, for example, via structured query language inquiries, one would require, for the nine columns, a total of (9*9-9)-3=69 data tables including the administrative effort (the expression „-3" considers the three 1:N relationships).

As indicated earlier, one also needs a combination of data and classes during an analysis. One must also be able to fall back on these classes in order thus to be able to come up with general statements (for example, all errors of omission or all persons at the control stand or all analogous displays for the combination of the execution errors „too much“ and „too little“ into the class „quantitative error“). In a structured query language inquiry, this would have to be done by means of expensive revision of the structured query language inquiry or the databank structure. Every newly formed class here would increase the number of required data structures according to equation 13 at n + 1 new against n old classes by

$$[(n+1)(n+1-1)] - [n(n-1)]= 2n \tag{14}$$

where:

n Number of additional entities in N:M Relationship or the newly formed classes.

It is interesting to note that it is immaterial for this consideration whether, to retrieve the information, data structures (tables) of 1:N relationships are built up or whether this is done by means of an inquiry (for example, with structured query language) because an inquiry is nothing other than a result table gained by means of sequential processing of an original table. If one furthermore keeps in mind that the acquisition model permits a differentiation of the concepts in any desired sub-concepts, than this leads to an additional increase in the relationships to be considered between the individual concepts because every degree of detailing of a concept can be formally treated like a new class.

Another increase in the analysis effort is to be expected if one has to interconnect not only bivalent statements (for example, omissions during procedures) by trivalent or quadrivalent statements (for example, omissions during procedures under time pressure). These multi-parametric inquiries or inquiries as regards conditioned frequencies again would increase the number of objects, considering all possible combinations, by

$$\sum_{i=2}^{k} \binom{n}{i} = \sum_{i=2}^{k} \frac{n!}{i!(n-i)!} \tag{15}$$

where:

n *Number of entities that are to be combined*

k *Maximum desired valence of statements.*

If, for instance, in the case of n=100 concepts, one were to try to set up random combinations of k=3 conditions, in each case, then one would already have 166,650 possibilities of setting up new objects or relations with the existing concepts. For each of these possibilities, it would be required to give a frequency, if all relations that can be possibly combined are to be analyzed by way of frequency analysis. If it is also desired, for each of these combinations, to find those factors with which they are in a reciprocal relationship, then we need a total of just as many data structures in the form of 1:N relations as we need objects because for each object i we seek the relations [Object]$_i$-g>0- [Reciprocal factors].

As this example shows, the limit of practical application of simple analysis methods is reached precisely by the inquiry as to concept combinations. To connect this with the discussion at the end of Chapter 3, one must also - on the basis of this problem of combination-connected increase in relations between entities or between concepts - discard a descriptor-oriented process for detailed description and analysis of events. One can thus say that it is not just a description but also the analysis of information from the description model that is impossible with the help of traditional methods (for example, structured query language related to specific descriptors) because the data structure of the description model has properties whose complexity is similar to that of the natural linguistic text flow.

This problem connected with coding and retrieval of information under such conditions (random access, determination of similarity, variable degree of resolution) is nothing new. Here, the combinatory increase in the number of relations - necessarily connected with this - is referred as the problem of relations in artificial intelligence research or as the problem of a combinatory explosion in quite general terms (see Kempke, 1988; Sträter, 1991). Finding a solution to this coding problem is one goal of research on artificial intelligence and attendant research in the field of cognition psychology. A solution is sought especially in these branches of research because human memory accomplished precisely those performances that are required to solve this coding and retrieval problem.

4.2 Approaches to the Analysis Model from Artificial Intelligence

In order to solve the coding and retrieval problem, the literature on artificial intelligence discusses object-related and rule-related expert systems, fuzzy sets, probabilistic networks, as well as neuronal networks. Neuronal networks, furthermore, can be subdivided into associative and connectionism networks that differ essentially in that the connectionism networks are capable of making semantic statements whereas associative networks are not. These various approaches and their essential aspects are presented briefly in Appendix 4. At this point, all we need is a comparison of the methods regarding the performance characteristics that the analysis model must comply with. In our past discussion, we addressed the following requirements that are summarized in Table 24:

- Semantic Processing of Information to get qualitative statements about concepts or classes as well as their combinations and interactions:
  This characteristic complies with all approaches in that the collected data are depicted as relations and objects within a search area or graphs (for example, as semantic networks). In associative networks, the degree of conductivity of the various relations, however, is so high that the connection between the input side and the output side can no longer be interpreted semantically.

- Determination of Frequencies of Concepts or of their combinations and reciprocal interactions to get quantitative statements:
  This characteristic likewise meets all approaches in that, within the search area, relations and objects are weighted. In object-oriented and rule-oriented systems of experts, however, frequencies are given merely explicitly for individual objects or relations. There is no processing there, in the sense that frequencies are calculated for a combination of several objects or relations.

- Ability to learn (insertion in or formation of new classes) to be able to process the variability of the events:
  Learning takes place either by changing the weighting of relations and objects or by supplementing new relations and objects. This possibility also exists in all approaches. Rule-oriented and object-oriented systems of experts, however, are limited - when it comes to the ability to learn - to the supplementation of rules or objects. Something

similar applies to fuzzy sets that can be learned only by changing or supplementing membership functions.

- Determination of Similarity, to be able to ensure a transferability of different events to a question or in order to be able to evaluate a certain situation that prevailed in differing events:
  Rule-based systems cannot perform a determination of similarity between various events because no comparison mechanisms are available. All similarities must be formulated there explicitly as a rule. Object-oriented systems permit a determination of similarity in that similarity is defined as the number of characteristics in which the various object structures correspond to each other. These characteristics can be compared to each other by means of a suitable interference mechanism. To be sure, fuzzy sets represent similarities via the membership function; but they do not permit any determination of similarity because a membership function always presupposes that similarities have been determined and that they can be imaged on the dimension underlying the membership function. In other words, similarities are firmly defined here. In probabilistic, associative, and connectionism networks, similarities are determined in that two patterns of characteristics, that are to be compared, correspond to each other with regard to the activity distribution in the networks. More abstract statements on the other hand are obtained in that characteristics are compared on an abstract level of an object hierarchy. This means that a transferability of different individual events to a question (for instance, a certain error type, such as „omit“) is simultaneously possible.

- Variable access to the concepts, in order to be able to supply with indications the various evaluation parameters of the different HRA methods (essentially, error types, time indications, shaping factors):
  Variable access from different perspectives is basically possible only when equal entities are matched up with differing classes and when one can analyze the entities with relation to these differing classes. This property of entities - of being represented equally in several classes - is referred to as polymorphism (see, for example, Heuer, 1992). The simplest form of a polymorphism is an M:N Relationship. Rule-oriented systems can indicate polymorphisms only by means of individual rules. Object-oriented systems represent polymorphisms in that entities are inherited, in other words, they can be passed on to subordinate entities. In fuzzy sets, the overlap areas of member-

ship functions represent polymorphous relationship. Probabilistic networks permit an analysis of polymorphism only when all transition probabilities between all nodes of the network are known. Connectionism networks can depict polymorphisms in that a distributed representation of the semantic information is performed in the hidden layer. Associative networks cannot permit any polymorphisms because the information on the hidden layer is not of the semantic type.

- Random degree of detailing in order to be able to give data on different degree of resolution for differing HRA methods (in particular, holistic and decompositional methods):
  Rule-based systems, fuzzy sets, and probabilistic networks can achieve random degrees of resolution only in that each stage of detailing is achieved by a quantity of new rules or objects. An analysis of randomly selected detailing stages is always connected with an explosion of relations or objects that result in a combined manner. Object-oriented systems can attain any degree of detailing by encapsulation of the inherited objects or properties. Encapsulation here means that an inherited object or an inherited property can take on a specific value. A combination related explosion is dammed up in that analyzable combinations are given in advance by way of the mechanism of inheritance. Associated and connectionism networks attain any degrees of resolution by means of specific resolution of the objects in the hidden layers.

The comparison of the artificial intelligence procedures and of performance characteristics that was performed is summarized in Table 24.

In the table, ⇩ means not suitable regarding this characteristic; ⇧ means theoretically suitable; and ⬆ means theoretically suitable and practicable. The comparison in the table shows that only connectionism networks meet all performance characteristics of the desired analysis model. This is essentially the determination of frequencies with a simultaneous demand for variable access and any degree of detailing of the information. This approach, of course, is also the approach that, in formal terms, is least specified and it is the approach that leaves the most degrees of freedom to the developer. The discussion in Appendix 4 shows in what direction connectionism networks must be developed further.

Table 24 Comparison of the Artificial Intelligence Approaches Regarding the Requirements of the Analysis Model

A)

General Performance Characteristics Approach	***Semantic Processing***	***Learning Ability***	***Frequencies***
Rule oriented expert systems	⬆ yes	⇧ By means of modification of weights or supplementation of new rules	⇩ Only related to rules, not to objects
Object oriented expert systems	⬆ yes	⇧ By modification of weights or supplementation of new objects	⇩ Only related to objects, not to relations
Fuzzy sets	⬆ yes	⇧ Not provided, conditioned by new membership functions	⬆ related to membership functions
Probabilistic networks	⬆ yes	⬆ Through modification of weights or new objects/relations	⇧ conditional, requiring probabilities
Associated networks	⇩ No semantic relationship between input and output	⬆ Through modification of weights or new objects/relations	⬆ As relations and weights of objects
Connectionism networks	⬆ yes	⬆ Through modification of weights or new objects/relations	⬆ As relations and weights of objects

B)

Specific performance characteristics	***Determination of similarity***	***Variable access***	***Random detailing***
Rule-based Systems	⇩ No, because no mechanism is present	⇩ Combination oriented explosion of individual rules	⇩ Only by combination of individual rules
Object oriented systems	⬆ By means of object related interference mechanism	⇧ Predetermined by class formation and inheritance of objects	⬆ By means of encapsulation of inherited objects
Fuzzy-sets	⇩ No, similarities must already be known	⇧ Predetermined as overlapping area of membership functions	⇩ Only by means of combination of individual objects
Probabilistic networks	⬆ By means of activity distribution	⇧ Only when all relations are known	⇩ Only by means of combination of individual objects
Associated networks	⬆ By means of activity distribution	⇩ No, because [there is] no semantic information	⬆ By means of distributed representation
Connectionism networks	⬆ By means of activity distribution	⬆ By means of connectivity	⬆ By means of distributed representation

4.3 Development of Analysis Model

A connectionism network was chosen as point of departure for an analysis model. Essential degrees of freedom of connectionism networks are the topology of the network, the activation of the individual nodes, and the processing mechanism between the nodes. These typical properties must be determined in order to arrive at an analysis model.

4.3.1 Network Topology

To find a suitable network topology, a part of the example from Figure 26 will be converted into a connectionism network: the branch „omit opening valve" is chosen. In analyzing the event, we want to find the frequency with which this concept combination occurs in all collected events. For this purpose, we must inquire as to the following trivalent statement:

h(AND Object= Valve AND Action=open AND indicator=omit)

For qualitative analyses, however, we also want to find out with what factors the statement A = omit opening valve is still connected. This question is answered by all of the relations with shaping factors that spring from statement A where the frequency is g>0. For instance, we would get the following statement:

(AND Object= Valve AND Action=open AND indicator=omit)

— g>0®

[Property] Î {Time pressure, preparation for work, ...}

Figure 29 shows the trivalent statement of the example „omit opening valve" as a Venn Diagram. The double hachured overlap area from the figure then represents the predicate-logic statement A = „omit opening valve."

To be able to determine frequencies and relations with other concepts for this statement, we can basically consider different network topologies that are discussed in detail in Appendix 4. The simplest way is to connect the concepts, used in the events, with the events in which they are used. This solution is designated as a connectionism network with event-oriented topology and offers the advantage that - to form and analyze this network - one only needs the indications that emerge directly from the data collected in the description model. The following solution thus gets along without any major effort in terms of restructuring or calculation.

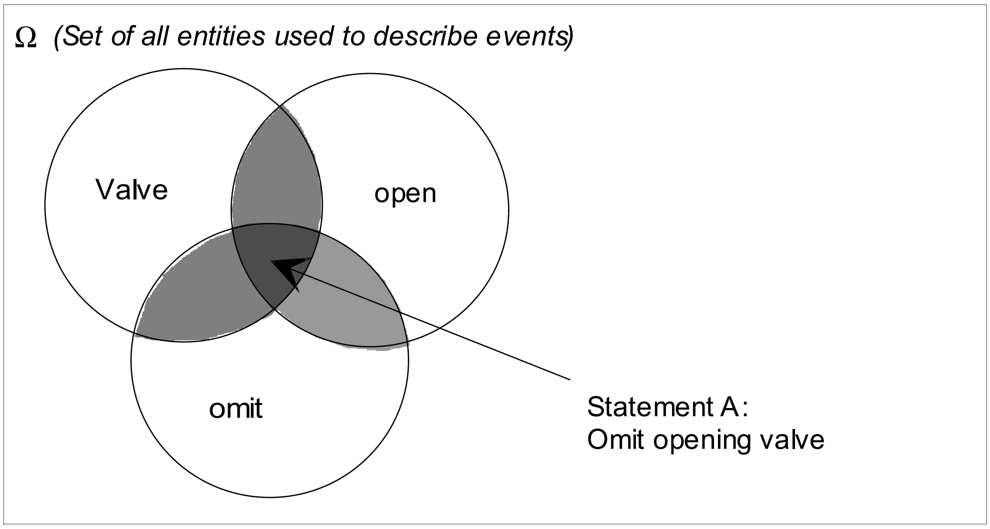

Figure 29 Statement „Omit opening valve“ as Venn Diagram

Figure 30 shows an event-related topology. In the figure, we assume by way of simplification that only three cases were observed. The nodes of the network in the figure represent the concepts of event description; the numbers in the nodes show the frequency with which the concepts occurred.

In event 1, a valve was opened and in events 2 and 3 the opening of a valve was omitted. Because each event occurred once, the weight of the event nodes is 1. The weight of the concepts depends on how often they were used (for example, the concept „omit“ was used in events 2 and 3, in other words, twice). Furthermore, the figure clearly shows the characteristic aspect of an event-related topology: the concepts that were used to describe the event were matched up in a simple manner with the events in which these concepts occurred.

In this topology, each event within the network retains its very specific concept constellation; this ability is referred to as encapsulation. This also means that every concept is represented in a distributed manner because it is used to describe differing events. Overall, this topology is thus in a position to depict polymorphous relationships. A concept, however, is also present explicitly so that one can fall back on it as an individual concept.

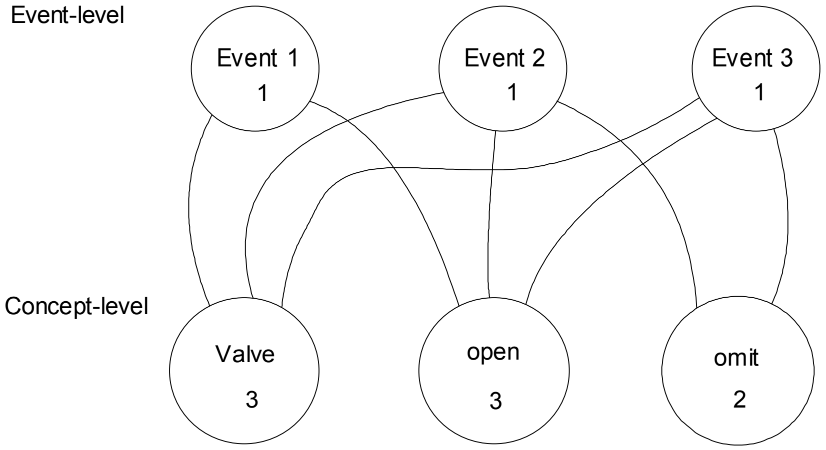

Figure 30 Event-Related Topology to Analyze Practical Operational Experience

Relations between concepts are accomplished in event-related topology not as direct connections between the concepts but rather as „detours“ via the event nodes at which the elements of the statement are present. For example, the relation between the concept nodes „valve“ and „omit“ run via the event nodes „Event 2" and „Event 3.“ A statement is thus always obtained by two steps: (1) A search for the events in which the individual elements of the statements occurred (all event nodes that are connected with „valve“ and „omit.“ (2) A count of all events in which all elements of the statement occurred (all event nodes at which „valve“ and „omit“ occurred simultaneously). In event-related topology, these steps are independent of the valence of the statement and this means that the processing effort is also independent of the valence of the statement.

Of course, there is no general regulation or there is no processing mechanism for retrieving the information contained in the static network. In the following, we will show how the processing mechanism or the activation of the individual nodes must be arranged so that frequencies and relations of any n-valence statements can be determined.

4.3.2 Activation Function

To process information, all nodes of connectionism networks have similar properties, such as neuronal cells. Figure 31 illustrates the general structure of a node. Here we distinguish the following: dendrite a_i on the input side, and Axon a_j on the output side and the cell o_j. To process the input information and to transform it into an output information, the cell employs a so-called activation function f(o_j). Dendrites and axon have the weightings w_{ij} for the input side and w'$_{jk}$ for the output side.

The activation function f(o_j) converts the sum of all weighted activations (w_{ij} *o_j) that are directed toward nodes o_j into an output activation a_j. Within a connectionism network, by the way, there is a uniform activation function that is specified for all nodes, independently of the place where the nodes happen to be inside the network.

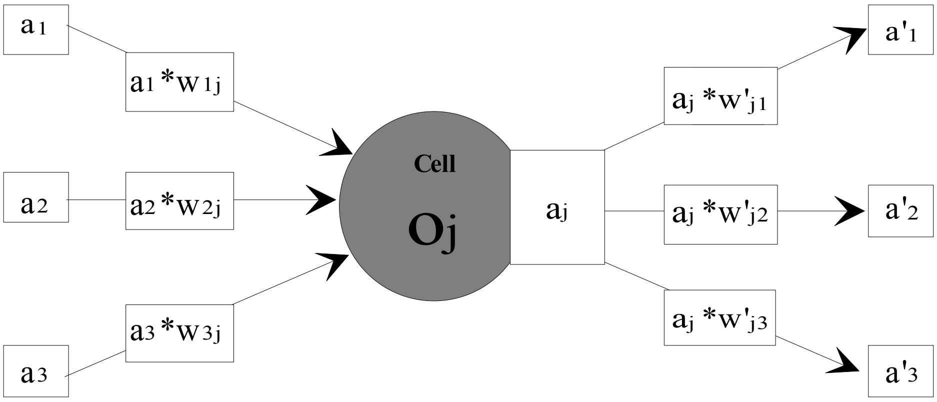

Figure 31 Structure of a Cell in the Connectionism Network and Flow of Activation

To be able to calculate frequencies of any combinations of concepts within the cell structure that is organized in an event related fashion, one must use the activation function according to equation 16. The activation function employs the following circumstances here: the frequency, with which a concept was mentioned in all events, is given by its weight o_j. Each concept always is used to describe an event; therefore, it passes its weight with the intensity of 1/o_j on to each node on the event level. The individual dimensions that must be known for the activation function thus are the frequency with which a concept is used and the relations to the events in which it was used. Both magnitudes can be obtained directly from the following description model:

$$a_j = \min\left(o_j * \sum_{i=1}^{n_i} w_{ij} * a_i \ ; o_j \right)$$

$$\text{and} \qquad (16)$$

$$w'_{jk} = \frac{1}{n_j}$$

where:

a_i *Activation of node i*

w_{ij} *Weight of relation directed from node i to node j*

n_i *Number of relations moving toward node j*

o_j *Weight of node j (corresponds to frequency of utilization)*

a_j *Activation of node j*

w'_{ik} *Weight of relation k starting from node j*

n_j *Number of relations starting from node j*

Why the activation function must be thus can be seen if one visualizes the processing mechanism with whose help one can make any n-valent statement on the basis of the events.

4.3.3 Processing Mechanism

Processing within connectionism networks takes place in that an input information first of all is converted, within an input layer, into an activation of nodes (in the sense of the electro-physiological activation of a nerve cell). This pattern of input activities is the propagated over one or several concealed layers through to the output layer. The activation of the nodes of the output layer then represents the answer to the question we are after; in this case, in other words, this is the frequency with which a particular concept combination was observed within the collected events. The above presented activation function here takes care of information transmission between the individual nodes. As far as the event related topology is concerned, this leads to the principle of a connectionism data procurement described below.

- **Principle of Connectionism Data Procurement**

Processing of events within the event-related topology specifically requires several layers. They are illustrated by way of example in Figure 32. The example, given above, was expanded in the figure for an event-related topology. The following were introduced additionally when compared to Figure 30: (1) An event level and a threshold determination about the event level in order to count those cases in which a certain statement was observed. (2) An activation scheme in order to convert a semantic statement or question into a form that can be read by the connectionism network (an activation).

Below, we will explain in greater detail how a question is converted into an activation scheme; at this point we would like first of all to describe the basic procedure of connectionism data procurement:

- A question is converted into an n-valence statement and the latter is then provided with an activation scheme. The activation scheme is then broken down into a combination of monovalent statements and is distributed over the individual concepts. For this purpose, and in this case, a maximum possible activation of $a_{question}=1$ is distributed over all n monovalent statements (the complete formalism for the activation scheme will be presented below). Basically, every concept can be used to formulate the question; therefore, any combinations of concepts and valences of inquiries are possible.

- The monovalent statements are propagated in the event related topology to the nodes in the event layer. The nodes of the event level first count the number of the monovalent statement that are contained in the event. This is done according to the activation function by adding up the activations. The activation of the nodes then represents the share of the monovalent statements that are contained in the event. In another step, one performs a threshold determination by a formalism described below in order to identify all events that contain the entire n-valent statement.

The threshold determination examines whether the entire activation, that was given off by the activation scheme, arrived at the corresponding event node and thus decides as to whether the activity, arriving at the event node, suffices in order to confirm the wanted n-valent statement. If that is not the case, then no activation is passed on; in the other case, all monovalent statements are contained in the event, and, after threshold determination, the activation a=1 is passed on by the event level.

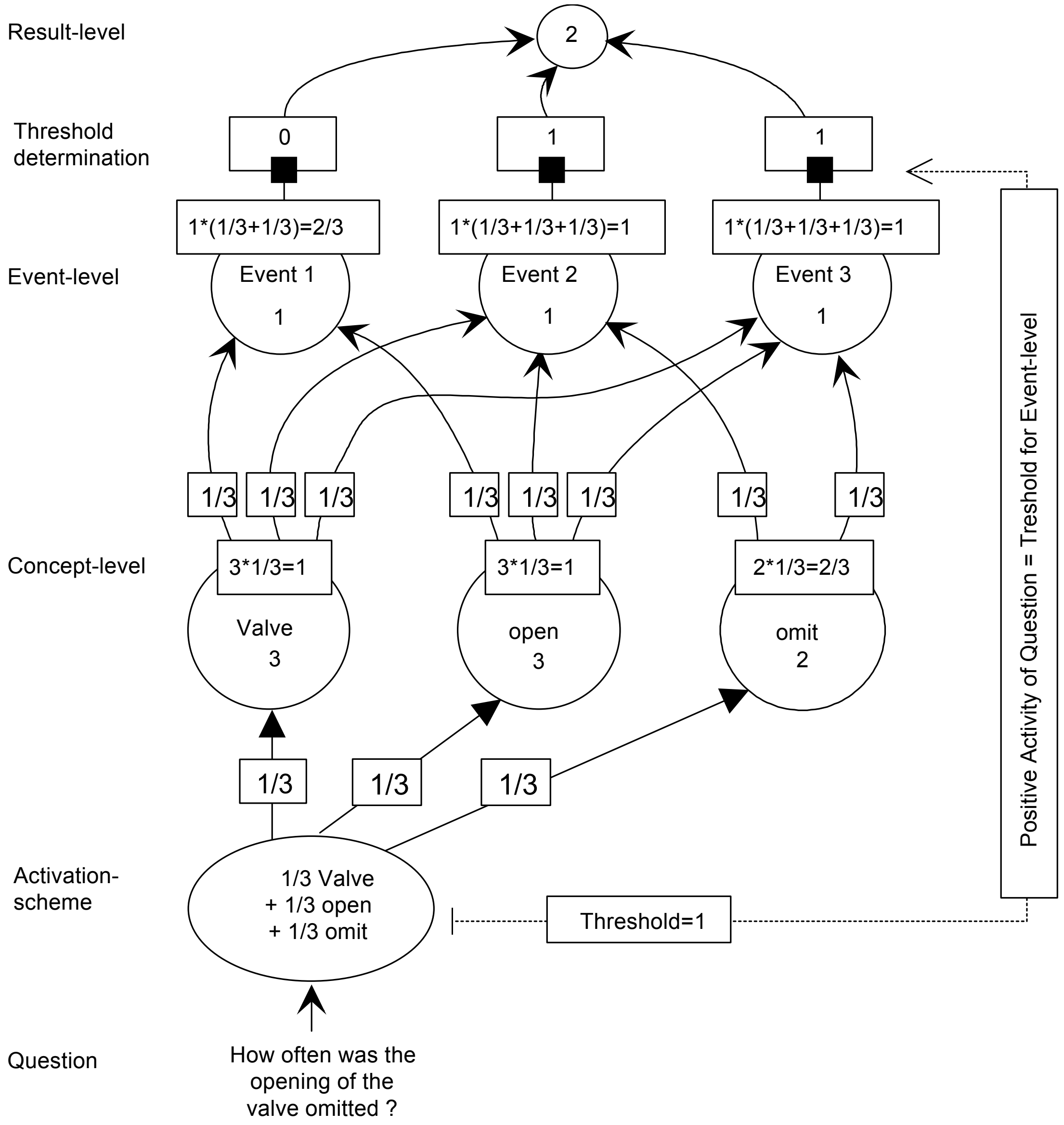

Figure 32 Illustration of the Principle of Connectionism Data Procurement

Looking at it overall, one can thus interrogate frequencies of existing concepts for concept combinations in the connectionism model in that an inquiry is processed from bottom up through the network. If, on the event layer, we have identified those events that contain the n-valent statement, then one can find - only by means of so-called back propagation - those concepts that were additionally of significance in the events in that now the activation, present on the event level, is propagated from top down through the network. This is possible because the network itself is non-directional and the direction of processing is predetermined only by the direction of propagation. In back propagation, in the simplest case, all nodes are provided with an activation of one on the event level that are connected with the nodes that are found as solution on the event level.

By means of propagation and back propagation, the network is able to obtain, from the events, quantitative statements (frequencies of occurrence of certain errors due to propagation) and qualitative statements (for example, interactions between concepts by way of back propagation). A propagation and back propagation of the bivalent statement ‘AND Valve AND open’ would, in the above network, determine the frequency h=3 and ‘omit’ as possible error type (in all event nodes, the concepts ‘valve’ and ‘open’ were given whereas in events 2 and 3 the indication ‘omit’ was given additionally).

- **Threshold Condition and Activation Scheme**

Two measurement points are required for data retrieval in the theory of connectionism models: point of departure and point of inquiry. Kohonen (1988) designated the point of inquiry also as key or search argument and the point of departure also as background or context. In the above- described network, the event level is the point of inquiry and the activation scheme is the point of departure. Activations between two measurement points determine - via the simple condition of activation equality - whether an inquiry or statement does or does not apply. An activation equality between point of departure and point of inquiry is then converted, with the help of the threshold function, into a dichotomous statement (statement applies or does not apply). Here we proceed in the following manner:

If one restricts the maximum possible activation in the network a=1, then, from the definition of the valence of a statement (equation 8), we get the following interrelationship:

$$\frac{|AND|}{n}+\frac{|AND\ NOT|}{n}=1 \tag{17}$$

where:

[AND]	*Number of concepts tied in with AND*
[AND NOT]	*Number of concepts tied in with AND NOT*
n	*Valence of statement*

When AND NOT statements are implemented as negative activation, then, as maximum possible activation, we get a network that is designated as threshold value:

$$s = \frac{|AND|}{n} = 1 - \frac{|AND\ NOT|}{n} \qquad (18)$$

where:

s	*Threshold value*
[AND]	*Number of concepts tied in with AND*
[AND NOT]	*Number of concepts tied in with AND NOT*
n	*Valence of statement*

In order to involve all monovalent statements on the concept level equally in the process of data procurement, the activation must be broken down according to the following formula over the various concepts in an n-valent statement.

$$a_j = \begin{cases} \dfrac{1}{|AND| + |AND\ NOT|} & \mid\ j \text{ is } AND - Statement \\ -\dfrac{1}{|AND| + |AND\ NOT|} & \mid\ j \text{ is } AND\ NOT - Statement \end{cases} \qquad (19)$$

where:

a_j	*Activation of the concept node of the monovalent statement j*
j	*Monovalent statement j of an altogether n-valent statement*
[AND]	*Number of concepts tied in with AND*
[AND NOT]	*Number of concepts tied in with AND NOT*

This activation is then propagated by the network. As will be shown in the examples below, this simple distribution condition suffices in order correctly to calculate also frequencies for more complex statements with AND, AND NOT, or OR tie-ins.

If the activation is propagated by the network up to the event level, then the threshold function performs a threshold value calculation. By means of the threshold value calculation, we identify those nodes for which the statement from the activation scheme applies.

The threshold function looks like this because only the AND statements determine the maximum activation arriving at the event level:

$$a'_j = \begin{cases} 0 & \mid \left(a_j < s\right) \\ 1 & \mid \left(a_j \geq s\right) \end{cases} \tag{20}$$

where:

a'_j *corrected activation of node j on event level after threshold value calculation*

a_j *activation of node j on the event level prior to threshold value calculation*

s *Threshold value*

From the calculation of the threshold value we can see that, overall, an activation is propagated in the value arranged between 0 and 1 within the network. The activation on the event level thus sometimes reflects the relative frequency with which the concepts of the wanted n-valent statement are contained in the event. This shows that the level of activation of nodes on the event layer is also a measure as to the extent to which the discovered events resemble each other regarding the inquiry, in other words, the extent to which the events are transferable to the wanted statement.

The formula for calculating the threshold value furthermore shows that - by means of minor changes of the threshold value and the distribution of activation - one can also use other logic operators, such as AND NOT and OR, for the purpose of formulating the questions. How this works will be shown below by modification of the activation scheme for the above network.

- **AND NOT Inquiry in Connectionism Network**

That this approach can also correctly reproduce statements tied in with AND NOT can be seen easily in that the query A AND NOT A causes a situation where those activities that were built up by statement A are practically erased again by the statement AND NOT A. A negation is thus accomplished in the connectionism approach as inhibition of negative activation. This is illustrated in Figure 33.

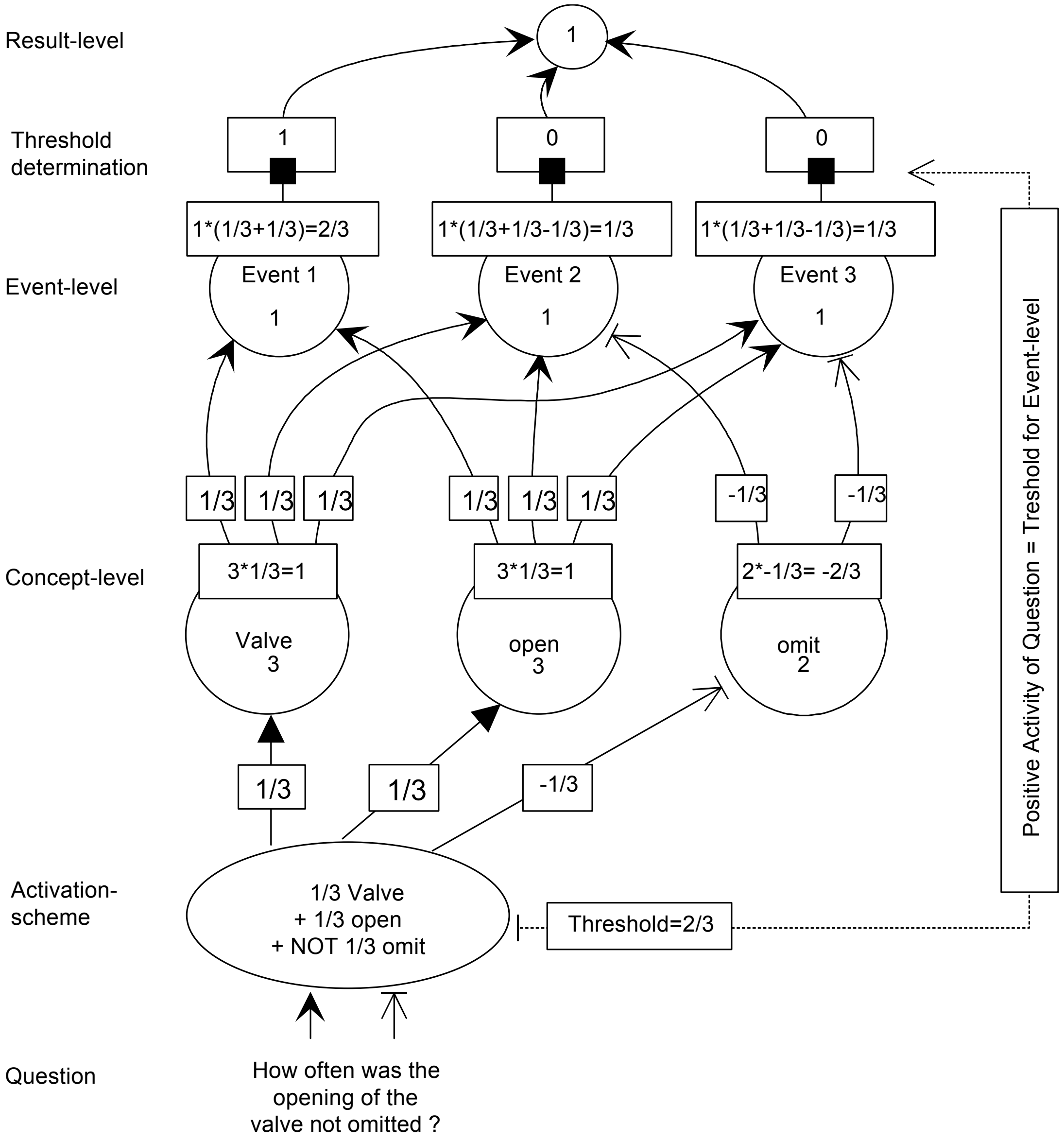

Figure 33 Connectionism Data Procurement in Case of AND NOT tie in

In the figure, only the AND tied statements get a positive activation from the activation scheme; AND NOT tied statements get a negative activation. If one tracks the activities through the network then one finds that AND NOT tie ins cause the erasing of solutions that have already been found.

- **OR Inquiry**

To clarify the OR tie in, it is a good idea to modify the example from Figure 33 slightly in that one assumes that three, each, different types of valves were to be opened in the three events (Type X, Type Y and Type Z). This means that, within the network, the node „valve" is the generic term for the different valve types (Figure 34). If one tracks the activations, then one can easily see that the basic course of activations in the OR tie in „Valve Type X OR Valve Type Y OR Valve Type Z" does not change when compared to Figure 32.

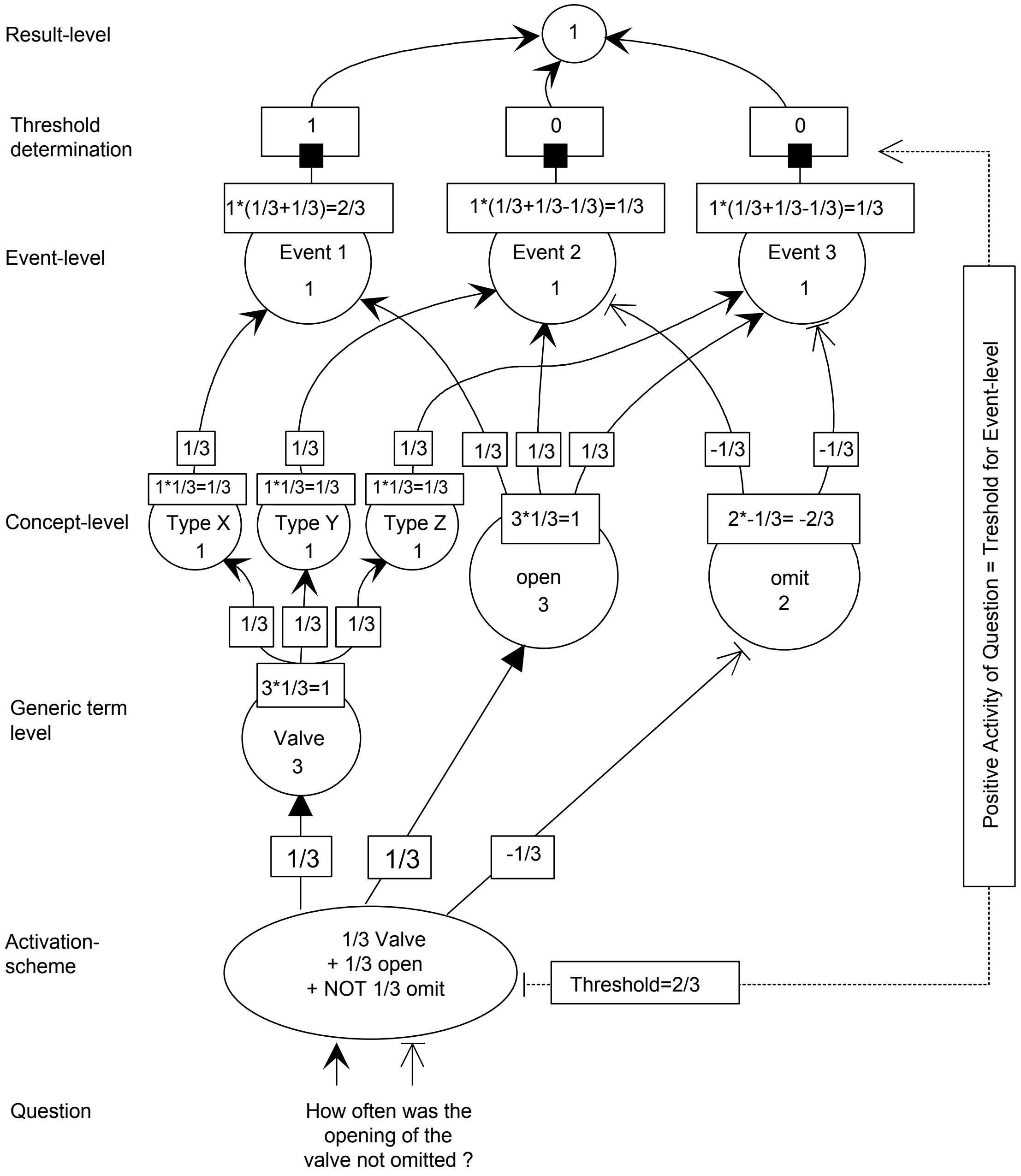

Figure 34 Connectionism Data Procurement in Case of OR tie in

This means that the generic term/sub-concept structures do not influence the accuracy of prediction of the network. This means that the connectionism network is in a position for any concept hierarchies to give correct frequencies on a randomly detailed level.

This performance is not readily possible, for example, in probabilistic models (see Appendix 4 concerning this problem complex).

Within a concept hierarchy, the network is also in a position to supply correct frequencies for a statement such as „omit opening valve but not valve of Type X.“ In this case, the activation scheme distributes its activation over the concepts nodes of the quadrivalent statement according to the following activation scheme:

AND Valve AND open AND omit
AND NOT Type X
$\vec{a} = \{a_{Valve} = 0.25, a_{open} = 0.25, a_{omit} = 0.25, a_{TypeX} - 0.25\}$
$s = 0.75$

- **Complex Statements**

Complex statements consist of m individual sentences with, in each case, n-valent statements (see equation 10, above). A complex statement [A] for instance would contain the two sentences:

A1 = AND (Valve AND open AND omit)
A2 = AND (Type X AND open AND omit)
$\vec{a} = \{a_{Valve} = 1/6, a_{open} = 1/6, a_{omit} = 1/6, a_{TypeX} = 1/6, a_{open} = 1/6, a_{omit} = 1/6\}$
$s = 1.0$

Complex statements, that are only AND tied, thus can be treated as m*n simple statements. The situation is different when both sentences are OR tied up with each other. The statement here could sound like this:

A1 = AND (Valve AND open AND omit)
A2 = OR (Type X AND open AND omit)

Then the activation scheme for both sentences is as follows:

$$\vec{a}_1 = \{a_{Valve} = 0.3, a_{open} = 0.3, a_{omit} = 0.3\}$$

$$s_1 = 1.0$$

$$\vec{a}_2 = \{a_{TypeX} = 0.3, a_{open} = 0.3, a_{omit} = 0.3\}$$

$$s_2 = 1.0$$

Complex statements - where frequencies are to be determined for several OR tied sentences - must be processed sequentially because, in this case, there is a possibility that the activations are twice propagated upon the event layer by a certain concept (in our example ‘Type X’). The corresponding node on the event layer (in the figure, the left hand node) would merely add up the activations arriving at it; therefore, it would get an activation above the threshold value and the network would thus arrive at a false result. In the example, the left hand node on the event level in the network would also be counted although no error of omission was observed because it, as a whole, gets the activations a_{valve}, a_{open} and a_{TypeX} and thus reaches the threshold s = 1.0. In the program illustrated in Appendix 1, this problem was solved in that the activation scheme in such cases is propagated for both sentences, one after the other, through the network.

4.4 Model for Analysis of Event Descriptions

In the preceding section, we presented the basic procedure involved in an analysis of the data of the description model; that procedure will now be applied to the complete data structure of the description model. This purpose, we need minor expansions of the structure of the network and of the procedure for processing complex statements within the network.

4.4.1 Structure of Network to Predict Human Reliability

The activation level, the concept level, and the event level do not differ in terms of structure. Differences do prevail in the intermediate layers, the so-called hidden layers. These expansions are shown in Figure 35.

Regarding the event level, a subdivision was made in Chapter 3 of the event into individual MMS and, thereupon, into individual sets per MMS component (in the figure, event level, MMS level, and set level). Furthermore, it seems to make sense to tie the above-mentioned possibility of class formation or of OR inquiry systematically into the network structure as another level (in the figure, the concept level). The activation scheme can consist of any complex statements; therefore, this level will hereafter be called the context level.

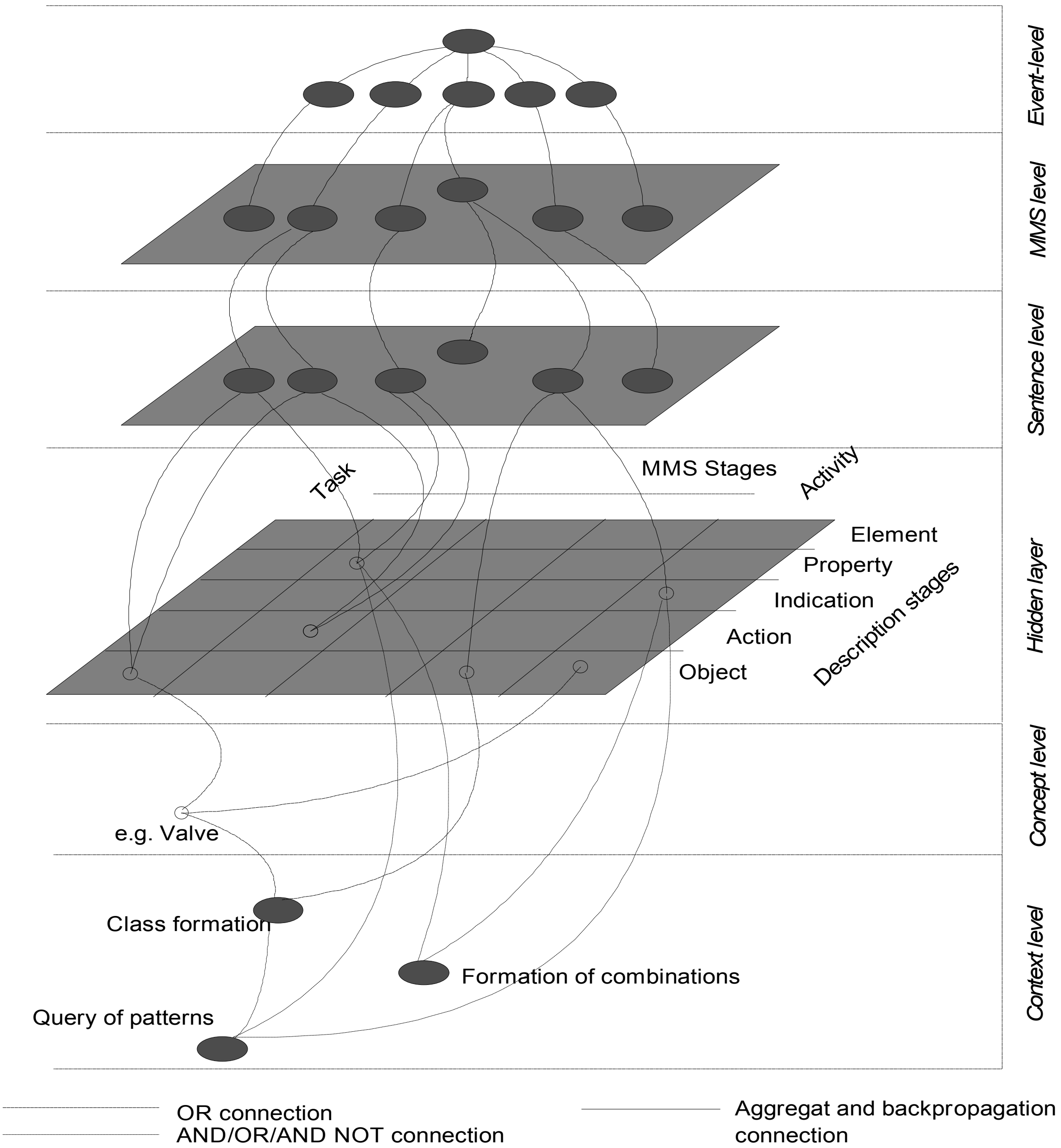

Figure 35 Illustration of the Connectionism Network to Analyze Practical Operational Experience

Two layers are required to be able correctly to interrelate concepts and events: (1) A hidden layer accomplishes a tie in with the concept level and the set level. The hidden layer establishes the conditions under which a concept was used (for example, the indication 'omit' related to the task stage of the MMS or the Object 'valve' related to the activity stage, etc.). A distributed representation of the semantic information takes place by means of the introduction of such a hidden layer. (2) A set level takes care of a correct match up of the occurred errors and shaping factors with the concepts and MMS components. If, for example, the two sets S_1='omit opening valve' and S_2='close switch' were mentioned in an event related to the MMS component 'task,' then one must make sure that the error 'omit' in the analysis is not related to the concept 'switch.'

Specifically, we run through the network structure, as illustrated in Figure 35, in the following manner.

1. On the context level, and n-valent statement is converted - according to the above described procedure - into an activation scheme. Each activation scheme (in the figure, hachured nodes on the context level) can in this case consist of individual classes, a simple combination of classes or concepts, or a complex concept pattern. If the activation scheme has been activated, then the activation is propagated upon the concept level.
2. On the concept level, the individual mono-valent statements are projected upon the concepts that were used in the observed events for purposes of description (for instance, the class 'time error' is later imaged upon the concepts 'too early' and 'too late'). From here on in, the activity is further propagated into the hidden layer. The nodes in the hidden layer are determined with respect to the description stages and the MMS components. Each node thus corresponds to a statement having the following form: 'Task.Object=Valve' or 'Activity.Indication=too early.'
3. The activation that was sent out by the activation scheme diverges up to the hidden layer. Now the activation, present in a distributed form in the hidden layer is collected in the subsequent set layer (aggregated, illustrated with solid lines in the figure). As a result, one identifies all those sets in which the interrogated i^{th} statement occurred.
4. The MMS level collects the activation of the set layer. Once all n statements have been propagated through the network, all nodes on the MMS level - where the n-

valent statement applies - have precisely the activation that was sent out by the activation system. They represent the solution of the n-valent inquiry. The case is where the n-valent statement applies are identified by renewed aggregation on the event level.

5. In another processing step, one can now back propagate the activations from the nodes on the event level or the MMS level as activation pattern through the network. The procedure here corresponds to the above-mentioned four steps in reverse sequence. By means of this back propagation, one can now identify, on the concept level, those concepts that are in a relation with the original inquiry and in that way one can determine reciprocal interactions.

4.4.2 Processing of Complex Statements within the Network

Concerning the activation function, the calculation of the activation scheme, and the distribution of the activations over the nodes of the concept level, one does not need any modifications of the procedure described in the preceding section. To process any complex statements, however, the processing mechanism must be adapted to the network structure: as was described earlier, complex statements consist of several sentences and each sentence can consist of multivalent statements. Various sentences again can be AND tied in, AND NOT tied in, or OR tied in. Such complex statements must be broken down into individual sentences and must be propagated through the network sequentially (see Figure 36).

If one keeps in mind that the point of departure and the point of inquiry are always necessary for data retrieval in connectionism networks, then the point of inquiry is shifted by virtue of the sequential progress of complex statements in the following manner: The point of inquiry for each monovalent statement is the sentence level because, there, one identifies those sentences in which the concept occurred. If a sentence was propagated through the network (in the figure, A_1), then, by means of a threshold calculation, we need to make a decision as to which nodes on the sentence level verify the statements in the sentence. If this sentence is followed by a sentence that is OR-tied with the preceding one (in the figure A_2), then the latter must be propagated in an analogous fashion up to the sentence level. If a sentence now follows that is AND tied with preceding one (in the figure A_3), then, in short range terms, there is a change in the point of inquiry for the activity that has so far been propagated through the net. The point of inquiry, is, briefly, the MMS level because only now are we to identify those MMS in which the sentences that had been propagated so far actually occurred. Only then follows the propagation of the next AND tied sentence with which the entire procedure starts all over again.

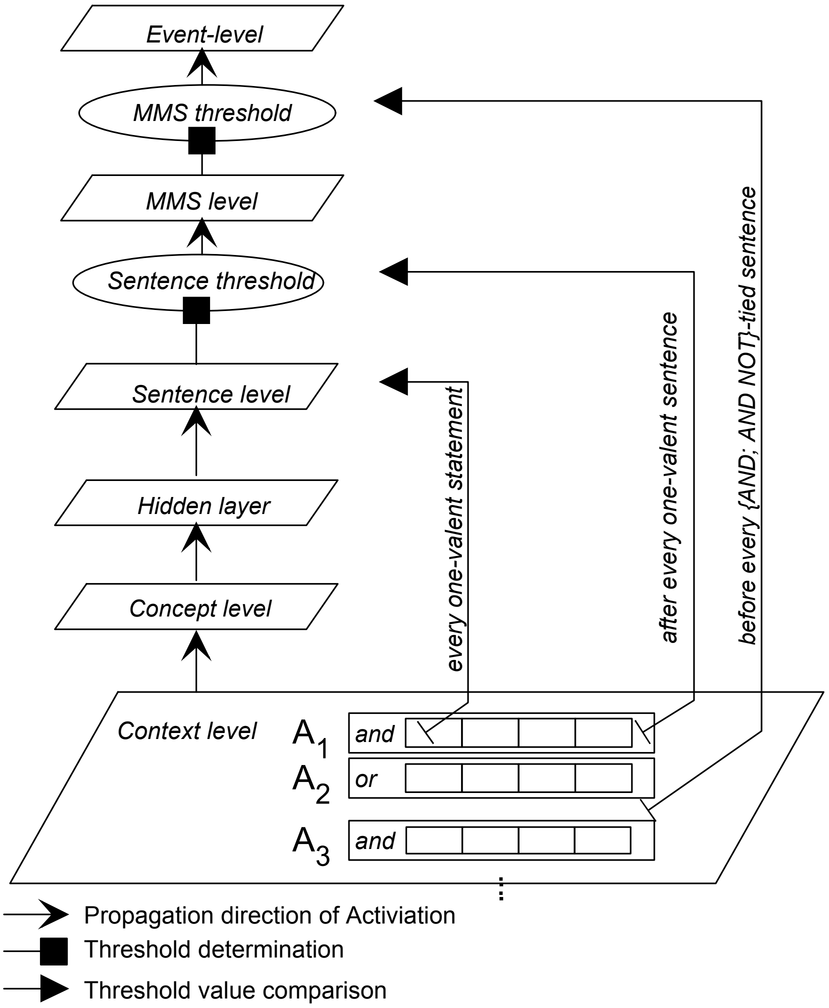

Figure 36 Threshold Value Calculations in the Case of Complex Statements

4.4.3 Uncertainties in Data

Once frequencies have been determined for a statement, it also makes sense, in some form, to be able to make statements as to how informative or how reliable the determined frequency is. To calculate the uncertainties of statements, one can take a look at the following dimensions: If a frequency h_{12} has been determined between nodes O_1 and O_2, then, for uncertainty considerations, one can employ the theoretically possible maximum and minimum frequency of joint appearance. We now take the following along the lines of the definition of complete dependence and complete independence of two probabilities:

The maximum possible connection strength is given via the assumption of the complete dependence of between two objects. The frequency is:

$$h_{\max} = \min\left(h(o_1); h(o_2)\right) \tag{21}$$

the following applies generally:

$$h_{\max} = \min\left(h(o_1); h(o_2); \ldots; h(o_i); \ldots; h(o_m)\right)$$

The minimum connection intensity results accordingly via the assumption of the complete independence of both objects. The following shall be used as estimated value for the frequency:

$$\begin{aligned} & h_{\min} = \hat{P}_1 * \hat{P}_2 * h_{\max} = \frac{h(o_1) * h(o_2)}{\left(h(o_1) + h(o_2)\right)^2} * h_{\max} \\ & \textit{and} \\ & \hat{P}_1 = \frac{h(o_1)}{\left(h(o_1) + h(o_2)\right)} \wedge \hat{P}_2 = \frac{h(o_2)}{\left(h(o_1) + h(o_2)\right)} \end{aligned} \tag{22}$$

the following applies generally:

$$h_{\min} = \frac{\prod_{i=1}^{m} \left(h(o_i)\right)}{\left(\sum_{i=1}^{m} \left(h(o_i)\right)\right)^m} * h_{\max}$$

where:

o_j *weights of all j nodes that are used during the inquiry*

m *Valance of statement (number of j nodes)*

The uncertainty dimensions presented here are not uncertainties based on a specific statistical distribution. They are uncertainties that materialized due to the used concepts within an event description. It falls from this definition of uncertainty that uncertainties can be made only for multivalent statements. The measure of uncertainty furthermore can be related to individual concepts, or, in the case of complex statements, also to individual sets. Both ways of calculating uncertainties are implemented in the program described in Appendix 1. Only data uncertainties related to the sets are analyzed in Chapter 5 and Appendix 6.

4.4.4 Quantitative and Qualitative Statements in the Model

Qualitative and quantitative statements are demarcated from each other particularly by their degree of abstraction. In the quantitative question, we pursue a holistic procedure in order, from a viewpoint of a certain parameter, to determine a frequency for a human error. In the qualitative question, on the other hand, we start with a narrowly outlined situational context in order to find possible shaping factors and improvements for it. Accordingly, inquires as to differing degrees of detailing are required for differing questions. Just how inquiries must be styled in order to get qualitative and quantitative indications as to human reliability with the help of an analysis model will be described below, using the example of error types, shaping factors, and reciprocal interrelationships.

- **Error Types**

Simple error types are omissions or errors in the performance of an activity (see Table 2, Chapter 1). For analysis purposes, these errors need merely be interrogated. Here are some examples:

The frequency of an error of omission is determined by the following inquiry:

h(Task.Indication=omit)

The frequency for a time error in the performance of an activity would be like this:

h(AND Activity.Indication=too early OR Activity.Indication=too late)

A general error in the performance of an activity would look like this:

h(Activity.Indication=[Indication])

where:

[Indication] All possible errors, such as too early, too late, omit, false, etc.

An error of confusion always signifies the omission of a task and the simultaneous performance of another false action. The frequency, with which an error of confusion occurs, is thus given by the following:

h(AND Task.Indication=omit AND Activity.Indication=false)

The relative frequency with which an error of omission can be observed during the opening of a valve within the collected events is calculated in the following manner:

$$h_{rel} = \frac{h(\mathrm{AND}\, Task.Object = Valve\, \mathrm{AND}\, Task.Action = open\, \mathrm{AND}\, Task.Indication{=}omit)}{h(\mathrm{AND}\, Task.Object = Valve\, A\mathrm{ND}\, Task.Action = open)}$$

- **Shaping Factors**

In general, looking at human reliability, it is assumed that PSF can impair the reliability of an action. The effectiveness of impairment here is given as the weighting factor for the PSF (see DRS-B, 1990) so that the probability of a human error in a task of Type i looks like this:

$$P_i = f\left(\frac{w_1}{PSF_1}, \frac{w_2}{PSF_2}, \ldots, \frac{w_n}{PSF_n}\right) \tag{23}$$

This interrelationship can be obtained with the evaluation model simply from the collected data because each PSF is represented as a node within the network. The weights w_i thus result consequently from the frequencies with which a shaping factor x was observed in connection with a human error of Type i: first of all, we determine the relations:

[error of Type i] ¾ g>0® [PSF x] = g_x *[error of Type i]*

The weight w_i by means of the ratio of errors of Type i under the condition that the property PSFx was observed is then related to the total number of all observed errors of Type i:

$$w_i(PSF_x) = \frac{g_x \left| \left[Error\ of\ Type\ i \right] \right.}{h(\left[Error\ of\ Type\ i \right])}$$

- **Interactions of PSF**

Interactions between PSF permit a broader analysis and a more precise prediction of the effectiveness of improvement measures. Also, interactions can easily be determined in that, starting with a PSF $[PSF]_X$ one calculates all relations g>0 to other shaping factors:

$$[PSF]_X \text{ — } g>0\text{®}\ [PSF]$$

The network in Figure 37 shows how such relations can be obtained by analyzing the connectionism network; it does that with the help of hypothetical interrelationships of PSF according to Harbour and Hill (1991). It should be noted here that the subdivision in the figure does not represent any interrelationships found in the course of practical professional experience. It is merely intended to demonstrate how - by analyzing the tasks from the description model - one can analyze reciprocal interactions with the help of the connectionism network. In the next chapter, we will explain which PSF and reciprocal interrelationships were actually found. The analysis could, for instance, permit the following statements and dynamic relations:

- Conclusion from error to possible cause (top-down): How can one recognize a personnel-caused error that can be traced back to the PSF called motivation? On the level of the situational patterns, one finds the factors of ergonomic design of operating elements and personnel selection. In this case, to determine interrelationships, one first of all determines, as point of departure, a personnel error of Type i (iteration 0) and one determines relations to PSF (iteration 1). In another iteration step, one determines additional PSF that are connected with the PSF factors on level 2, and so forth.
- Conclusion from individual causes to other possible causes (bottom-up): What shaping factors can one expect if one works in a deficient ergonomic work environment? One finds the factors of increased requirement and fatigue as main factors and personal abilities as subordinate factors. In this way of determining reciprocal interactions, one merely changes the point of departure. The procedure for determining the relations now starts iteratively from this PSF that leads to identical statements.

This iterative procedure can be used in order to analyze an event systematically for PSF that may have caused an error of Type i or that are connected with a certain PSF. Each iteration step, however, requires the two steps of propagation and back propagation. This means that the connectionism network - in addition to the possibility of retrospective determination of frequencies - also offers the possibility of support during the qualitatively oriented prospective analysis of events in that the knowledge, present in the network, is used for event analysis. This possibility was also implemented in the program presented in Appendix 1.

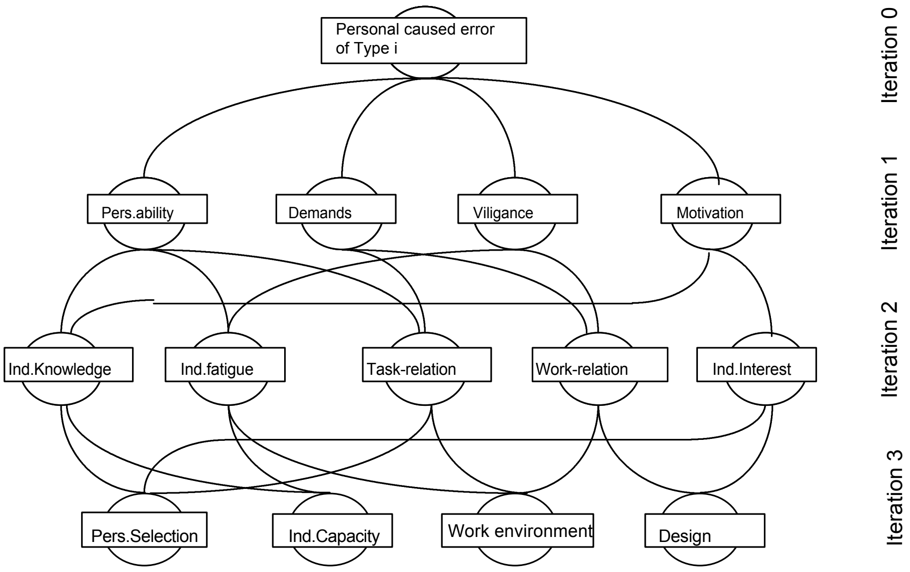

Figure 37 Hypothetical Interactions between Various PSF

4.5 Discussion of Analysis Model

The connectionism approach facilitates qualitative and quantitative analyses of data in a uniform model. As a result, it becomes possible to deposit, in a uniform database, both information for the evaluation of human reliability and for the optimization of the technical system. It also makes it possible to interrogate interrelationships of random concepts within the data structure (for example, relationships of errors and PSF). Permissible logical tie-ins between concepts here are AND, OR, AND NOT, related to the various components of the MMS and the different description stages (object, action, indication, property, element). With the help of the connectionism approach, one can perform these analysis possibilities on any desired degree of detailing of the event description. But this is possible by means of some methodological capacities of the analysis model which will be emphasized in the conclusion.

4.5.1 Methodological Abilities of the Connectionism Network

The discussion on the processing of complex data structures in this chapter showed that - in the attempt to determine frequencies for multivalent statements - the problem of the combinatory explosion sooner or later makes an analysis impossible (Kempke, 1988). This is why, when it came to analysis of the data supplied by the description model, it was impossible to use a simple analysis algorithm that is designed for 1:N relations (for example, a structured query language based databank system). The analysis model must analyze multiple M:N relations (among others, for the imaging of the description stages, for the merger of individual observations into classes, such as, for instance, certain error types, or for a desired degree of detailing of the event description). Accordingly, a connectionism algorithm was developed.

In developing the approach, we investigated known methods of artificial intelligence with respect to a possible benefit (Annex 4). But it turned out that there are primarily two reasons why these methods cannot be used for an analysis of the indications in the description model: (1) The data that are required by the methods basically cannot be obtained from practical operational experience (for instance, the probabilities of probabilistic networks) or procurement, as such, will require an effort that is greater than or equal to the effort that one would need in case of a simple search and counting of events (for instance, rule-based systems of experts). (2) The methods have weak points which, among other things, cause a situation wherein one cannot calculate any frequencies for polymorphous illustrations (which is what is involved in multiple M:N relations). The methodological advantages of the connectionism network developed here can thus be summarized in the following points.

- **Frequencies of Polymorphous Illustrations**

The crucial point of the connectionism network developed here is this: each relation between concepts is implemented by a detour via an event node that, taken by itself, contains all information involved in an event. Accordingly, each relation between inquiry nodes and result layer is not implemented in the network as an explicit relation, such as it happens customarily in network oriented approaches; instead, each relation is a consequence of an interference process consisting of propagation (from concept layer to event layer) and back propagation (from event layer to concept layer). Nauck et al., (1994) terms this ‘detour’ as a dynamic relation because the relations, built up by propagation/back propagation exist only during the run-time of the activation, in other words, only so long as the activity within the network is built up between point of inquiry and context.

Furthermore, conventional databank systems or symbol-processing approaches require that an object be unambiguously determined (specified) in semantic terms; it is present or it is not present (tertium non datur [there is no third way]). This requirement becomes a problem when the same object is differently specified and used in differing contexts. In this case, the match up problems can be avoided only by the encapsulation of the specific semantic significance of the objects. Accordingly, the requirement for object specificity in the network developed here was abandoned. Distributed representation prevails here on the hidden layer. As a result, the network - in addition to symbol processing - is also able to process incomplete patterns. This became possible in that the concepts - known from object-oriented approaches - of polymorphism and encapsulation of individual entities were implemented by a distributed representation within the hidden layer. Compared to the approaches developed in the past (see Nauck et al., 1994), the network developed here thus can draw explicit conclusions, that is to say, it can supply exact frequencies for any statements and at the same time it can work with incomplete knowledge.

Looking at it overall, this means that typical advantages of pattern processing and symbol processing were tied together: the possibility of explicit conclusions on the side of symbol processing as well as the possibility of association and processing of incomplete information on the side of pattern processing. This means that the approach presented here also has a certain degree of relevance regarding cognitive model formation which we will go into later in the concluding Chapter 6.

- **Avoiding Combinatory Explosion**

Redundancy increases as a result of distributed representation within the connectionism approach which means that coding becomes expensive; nevertheless, the network, compared to the descriptor-oriented approach, calls for less coding because not every n-valent statement that is possible by means of combination has to be kept explicitly in readiness within the network; instead, it is formed only by means of propagation and back propagation. With the help of this procedure and the use of hidden cells, the approach thus avoids the combinatory explosion of the entities required for analysis (objects, verbs, properties, etc.) and relations. This is shown clearly in Figure 38.

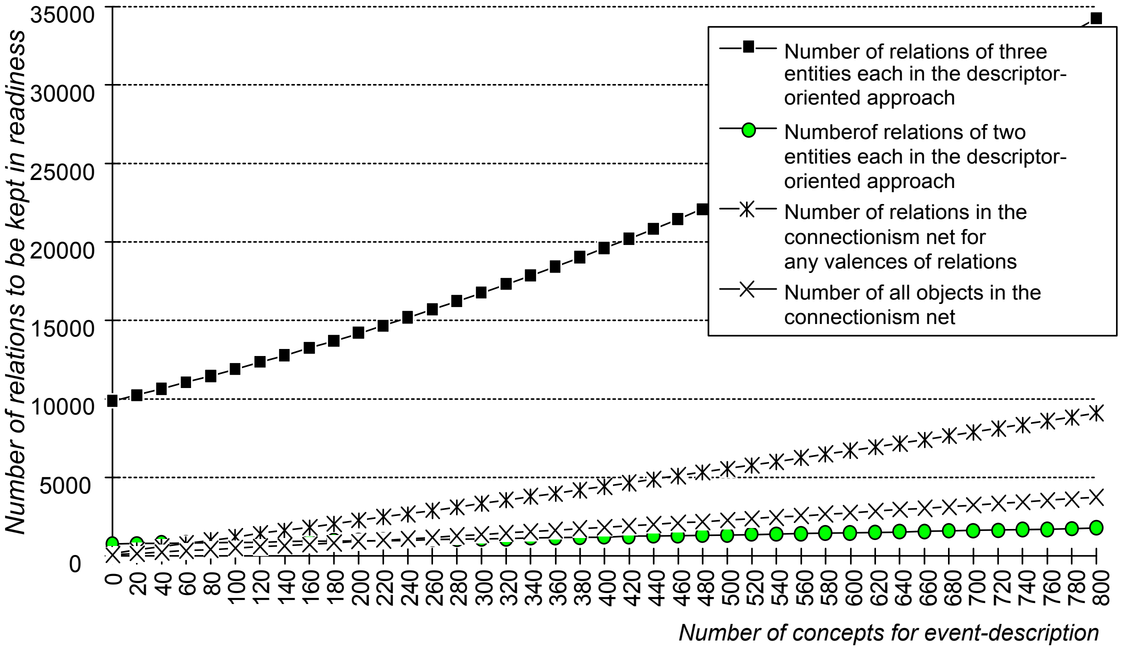

Figure 38 Curve Showing the Combinatory Explosion of Coding Effort for Descriptor Oriented Procedures when Compared to the Connectionism Network

The figure gives the number of required objects and relations for the descriptor-oriented approach and for the connectionism approach that must be pursued for the purpose of analyzing events. The larger the number of concepts for the event description and the higher the valence of the statements that are to be made, the more likely it is that the combinatory explosion of the descriptor-oriented approach will make itself failing. To calculate the curves, the combinatory explosions are calculated with equation 15 that was given earlier and it was assumed that 40 entities are required to describe the first event and that, after two additional events, a further entity must be supplemented for the description of the events. This is a very pessimistic assumption. In reality, the growth rates and thus the explosion effect are considerably higher, as we will see in Chapter 5.

Regarding the growth curve of the objects and relations in the connectionism network, we counted all required objects and their connections in order to tie all layers within the network together with each other (objects of concept layer, of hidden layer, of set layer, of MMS system layer, and of event layer). The growth rate is definitely less than in the case of the descriptor oriented approach for trivalent statements.

- **Illustration of Grammars as Network Structures**

In grammar, we usually make a subdivision of language elements into phonemes (sound symbols), morphemes (significance bearing symbols), words and sentences (see Dorsch et al., 1994). To model language processing, speech events are considered as a process - in psycho linguistics building on speech elements - in which the elements for instance cooperate via a probability process (a Markov Process). McClelland & Rummelhart (1981) showed with the help of their word recognition model that language modeling is basically also possible with connectionism networks. The problem in language processing is to achieve a suitable structuring of the language elements; for instance, one uses hierarchical graphs as form or organization (for instance, Chomsky, 1965), then the problem is represented by the fact that the complexity of language cannot be illustrated without a combinatory explosion of the modeling apparatus and this basically is the same problem that prevails in the analysis of practical operational experience.

If one looks at the model developed here from this linguistic angle, than it basically represents a language recognition system in which each language element in each case is implemented as one level within the network. The network here permits any connections between the levels so that linguistic interconnections materialize by virtue of the frequency with which certain relations are used. The correct reproduction of learned knowledge is then ensured by the propagation and back propagation of the activation scheme. The network designed here, however, starts only at the word level (although theoretically it could also be expanded to the level of phonemes and morphemes) and ends on a higher level than the sentence level because a MMS can grammatically speaking be viewed as a section and an event can be seen as a chapter. This means that the model presented here overall constitutes a contribution also to language recognition.

4.5.2 Peculiarities regarding Event Analysis

By virtue of its methodological possibilities, the approach developed here can solve typical problems of event analysis. This means that this approach, compared to past approaches regarding event analysis (for example, ASSET or HSYS, see Chapter 2) offers some advantages that will be listed below.

- **Analyzability of any Detailing Stages**

The algorithm is able to process any detailing stages. This can be seen in that the levels, as noted above, merely specify a grammatical structuring but not the contents that the network can process. This means that an event description can be better replicated because the original information of the event remains preserved and does not have to be reduced to a few descriptors. In that way, it becomes possible also to illustrate rare event constellations within the same description method, such as event constellations that can be observed often. Conventional analysis methods, such as the HSYS or the ASSET, presented in Chapter 2, do not permit this. A description of a rare event can be accomplished here only incompletely or in a falsified manner.

An analysis of the data structure in terms of content becomes possible in that concepts are combined into classes and that combinations of concepts and/or classes are formulated as inquires addressed to the network. This means that the analysis is completely object-oriented, that is to say, it can get along without any additional programming or administrative effort. That offers the advantage that one need not alter the entire acquisition structure and analysis structure in order to analyze novel questions. The model developed here can analyze any interrelationships (for example, between errors and PSF). In the case of descriptor-oriented methods, one can only analyze the question for which the descriptors were designed.

- **Variable Access**

By virtue of its structure, the network is in a position to access any of the knowledge represented in it. This is possible because not every interrelationship is illustrated by a direct connection; instead, it is established by means of a calculated connection between the event level as point of inquiry (key) and the activation scheme (context). By determining the nodes that are used as key or as context, one gets the desired interrelationship as an increased activation between these nodes.

That facilitates the most varied accesses to the information in the network, such as it is required for the analysis of human reliability within the various HRA methods. The knowledge within the network can thus be analyzed in a manner related to error types, PSF, or time parameters. This is not possible in conventional methods because, in this case, the access possibilities must be determined a priori. This means that the analysis model is more in keeping with the multi-aspect of human error, as discussed in Chapter 1, than is the conventional method for analyzing error descriptions.

- **Determination of Similarity, Learning Ability, and Transferability**

The connectionism network presented here can process patterns. The similarity between two events is represented within the network as the identical activity of the nodes on the MMS level or the event level. In that way, the network can also process incomplete data. These possibilities of pattern identification would not be possible in descriptor-oriented methods.

This property is important in analyzing events: (1) A summary of differing events on the basis of a similar pattern is required because each event, taken by itself, is unique and because similarities between different events must be found with regard to ergonomic marginal conditions. (2) Incomplete data have to be processed because event descriptions usually do not supply any complete indications as to an error and the prevailing PSF, although, nevertheless, indications should be possible regarding human reliability (for example, for the analysis of the event when little information is available in the beginning).

The connectionism network can also ‘learn’ from new events because each new event is inserted within the existing concept hierarchy and class hierarchy of available knowledge. When a new event can be described by relations between concepts that are already present in the network, then the existing relations are boosted. Other relations, that are not observed frequently, on the other hand, weaken their connection in relation to the boosted ones. Often observed concept constellations thus represent the experience that is represented within the network. Furthermore, the network can be supplemented by means of specific aspects of the new event in that new concepts are inserted in the already existing concept hierarchy and class hierarchy. As a result of both of these mechanisms, the entire network can learn and a determination of similarity between different events becomes possible. The transferability of different events, often discussed as being problematical, is facilitated by these properties of the analysis algorithm (ability to learn and determination of similarity).

- **Context-related Evaluation of Situations**

As we saw in Chapters 1 and 2, current error models and evaluation models are fixed upon a certain aspect of human reliability (for example, possible error types or PSF). The complexity of the situation or of the context cannot be considered in these methods because the models cannot provide any indications for such complex statements. On the other hand, the approach developed here - consisting of description model and analysis model - does permit a context-related analysis of events and thus also a context-related evaluation of human reliability. This context-relatedness is the common denominator under which both Dougherty (1992) and Mosneron-Dupin (1994) view the solutions for a more accurate and more realistic evaluation of human reliability.

The use of this method in evaluating events, described in the following chapter, will show how a context-related analysis is possible with the help of this approach and what results can be achieved.

5 Event Analysis and Prediction of Process

The event analysis process that was developed in the two preceding chapters will be used in this chapter for a systematic analysis of events. Using the analysis process presented in Chapter 3, we will describe events from practical operational experience in terms of content analysis and we will analyze them, as well as evaluate them, with the help of the analysis method given in Chapter 4. Then we will work out qualitative and quantitative predictions about human reliability. The description and analysis method was implemented as databank application in Microsoft ACCESS under the name of CAHR (Connectionism Assessment of Human Reliability). It is broken down into the acquisition and analysis of events as well as an analysis of the collected information for qualitative information (for example, effectiveness of optimization measures) and quantitative or probabilistic investigations. The databank is presented in Appendix 1.

5.1 Analysis of Sources on Practical Operational Experience

As source for event analysis, we used the databank entitled „Special Occurrence“ of the BEVOR that was described in Chapter 2. It was chosen because a large number of events were collected here (totaling more than 4,000 events); and because these events are present in standardized form and have a relatively uniform detailing level in the event illustration. Within the special occurrences, all events from 1965 to 1993 and only events in boiling water reactors were considered; events from other systems (for example, pressurized water reactors) were not considered. This ensures a relatively good comparability of event descriptions. The events were investigated in the following manner within the special occurrences.

1. Identification of possible Human Factors events
2. Investigation of Human Factors Events that were found
3. Analysis of collected Human Factors Events

5.1.1 Identification of Possible Human Factors Events

To select the events, we searched special occurrences with a selection of criteria or key concepts that point to human errors. Appendix 6 shows what criteria were used for a provisional classification of HF Events. We identified a total of 229 events in boiling water reactors. The subsequent analysis of these 229 discovered events, with the description model given in Chapter 3, showed that the criteria used led to false alarms in 39 events and that insufficient information in the description of the event was given in 25 events, in an effort to analyze the latter with the help of the description model. In general, the accuracy of this automatic prediction can be graded as rather good because the portion of false alarms was 23% and the portion of events with too little information was 15%. The subdivision of all of the events present in the databank in terms of HF, HR, and technical events is given in Figure 39.

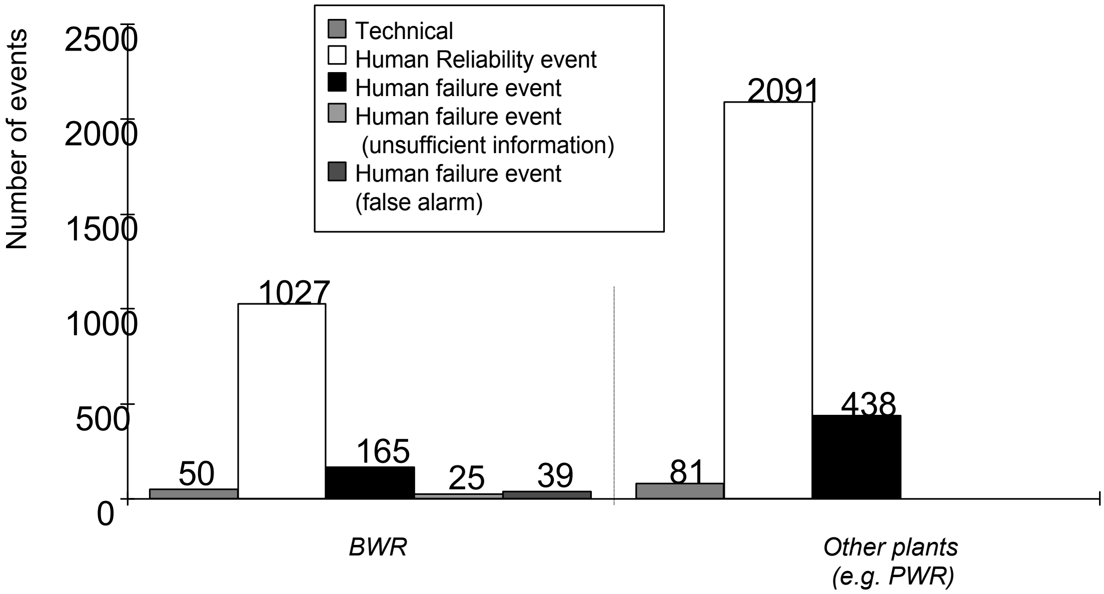

Figure 39 Distribution of HF Events as compared to HF Relevant Events and Technical Events

The figure, furthermore, shows that only a small part of all potential HF Events was investigated with those 165 events because, first of all, about 438 HF events from other system types were not investigated and, additionally, we have a large percentage of HF relevant events here. It is precisely this overwhelming portion of HF relevant events that can be significant in terms of human reliability if one is not to consider only the erroneous interventions of human beings but also the achievements of human beings in terms of faultlessly intervening in the technical system and correcting a case of trouble. This aspect, which cannot be charged to human error, is required also for a satisfactory quantitative estimate, as we will discuss in the further course of this chapter.

A representativeness test was performed to make sure that the selected events will be a representative random sample from the available data material. Figure 40 shows the distribution of the selected HF events in comparison to all of the non-HF events, broken down over the period of observation. The frequencies were standardized for a statistical comparison in order to equalize the frequency difference. One cannot detect any significant difference in random samples (HF events as against non-HF events). The correlation is around r=0.86. Likewise, it was impossible to find any significant differences between differing systems or differing years (in other words, different technical solutions).

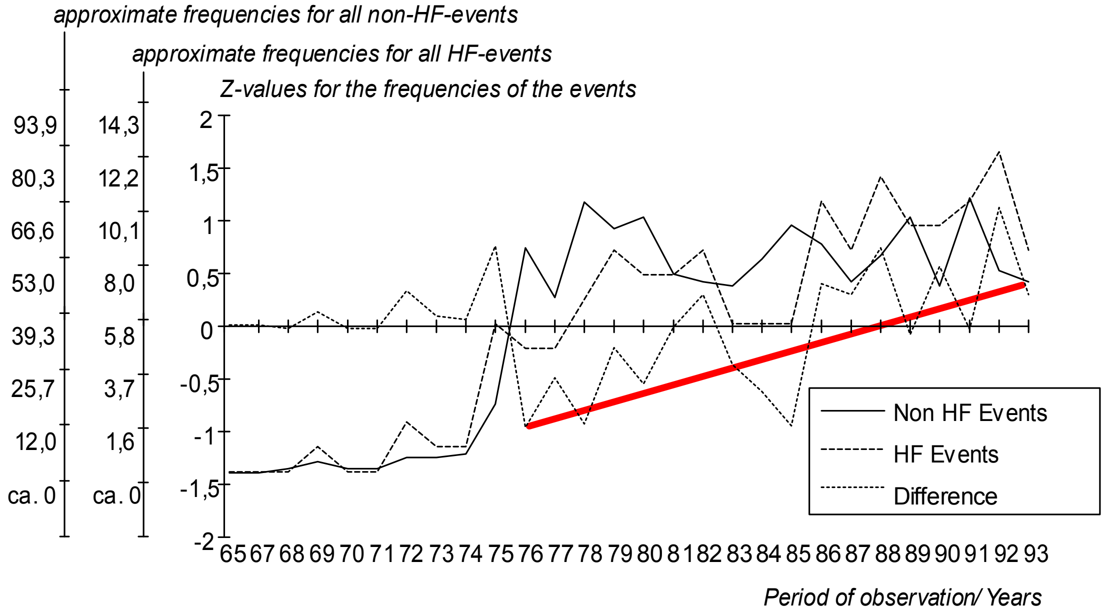

Figure 40 Test of Representativeness of Investigated HF Events

The figure also shows during what years human errors displayed a greater significance than technical errors (difference curve of standardized frequencies). A slight rise - which, in the final analysis, was steady - from 1976 to 1993 indicates that human interventions are of increasing significance (this is shown in the figure with a gray line). The rise thus represents the general realization that, as the degree of maturity of technical systems increases, there is also an increase in the relative share of human error actions (among others, Semmer, 1994). But this rise is not significant and cannot be explained either by the construction of new systems. The different appearance of the curves before and after 1976 can be traced back to different types of event reporting.

5.1.2 Investigation of HF Events

The remaining 165 events were investigated with the help of the method described in Chapter 3. We proceeded as following in analyzing the event descriptions:

1. First of all, we identify differing MMS in the description text. For that purpose, we used the characteristics of persons, places, and situations described in Chapter 3. On the whole, we identified 255 MMS in the 165 events, that is to say, on the average, each event consisted of 1.54 individual MMS.
2. The sentences or clauses in the description text, that relate to a particular MMS, thereupon were broken down, by means of sentence breakdown, to the essential information components or units of meaning (subject, predicate, object) and the latter were verbatim taken over into the scheme of event description (object, action, indication, property, element).
3. The concepts used were thereupon adapted to each other. We took two steps with this objective in mind: (1) Adaptation of forms of concepts (declinations, conjugations, such as, for example, open - opened or lined - lines). (2) Adaptation of semantic significance of concepts (for example, „emergency power diesel“ and „NSD[9]“ were combined into the concept of „Diesel“. The resultant overall taxonomy is very comprehensive with about 1000 concepts.[10] This multiplicity, however, is necessary in order to be able correctly to reproduce the specific information within the event. On account of the capacity of the analysis model, the number of concepts, however, is of subordinate significance. The number, furthermore, remains clearly visible when it comes to the event descrip-

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[9] in German "NSD" is the shortcut for "Notstromdiesel" which means „emergency power diesel“

[10] If the 1000 terms are subdivided according to the MMS-aspects (n=10) and the description stages (m=5), an average of about 20 terms per field is to be expected. This makes the taxonomy quiet comfortable to handle.

tion because the concepts are arranged with relation to the description structures (see Chapter 3) and because they are selected and reduced by means of class formation, as well as with the help of the criterion of utilization frequency (see Chapter 4 and Appendix 1).

4. In another step, we supplemented concepts and we marked them as follows: By means of „+“. When we added concepts for which we had unambiguous references elsewhere in the event description itself or in additional information sources (for example, forwarding news). We used „?“ when we added concepts for which we had only indirect hints in the event description (for example, statements by experts, observations and practical experience).
5. When we mentioned improvement measures taken with respect to the events, it was assumed that the measures mentioned there were also effective as PSF even though they were not themselves explicitly mentioned in the event description (for example, the measure and title „Improvement of Layout of Instructions“ indicated that the person had an instruction available and that the instruction was poorly arranged.
6. Finally, for each of the 255 identified MMS, we performed a classification of the MMS according to system ergonomics subdivisions in order to describe the cognitive load (see Table 17, Chapter 3). Furthermore, for each of the 255 MMS, we described the action Type (Type A, B, C in Chapter 2).

5.1.3 Analysis of HF Events

Regarding the analysis of the practical operational experience that was gathered with the help of the process presented in Chapters 3 and 4, it should be noted that the material, present in the special occurrences, supplies only unsatisfactory information when it comes to a complete investigation of the events. Many questions had to remain unanswered and this is expressed in the fact that many table boxes in the description structure had to remain blank. That it was nevertheless possible to perform a meaningful analysis is due to the circumstance that a certain error always remains an error even in case of incomplete information. For instance, an omission is independent as to whether a group or a person omitted doing something. Insufficient, however, is the degree of detailing of the information when statements are to be made about the causal and actional PSF observed in connection with the errors (for example, whether the error of omission was promoted by the absence of feedback or by a poor procedure). This information, which is important in the search for improvement measures, could be obtained from only some events. Although the available data source as a whole thus supplies less information than would be desirable for a detailed analysis of human actions with the above-described method, it was possible to identify errors and PSF that will be presented and discussed below.

5.2 Analysis of Data with a view to Qualitative Indications

In evaluating human reliability, we are first of all interested in a qualitative description of possible error types and PSF. They tell us how great the error potential of a situation is or what improvement measures would be available. Classifications that were used for this purpose were presented in detail in Chapter 2: there, we mentioned in particular various types of actions, phenomenological error types and causal error classifications or PSF as well as classifications for cognitive load. It was possible to develop the following findings regarding these aspects with the help of event analysis.

5.2.1 Identified Action Types

In Chapter 2, we presented and discussed the classification of action types according to IAEA-50 (1992). There we established, among other things, that the subdivision - so far performed in the literature on the subject - of action Type C (Actions after initiation of trouble) is incomplete. Among other things, it did not allow any situation-deteriorating actions in connection with the use of procedures.

In order to obtain data on action types from event analysis, we assigned an action type to each identified MMS. In analyzing the 255 MMS however we found that the subdivision of actions according to the IAEA cannot completely cover all observed action types. Essentially, the classification must be supplemented with additional action types and this calls for modifications of action Type C. Table 25 summarizes these modifications of action types and their description.

In the table, compared to the subdivision from Chapter 2, we first of all supplemented the action Types T, A0, and Ba. A MMS from Type T merely contains additional technical information. Type A0 characterizes a MMS in which no error occurred although an erroneous event materialized due to interactions with the current system state or other MMS. In Type Ba, we summarized the actions that followed the occurrence of a latent error, i.e. manifestation of a latent error.

In the IAEA, actions from Type C were subdivided in terms of the utilization of procedures and no utilization of procedures. Situation-degrading actions were found with procedures and therefore the subdivision of the IAEA does not depict all empirical interrelationships. The discovered interrelationships point to the conclusion that - even when procedures are utilized - there is to a certain degree the potential that situation-degrading actions might be committed. In the simplest case, this can be observed when the procedures are incomplete. That was the case with both situation-degrading actions.

Table 25 Classification of Discovered Action Types in the Investigated Events

Action Types	***Description***	***Frequency Observed***
Type T	Errors in automatic actions of the technical system. They were mentioned in the event descriptions and are important to the course of events; but they do not contain any human influence.	8
Type A0	The personnel themselves did not make any mistakes although an error event springs from interactions with the current system state (for example, occurrence of a latent technical defect, overlapping maintenance task - simultaneous or in the same space concerned).	4
Type A	Error during maintenance and care that lead to latent errors (identical to Type A according to IAEA).	44
Type Ba/ improving	Situation improving reaction to the occurrence of a latent Type A or Type A0 error.	40
Type Ba/ degrading	Situation degrading reaction to the occurrence of a latent Type A or Type A0 error.	8
Type B	Personnel actions that led to an initiating event (identical to Type B according to IAEA).	116
Type C/ improving	Situation improving measures without procedure in a faulty system state (Type C3 and Type C5 according to IAEA).	12
	Situation improving measures with procedure in a faulty system state (Type C3 according to IAEA).	1
Type C/ degrading	Situation degrading measures without procedure in a faulty system state (C4 according to IAEA).	20
	Situation degrading measures with procedure in a faulty system state (not contained in the IAEA classification).	2

If one analyzes the action types specifically, then the absolute frequency data are not so decisive. The fact that, in the events, one can observe primarily B actions, in other words, initiating events, is for instance to be explained only by saying that events below a certain safety engineering threshold do not have to be reported. Instead, what is decided is which relative frequencies can be observed. If one compares the situation-degrading actions from Type Ba to those from Type C, then we find the following: It is easier to remedy trouble that occurs in an otherwise trouble free situation (error share for Type Ba about 0.16≈8/(40+8)) than in a situation in which an error has already been committed (error share for Type C about 0.62≈(20+2)/(20+2+12+1)).

The relation between improving and degrading interventions thus shows that operators in the overwhelming number of events are capable of correctly reacting to spontaneous system changes (independence between initiator and recovery possibility in the case of Ba). In already faulty states, on the other hand, they are having problems (dependence between initiator and recovery possibility in the case of C). A C action is always preceded by a B action; on the other hand, a Ba action is preceded either by a Type A action or a Type T action; therefore, the interrelationships of the action types point to different recovery possibilities. Such recovery possibilities are evaluated in THERP with the so-called dependence model which we will once again touch on later.

5.2.2 Identified Error Types

In Chapters 1 and 3, we differentiated between possible types of human errors (table 2 and 14). With the help of event analysis, we were able to ascertain the extent to which they are adequate when it comes to performing a complete description of all error types. Table 26 summarizes the discovered error types. Here we find - deviating from Tables 2 and 14 - a subdivision oriented by the structure of the MMS to be more suitable. Along with the error types, compiled from the literature in Chapters 1 and 3, we get the following additional ones from the event descriptions:

- The expression ‘not possible’ refers to an error that, on the basis of external circumstances, led to a task error (for example, interlocks of a system state make it impossible to intervene manual activation, extremely poor arrangements of operating elements make the required intervention during the necessary time frame impossible, missing communications possibilities cause a situation where information cannot be passed on, etc.). The error type ‘not possible’ thus is a form of omission which, however, is characterized by the effort of the human individual not to perform this omission.

- The expression ‘missing’ designates another form of omission where not along due to situational facts (for example, interlocks) but basically there is no possibility of intervention although it would have led to a situation improvement (for instance, absent signaling of a system state).
- The expression ‘wrong’ is defined according to Table 2 as a error of execution where the object of the action was wrong (for example, a valve A was opened although it was not supposed to have been opened). If action A is omitted and if action B is performed wrong, then we are dealing with an error of confusion (see Chapter 3 and 4).
- The expression ‘faulty’ refers to a setting error. In contrast to ‘wrong’, it is not the entire action that is wrong but only the performance of the action. For instance, valve A was closed instead of being opened; in this case, it was the correct valve but the action was faulty (see Chapter 3).
- The expression ‘too inaccurate’ represents an error where, from the description of the event, one could not precisely figure out what error of commission was involved.

A closer look at the Table shows that the quantitative errors of commission listed there more or less correspond to those in Table 14 from Chapter 3 (marked in the Table with „◆“. The expressions ‘too fast,’ ‘too long,’ ‘too tight,’ ‘ too weak,’ and ‘too far’ are merely more accurate descriptions of the time and setting errors (too early, too late; too much, too little). The error type ‘too inaccurate’ signifies merely that there was no information for further specification. Furthermore, in Table 26, as compared to Table 14, the error type ‘faulty’ for task error and the error type ‘omit’ for errors of commission during order dispatch were allowed (for example, when order dispatch was not reported back). These inconsistencies likewise reside in the deficient depth of detailing of the description because in these cases the relationship between task and activity was unclear. A genuine expansion would thus be feasible only for the error types ‘not possible’ and ‘missing.’ Both error types are a sub-quantity of the error of omission where the technical system does not offer possibilities that the operator demands of it, although they would have been necessary for the purpose of improving the situation. They thus show that omissions must be viewed in a considerably more multi-layered fashion than so far: If the task is ‘not possible,’ then this points to deficient layout of the overall task regarding the subtask that is just to be accomplished; if the task if ‘missing,’ then this points to defective intervention possibilities by the individual in the technical system.

Table 26 Error Types Observed in the Investigation and their frequencies within the identified MMS[11]

a) Task Error

Task Error	*Task*	*Person*	*Feedback*	*Order*
◆ omit	56	39	2	3
◆ faulty	22	2	14	27
not possible	14	2	14	11
missing	1	0	22	0
◆ wrong	0	6	0	0

b) Error of Commission

Qualitative Error of Commission	*Activity*	*Order dispatch*
◆ wrong	85	0
◆ faulty	29	1
◆ omit	0	4
Quantitative Error of Commission	*Activity*	*Order dispatch*
Time Error		
◆ too early	9	0
◆ too late	7	0
too fast	6	0
too long	1	0
Setting Error		
◆ too much	12	0
◆ too little	17	0
too tight	1	0
too weak	1	0
too far	2	0
too inaccurate	5	1

If one compares the frequencies in task errors in the table, then one finds that there is an opposite connection between frequencies related to ‘task’ and ‘person’ on the one hand as well as ‘feedback’ on the other hand. Errors in feedback mostly consist of faulty and missing information and not so much of omissions by persons as they fail to consider them. Accordingly, feedback seems to be an essential factor in the reliability of the acting person. More detailed interrelationships of this kind can be found if one investigates the reciprocal relationships between differing error types.

5.2.3 Causal Performance Shaping Factors

A human error comes about within the MMS only if the flow of information in the MMS is disturbed at any point (Chapter 3). It is expressed in the form of trouble at the system output of the MMS. Interrelationships between errors in the various components of the

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[11] The extension of the error types is in broad accordance to the discussion of error types for errors of commission by Hollnagel (1999).

MMS provide a hint as to which MMS components contributed to the error and require improvement in order to prevent human errors. They furthermore show what weak points in the MMS components can be compensated for rather by the human individual.

To determine such interrelationships within the 255 MMS, we first of all determined, for each MMS component, the frequency of a disturbance in the information flow (for example, number of errors of commission). For every possible combination of MMS components, we determined, in another step, the frequency of the interrelationship of the errors (for example, number of errors of commission based on errors in order issuing). The frequencies here are smaller than or equal to the frequencies that were determined in Table 26 with relation to the different MMS components because several error types can be given per MMS component (in one event, for example, a valve A in a MMS may have been closed too late and a valve B may have been opened too early). Table 27 shows the determined frequencies, their distribution over the MMS components, as well as their interactions. Correlations in this connection do not represent a meaningful measure; therefore, the connection between two reference magnitudes will be expressed by the maximum possible relative share. That share is determined by the following equation:

$$h_{\mathrm{maximal}\,relative} = \frac{h_{\text{Common occurrence of reference magnitude 1 and reference magnitude 2}}}{\min\left(h_{\text{reference magnitude 1}}\,;\,h_{\text{reference magnitude 2}}\right)} \qquad (24)$$

Along with the trivial statement that errors of the person can be expressed in the form of errors of commission to the extent of 87%, we can gain the following statements from the interrelationships observed in Table 27:

- Feedback assumes a central role in human reliability. If an error can be observed in feedback, then there were errors of commission in 84% of the events and task errors were found in 55% of the events.
- After feedback, order issue is the second most important factor for task errors and errors of commission. Weaknesses in order issue can be compensated more easily when compared to errors in feedback.
- The strong connection of errors in order dispatch with task errors, points to the significance of organizational aspects.

Table 27 Frequency of Causal PSF and Relationships of the Information Flow within the MMS

Maximal relative portion	Task	Person	Activity	Feedback	Order-issue	Order-dispatch	Environment
Task							
Person	0,40						
Activity	0,61	0,87					
Feedback	0,55	0,30	***0,84***				
Order-issue	0,46	0,27	0,68	0,24			
Order-dispatch	0,67	0,33	0,17	0,17	0,17		
Environment	0,00	0,00	1,00	0,00	0,00	0,00	
Error-frequencies	90	47	156	49	41	6	1

To be able to illustrate the significance of the differing MMS components with respect to each other, it is a good idea to visualize the reciprocal interactions from Table 27 by means of a Non-metric Multi-Dimensional Scaling [NMDS]. A NMDS calculates the average connection between several mutually elements. The principle of the NMDS is easiest to understand when one visualizes how, from the individual information items in a distance table, contained in an auto atlas, one can reconstruct a map. In a Metric Multi-Dimensional Scaling [MDS] we have available the interval-scaled distance kilometers for reconstruction purposes (for example, Munich is 580 km from Duesseldorf). In an NMDS, we only have available, for each connection between cities, relative statements having the following form: „Munich is farther from Hamburg than it is from Duesseldorf.“[12] These information items suffice in order completely to reconstruct the location of the cities with respect to each other (for further details, see, for example, Borg & Staufenbiel, 1989). To calculate the point constellation, a NMDS proceeds in the following manner: a randomly chosen point constellation is adapted as accurately as possible to the relative statements by means of an iterative procedure. The measure for the quality of adaptation is the alienation, also called "stress" [not in the psychological sense]. It represents the remaining disorder within the calculated point constellation in comparison to the ideal point constellation and ranges from 0 for optimum agreement up to 1 for no agreement at all.

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[12] The reader should feel free to imagine any other constellation of cities than the three German ones (Munich, Hamburg, Düsseldorf) mentioned here, e.g. SanDiego, Dallas, LasVegas.

The advantage of this process consists of the fact that the location of the points with respect to each other can be interpreted in terms of content and that the individual observations can thus be viewed in an across-the-board interrelationship (see also Eye & Marx, 1984). Here, we can consider factor analyses, cluster analyses, or groupings according to content viewpoints. This means that, with the help of an NMDS, we can determine which general factors are effective in the observed interrelationships. NMDS is a process that is more sturdy when compared to the data level of the observed interrelationships; therefore, in this case, we select an NMDS instead of an MDS. It was performed with a program based on an algorithm developed by Gausepohl (1989). Figure 41 shows the result of a NMDS of the table entries from Table 27. The alienation is about 0.23.

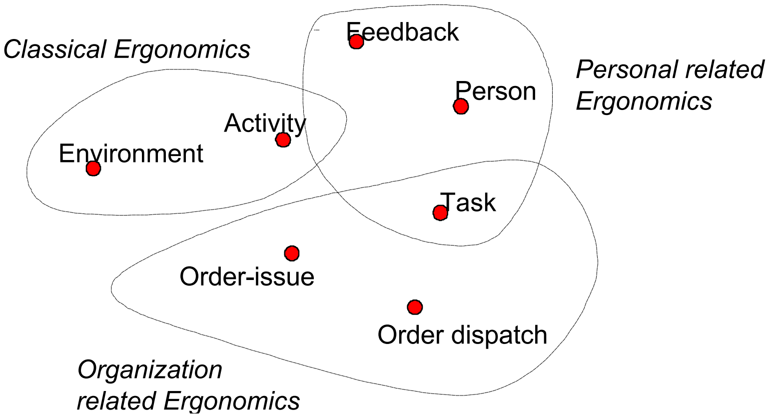

Figure 41 NMDS of Errors in Information flow of MMS

If one groups the point pattern according to content viewpoints, then the result of NMDS can be interpreted as follows: the greater the distance of the remaining points to the point ‘person,’ the more easily the person can compensate errors of this MMS component or, in other words, the closer a point is to the ‘person’ point, the more direct is its influence on the person (i.e., the dependency between the MMS components). As noted earlier, it is especially the feedback that exerts essential influence on the reliability of the acting individual. NMDS thus shows that (1) the immediate work environment is more important for the active person than organizational measures and (2) organizational measures make essential contributions to the origin of the error. The figure thus points to an integral layout approach that considers ergonomic, human, and organizational factors.

5.2.4 Identified Error Conditions or Actional PSF

Within the investigated events, it was possible to identify a total of 30 conditions under which human errors occurred. They are described in greater detail in Table 28.

Not all PSF were mentioned explicitly but rather are based partly on assumptions that were arrived at from the event descriptions; it was therefore required to give the uncertainties of the factors (Figure 42). As described earlier, in the event description, the factors that were obtained on the basis of hints were prefixed with „+“; factors that were obtained on the basis of presumptions were prefixed with „?“ (see also Appendix 3). Continuing the analysis of PSF, no further distinction is made between certain and uncertain factors.

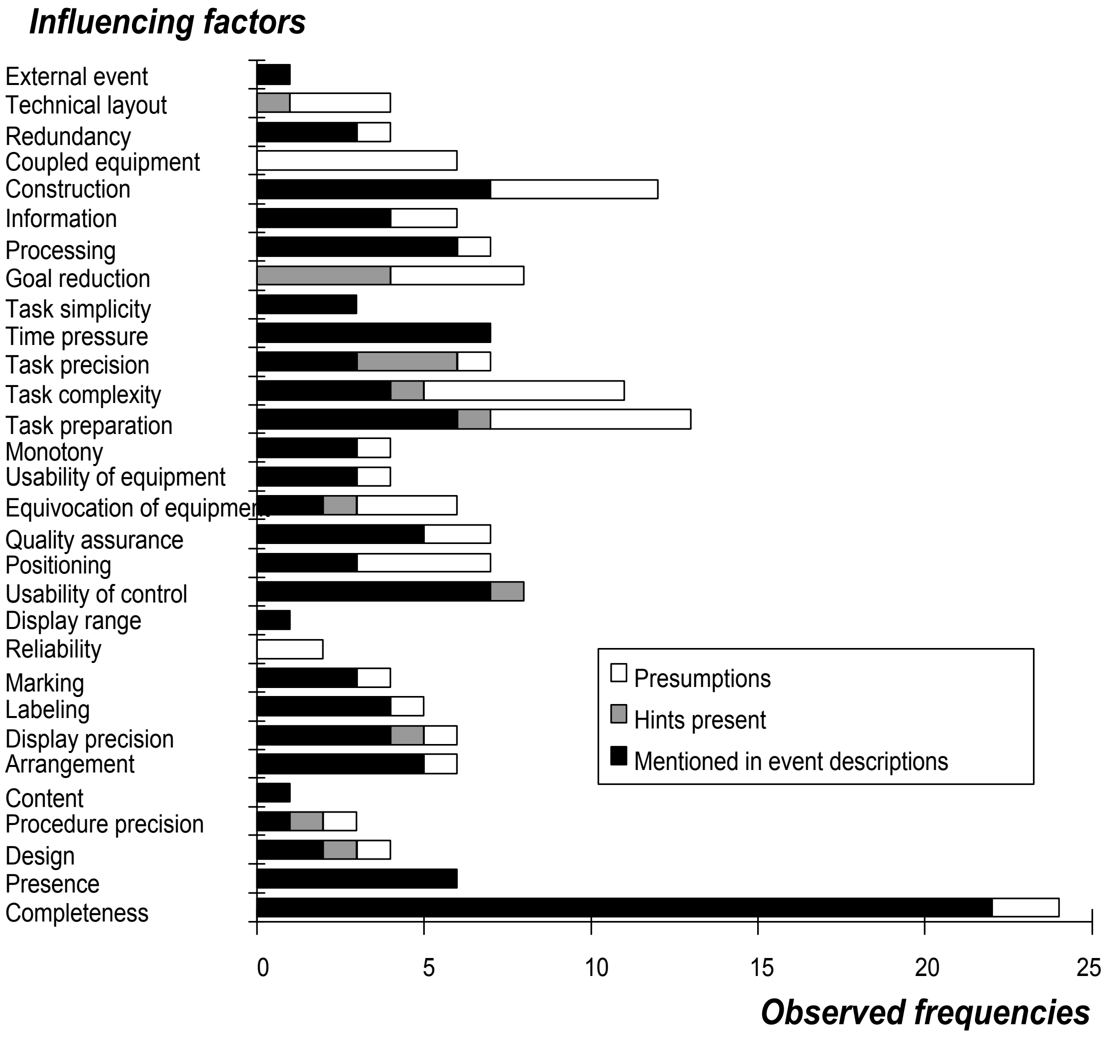

Figure 42 Identified Performance Shaping Factors with their uncertainties

Table 28. Compilation of Conditions Identified for a Human Error

Property	***Description***	***n***
Task		
Task preparation	Task planning, organization, or preparations were insufficient	13
Simplicity of Task	The task to be performed is so well practiced that slight deviations from tasks currently to be performed were not considered.	3
Complexity of Task	The task is too complex due to situational conditions.	6
Precision	The task was stated inaccurately.	7
Time-Pressure	The task had to be performed under pressure of time.	6
Order Issue		
Clarity/ Precision of Procedures	The instructions, made out ad-hoc, are not sufficiently precise.	3
Design of Procedures	The instructions are poorly styled in ergonomic terms.	4
Content	The content of the instructions is wrong.	1
Completeness	The instructions are not sufficiently precise.	24
Presence	There are no instructions.	7
Person		
Processing	The person acts in the habitual fashion.	7
Information	The person did not use the information or knowledge or the information or knowledge did not suffice in order to accomplish the task correctly.	8
Goal reduction	In a decision-making situation, the person impermissably simplifies the situation.	11
Activity		
Usability of Control	The operating elements of a component are difficult to work.	12
Handling/Usability of Equipment	A movable object is difficult to handle.	4
Monotony	The activity is monotonous so that vigilance effects occur (for example, inertia, search for change of pace).	4
Positioning/ -ability	It is difficult to move an operating element into a desired position.	7
Quality assurance	Work done is, in conclusion, inadequately checked.	7
Equivocation of Equipment	Objects are not so designed that they were built in or inserted without danger of confusion (for example, twisted plugs).	6
Feedback		
Arrangement of Equipment	The information is arranged unfavorable in ergonomic terms as regards the task.	6
Display range	On account of the limited display range, the information is not correctly displayed (exceeding the display spread).	1
Accuracy of display/Display Precision	The information is not correctly displayed because of the inaccuracy of the display.	4
Labeling	The display is inadequately labeled.	5
Marking	The displays do not have a marking of the system states that are connected to the value of the process magnitudes.	6
Reliability	The display is not reliable.	2
System		
Technical Layout	The structure is not sufficiently designed for overloads.	4
External Event	An event, acting from outside the system, leads to an erroneous system state.	1
Construction	Objects are awkwardly constructed (for example, bulky construction).	8
Redundancy	A system either lacks redundancy (for example, by means of clearing) or the redundancy had failed with the rest (for example, due to a common cause).	4
Coupled Equipment	Electrical components are poorly constructed (for example, coupling, meshing).	6

In accordance with the distribution of the man-machine system components, we thus get performance-shaping factors that are involved in ergonomic layout of operating and work resources (such as, for example, no markings, unsuitable arrangements of operating devices), organizational performance-shaping factors relating to the styling of written aids (such as, for example, lack of completeness in instructions) or relating to organizational tie-in (such as, for example, deficient task preparation or quality control). Performance-shaping factors thus on the whole always reveal a deviation of situational facts from the expectations of the human individual or, in other words, the effort that the individual must make in a certain direction in order to adapt himself to the situation or to adapt the situation to his needs. They thus point to the conflict between typically human ways of behavior and technical or organizational facts.

With the help of this consideration, we can differentiate two groups basically: loading and coping factors (see Chapter 3). Loading factors describe the influence that can be traced back to the properties of the situation, in other words, to all man-machine system components that act upon the individual. Coping factors describe influence that can be traced back to the properties of the individual (all factors related to the person). Typical loading factors are time pressure in task preparation or difficulty of task. Typical coping factors are faulty information processing or goal reduction of the human individual. The effect of performance-shaping factors becomes particularly problematical when the individual himself or herself creates additional loads by virtue of his or her abilities and needs. The following factors are particularly important regarding this aspect:

Simplicity: Human beings have a natural desire to reduce the complexity of their environment as much as possible. This striving for reduction can have negative consequences along with the positive effect deriving from the ability to circumvent complex situations. The factor of simplicity describes this negative effect of practiced proficiency. If a situation is highly practiced (skill based) due to practice or many repetitions of performance and if it is most familiar, then a person will work on this situation with less attention and on an unconscious or only partly conscious level (subliminal). No further attention is devoted to minor deviations of the error-prone situation from the planned situation.

Of course, a subliminal information processing action explains only a part of the errors observed in event analysis. Even without minor situational deviations, actions, that so far have always been carried out thoughtlessly, can suddenly be performed in a faulty manner. That happens, for instance, when a clearing switch is turned on together with a component switch although, actually, the component switch should have been turned on by itself for testing purposes. The reason behind this type of error is difficult to fathom. Rasmussen (1986) explained this error by saying that previously explicitly present knowledge is automated as a result of routine practice or multiple execution of task. Exercises in practiced ways of behavior are viewed here as the result of the procedure for automation that is referred to as compilation according to the Adaptive Control of Thought Theory of Anderson (1983).

In the events, however, one must note that this type of errors will lead not so much to omissions or errors of commission but rather to errors of confusion. This means that such errors could not be explained only in terms of the process of compilation because the latter does not alter knowledge itself in a substantial fashion (Anderson, 1983) and because one would therefore not have to look forward to any confusion. The observed errors thus rather reflect an effect that has been known for a long time in cognitive psychology as interference. Interference is observed particularly in connection with highly practiced abilities of the individual, such as speech or motor skills. The best known example is the famous Freudian slip (see also Wehner, 1984). Interference observations in connection with dichotic hearing in the final analysis led, for instance, to the known filter model of Broadbent (1958). Interference generally occurs when differing situation requirements use common abilities of the individual. In the above example, that would be the partial skill - highly practiced on the basis of daily operations - of activating a component switch always together with the clearing switch which interferes with the less well practiced partial skill of working the component switch alone. In subliminal information processing procedures, the "stronger," that is to say, the more practiced ways of behavior are then adopted. In other words, the phenomenon of the error of confusion is closely tied to the "simplicity" factor.

When it comes to practical use, one may conclude that training programs would have to be designed rather strategically and must not be used only for practicing skills in a certain situation. These strategies must be particularly suitable in order to be able commensurately to react both in practiced (simplicity factor) and in unpracticed situations (complexity factor) (see Günzel, 1993).

Equivocation of Equipment: The factor was observed in event analysis exclusively in connection with the production, operation, and maintenance of technical components; in shut-down states (non full power states), however, it represents a performance-shaping factor of special significance: if, when it comes to connecting two lines, for example, a pressure line and a suction line, are coded in the same form, then one can expect a far greater probability of confusion among the two lines than if they had different forms. The equivocation of equipment, however, relates not only to the connection of lines but also to the twisting during the installation of plugs or the connection of electrical links. That this performance-shaping factor is very significant in the field of production and operation was observed, for instance, also in the manufacture of electronic components. Albers (1995), for example, classifies it as a factor that is essential for zero defect production in connection with assembly line work. According to Bubb (1992), it can be considered as a subaspect of compatibility.

The " equivocation of equipment" factor and, along with it, errors of confusion, in general, moreover express one of the most difficult ergonomic questions: how great should the freedom of action of the individual in a technical system be? The phenomenon of confusion is thus also to a certain extent relevant to activities outside the process of manufacturing and equipment operation, in other words, in production and monitoring.

This is also confirmed by an analysis of a total of 19 additional errors of confusion that were observed in the events. The confusion itself is independent of things that are confused. Different technical systems are confused just as much as electrical or mechanical components or rooms. When it comes to analyzing errors of confusion, one should therefore focus not so much on the technical facts but rather on the flow of information in the man-machine system: in three events it was possible to observe the previously discussed factor of simplicity and insufficient information processing on the part of the persons involved. External factors involved in errors of commission are related to the input side of the man-machine system and they consist of precision, time pressure, and task preparation as well as - related to instructions - the content, clarity, and completeness of procedures and finally - regarding feedback - labeling, marking and arrangements. These factors are accompanied by the factor of "redundancy" and the factor of "coupled equipment" as well as the factor of "quality assurance."

The external performance-shaping factors point to incomplete information on the input side of the person; therefore, errors of confusion come up as interference effect between the internal ideas of the individual (his or her mental models), that change due to learning and adaptation, and the varying facts of his or her situational environment (see also Norman, 1993). The central road in the origin of errors of confusion is thus represented by the faulty transmission of learned units of perception, cognitive strategies or partial skills to situations to which they do not apply. Compatibility between the internal model and the situational environment is decisive when it comes to avoiding errors of confusion (see Spanner, 1993; Bubb 1992).

The main difficulty in effectively avoiding errors of confusion here consists in the following: the inner mental models can change and are difficult to access (among others, Gentner & Stevens, 1983). On account of the observed outer factors, however, one may conclude that the overwhelming portion of errors of confusion can be avoided by more precise task assignment. Quality control is another possibility of determining confusion and preventing possible consequences. But it is basically available only when the executor himself or herself was not given any way of control over his task performance (open loop action). In order actively to prevent errors of confusion, one must prefer those measures that create a possibility of controlling task execution (closed loop action). Factors in this kind of control by means of feedback are marking and labeling as well as arrangement. If one looks at these considerations concerning the importance of feedback, then a "soft guidance" by the individual - by means of (1) depiction of safety limits and (2) restriction of human freedom of action to actions within a safety spread - represents a possibility of avoiding errors of confusion.

Task precision, design and precision of procedures: These factors in some way feature action conditions that are similar to those connected with the factor of simplicity. The common feature of these factors is represented by the realization that they go along with the depth of detailing of information that is transmitted for the purpose of order issue in written or verbal form. Here again, persons try to achieve the most effective possible information transmission or to attain the least possible effort for the purpose of drafting an order.

The omission of redundant information is the foundation of any effective information transmission (see Attneave, 1974). If the order-issuing person can assume that the recipient will thoughtlessly carry out the issue of order even with less information, then information - that may be significant for handling the current situation - will be omitted. On the other hand, the information recipient also tries not to absorb too much redundant information, that is to say, he or she wants to know whether he or she can or cannot attain the desired state with his or her existing knowledge. If this is not the case, then he or she will need more detailed information; if that is the case, then additional information is redundant and will be perceived as being as superfluous or even irritating.

In the light of these considerations, the effectiveness of administrative measures to prevent human errors must be graded as being rather limited. Effective information transmission cannot be achieved by having procedures or verbal as well as written instructions contain highly detailed directions, without exception and at any time. Instead, it should mention the essential deviations from existing knowledge. People are able to learn and this means that the depth of information of written instructions should be variable (for example, when needed, they should supply additional information via computer-assisted procedures or additional information sheets).

Marking and Labeling: Compared to other performance-shaping factors inherent in feedback, marking and labeling are factors that point to the deficient semantic significance of information that is fed back. Both factors clearly show that the significance of the components is often not directly imparted to the operator. Instead, it is assumed that he is familiar with this significance by virtue of his education (for example, that pump Z will kick in when the filling level is X). Looking at these factors, one can therefore also observe a typical human property based on the fact that the person is in a position to learn and to automate ways of behavior; knowledge is not always used explicitly, that is to say, consciously. In case of known and highly practiced ways of behavior, it is used only implicitly, that is to say, by way of context information. It is tapped consciously only when there are deviations from known situations (see Mandl & Spada, 1988).

When it comes to designing technical components, it is necessary, in light of these considerations, to give the operator feedback as to the significance of the components and the currently displayed values. In the simplest case, this can be done by putting under the current value a qualitative color code in red (= faulty) and green (= faultless) areas on an analogous display. The significance may vary in different situations; it is therefore required to depict the safety margins in consonance with the given situations. The latter can changed in time; therefore, this is another example that we may use computer-assisted systems for process visualization, such as they are used, for instance, for the purpose of starting up nuclear industry systems (for example, in Löhr et al., 1992).

Arrangement: The factor of arrangement is another significant factor. In some events, it was found that the arrangement of the operating elements was not the best for tasks that were to be handled within the event. An analysis of additional situational conditions, that were in effect during these events, showed the following: not only were the hitherto not ergonomically designed operating elements arranged inadequately; but operating elements in the control panel or in local control stands - where one can assume an ergonomical design at least to some degree - were not designed in a task-related and ergonomic fashion. The ergonomic quality of the control panel thus - in relation to the factor of arrangement - is not a fixed magnitude; instead, it always depends on the particular actions that happen to be performed at the particular moment. This means that this factor points up a basic ergonomic problem of so-called hard wired control stations; the information and operation cannot always be arranged in them in a task-related manner.

Within the events, the factor of arrangement was observed together with the factors of external event and coupled equipment. That indicates that the ergonomic design is of particular importance when the event is unknown and when it cannot be handled with the accustomed intervention. In such unexpected events, the latent weakness of inadequate arrangement causes faulty intervention. These considerations as a whole thus point to a situation-related processing of information that is possible by means of modern display screen systems. Compatibility between the various possible display screen contents must be preserved as an essential marginal condition for the situation-related processing of information. Sträter (1995) reported how this kind of information processing can be done in a systematic fashion.

5.2.5 Interrelationships of Error Conditions

The discussion of the various error conditions makes it obvious to think that they are interrelated in a meaningful form. These reciprocal interactions of different performance-shaping factors can be investigated in greater detail by taking a look at the common appearance of different factors. The description model and the analysis model makes it possible to indicate and analyze several performance-shaping factors; therefore, one can bring out reciprocal interactions between different conditions by analyzing their common appearance in individual events (and, there, in the individual man-machine systems). Table 29 summarizes the observed interrelationships of performance-shaping factors.

Table 29 Observed Interrelationships of Performance-Shaping Factors

2	Reliability																														▨
11	Goal reduction																													▨	
6	Time pressure																												▨	0,17	
7	Presence																											▨		0,29	
24	Completeness																										▨			0,18	
6	Equivocation of equipment																									▨	0,33			0,17	
6	Coupled equipment																								▨		0,33				
7	Processing																							▨							
4	Redundancy																						▨		0,25		0,25				
7	Quality assurance																					▨				0,17			0,17		
7	Procedure precision																				▨	0,14					0,14				
7	Positioning																			▨		0,14			0,17						
4	Monotony																		▨									0,50		0,50	
6	Marking																	▨						0,17			0,33		0,17		
8	Construction																▨		0,50	0,14							0,13	0,14		0,13	
6	Task complexity															▨					0,17			0,17							
5	Labeling														▨									0,20			0,40		0,20	0,20	
1	Content													▨	1,00												1,00				
8	Information												▨			0,17	0,13	0,17			0,14						0,38	0,14		0,25	
4	Usability of equipment											▨					0,50														
4	Design										▨					0,25					0,25			0,25							
1	External event									▨																			1,00		
3	Task simplicity								▨						0,33									0,67				0,33			
3	Task precision							▨					0,33			0,33	0,33				0,33										
12	Usability of control						▨									0,17	0,13	0,17	0,50	0,14			0,25		0,33		0,17	0,14		0,09	
4	Technical layout					▨														0,25											
13	Task preparation				▨		0,08		0,33						0,20					0,14	0,14		0,25	0,14	0,17		0,08		0,33	0,18	
4	Display precision			▨								0,25					0,25									0,25					0,50
1	Display range		▨																										1,00		
6	Arrangement	▨					0,17			1,00						0,17				0,17					0,17		0,33		0,17		
Absolute frequency	*Maximal relative frequency of commonly mentioned influencing factors*	Arrangement	Display range	Display precision	Task preparation	Technical layout	Usability of control	Task precision	Task simplicity	External event	Design	Usability of equipment	Information	Content	Labeling	Task complexity	Construction	Marking	Monotony	Positioning	Procedure precision	Quality assurance	Redundancy	Processing	Coupled equipment	Equivoc. of equipment	Completeness	Presence	Time pressure	Goal reduction	Reliability

The maximum shares of the different factors were calculated with respect to each other according to Equation 24 by way of table entries. The observed action and relationships of performance-shaping factors can be subdivided into three groups, regarding which some outstanding effects will be discussed.

- **Performance-Shaping Factors Pointing to Common Basic Causes**

Construction-Handling: The 50% connection between insufficient design of a technical system and poor handling makes it obvious that - in this constellation of performance-shaping factors - the technical system concerned is not optimized systematically for possible human intervention. This also becomes clear by the influence of the feedback whose important role in error generation and avoidance has already been touched on more often (25% connection between design and display accuracy and 50% connection between display accuracy and the reliability of displays). If one tracks the connection between design and handling further, then one can find two additional reciprocal effects: precision and clarity as well as design and monotony.

Precision of task-Clarity: Starting with the factor of precision, there is a connection to the factor of clarity (33%) which, again, is connected to the extent of 33% with the factor of "information." This link shows that, in many events, inaccurate task specification is compensated for by the knowledge of the person. If this compensation is not successful (for example, due to an unexpectedly complex situation, such as is made obvious by the connection to the factor of complexity), then this constellation of performance-shaping factor results in error.

Construction-Monotony: There is also a connection between construction and monotony. This would lead us to suspect that work environments with bad ergonomic design will lead to typical phenomena of monotonous work (50% connection to the factor of monotony). They, for instance, include the search for a change of pace for simplification of situation (goal reduction factor) and blaming the cause of the error on outside aspect (factor of presence of procedures and factor of clarity). That the factors of clarity and presence were considered in this context, also enables us to conclude that, in such work environments, one can increasingly observe inadequate ergonomic layout of written aids.

Usability of control-Coupled equipment: Another factor constellation, that enables us to conclude as to a common basic cause, is represented by Usability of control-Coupled equipment (33%). This connection always exists when a technical component is poorly constructed and difficult to operate. In this factor constellation likewise, one can establish the above-discussed connections with monotony (50%), completeness of procedure (17%), and complexity (17%), and one can interpret them in a similar fashion: the work environment as a whole is not laid out as would be required for satisfactory task accomplishments. Difficulties of successful task accomplishment in this case consist particularly of a situation where technical influence deriving from meshing (Coupled equipment) and reciprocal interactions between redundant systems are added (factor of redundancy). This kind of influence is hidden to the acting person, in other words, it is not immediately recognizable. Logically, such factors lead to errors in particular when additional ergonomic factors are laid out in a sub-optimal manner (connections with marking, arrangement, and positionability).

Summarizing, regarding the reciprocal interactions with a common cause, one can state the following: in this group, there is a general interrelationship between satisfaction with work or work comfort (operational comfort) and ergonomic layout or ergonomic quality of the work environment. The role of the factors of task preparation, redundancy, and circuitry in this connection additionally indicate that solutions for error avoidance should be sought not exclusively with relation to the acting person because the acting person cannot recognize this kind of influence. In such interrelationships, one needs management measures that will make recognizable and that will minimize such hidden influence for the acting person.

- **Performance-Shaping Factors That are in an Interrelationship**

Simplicity-Processing: A definite 67% connection was established between the simplicity of a task and errors during the information processing by a person. This connection was hinted at earlier in the discussion of the factor of simplicity: in case of simple tasks, the individual reduces the conscious focusing on these tasks and thus makes mistakes by using habitual forms of behavior. If one tracks additional interactions to other factors, then one finds that this affect is supported by effective characterization of operating elements (33%) or poor layout of procedures (25%). Additionally, errors are promoted by the fact that there is no adequate task preparation for simple tasks (33% connection). This connection likewise was touched on earlier through the effectiveness of information translation. Looking at it overall, habitual behavior can, on the basis of these observations, be partly guided into faultless paths by means of ergonomic layout. Another possibility can be proposed with a regard to the factor of task preparation: constantly recurring tasks and actions would be performed by different persons so that they will be forced to perform identical task preparation and so that they would be able to avoid effects they would slip in by force of habit. This possibility of enhancing human reliability is used in production enterprises with assembly line work under the name of "Job-Rotation." The idea is to prevent human errors that are expressed there in the form of qualitatively inferior products. Summarizing, this connection indicates that aspects rooted in the psychology of organization and cognitive errors are in a relationship with each other.

Time Pressure-Task Preparation: this constellation shows that, in some situations involving a critical time element, one tries to enlarge the window of time precisely by means of defective task preparation. That is pointed out also by the connection between this constellation and the factor of quality control (17%). From the connection to the factor of simplicity, one can see that this constellation leads to problems primarily in connection with simple tasks. The 17% connection to the goal reduction factor and the 14% connection to the processing factor furthermore would seem to indicate that one trusts the abilities of the individual in such situations. This constellation leads to errors if the individual is overloaded (for example, as a result of unfavorable ergonomic factors, such as arrangement, labeling, marking, or display range). The hidden factors of coupled equipment, external event, and redundancy were observed to be additionally triggering conditions that lead to an error in case of work overload.

Performance-shaping factors, that are in an interrelation, hereby clearly show that it is especially in situations - in which unfavorable situational conditions prevail (for example, concealed performance-shaping factors or less task preparation) - that, by means of ergonomic layout of work environment and task assignment, one can take meaningful precautions against errors, even if the ergonomic layout for routine operation is created as being less effective or as exaggerated.

- **Performance-Shaping Factors That Together Led to Error**

Completeness-Labeling: The combinations of the performance-shaping factor of completeness display ambivalent interrelationships: first of all, procedures are an indispensable aid with regard to the factors of coupled equipment, redundancy, and task preparation. In the case of these hidden performance-shaping factors, written procedures are thus an essential aid in recognizing possible points of influence and thus in error avoidance. This can also be seen by the fact that false contents in procedures are directly linked to the factor of completeness. When procedures are incomplete, this can be made up essentially only by the knowledge of the persons (38% connection to the factor of "information"). The ergonomic factors of arrangement, marking, equivocation of equipment, and usability of control, however, have a higher level connection to the factor of completeness. This means that the completeness of procedures in some way also appears to be a means for making up for other weak points in the work environment although they are not the direct cause of error. The effective compensation of written aids can also be observed with regard to the connection between goal reduction and presence of procedures because this constellation has essential connections to monotony, information, and characterization.

In summary, one can thus say regarding this group of interactions that error causes are complex and multi-causal. Effective error management thus cannot mean that one considers just a single cause. In other words, in many cases, errors cannot be avoided because one looks for a single cause (for example, a written document or the acting person). To ensure this, the question of personal guilt may not be an object of error analysis because that hinders a search for actual causes. We also find that procedures and their degree of detailing must always be drafted in cooperation with those who have to apply these procedures.

- **Overview of Reciprocal Interactions**

If one looks at the discussion of reciprocal interactions between performance-shaping factors as a whole, then it is obvious to say that the reciprocal interactions regarding typical human properties and ergonomic facts also display a systematic of indirect effects of performance-shaping factors (cf. Chapter 3, where these factors were mentioned as indirect PSF with concern towards management). As in the case of the error types, it would appear to be a good idea here to perform a non-metric multi-dimensional scaling of the interrelationships in order to visualize this indirect effect of the factors. Figure 43 shows the result of a non-metric multidimensional scaling using the method mentioned earlier. Alienation is about 0.35.

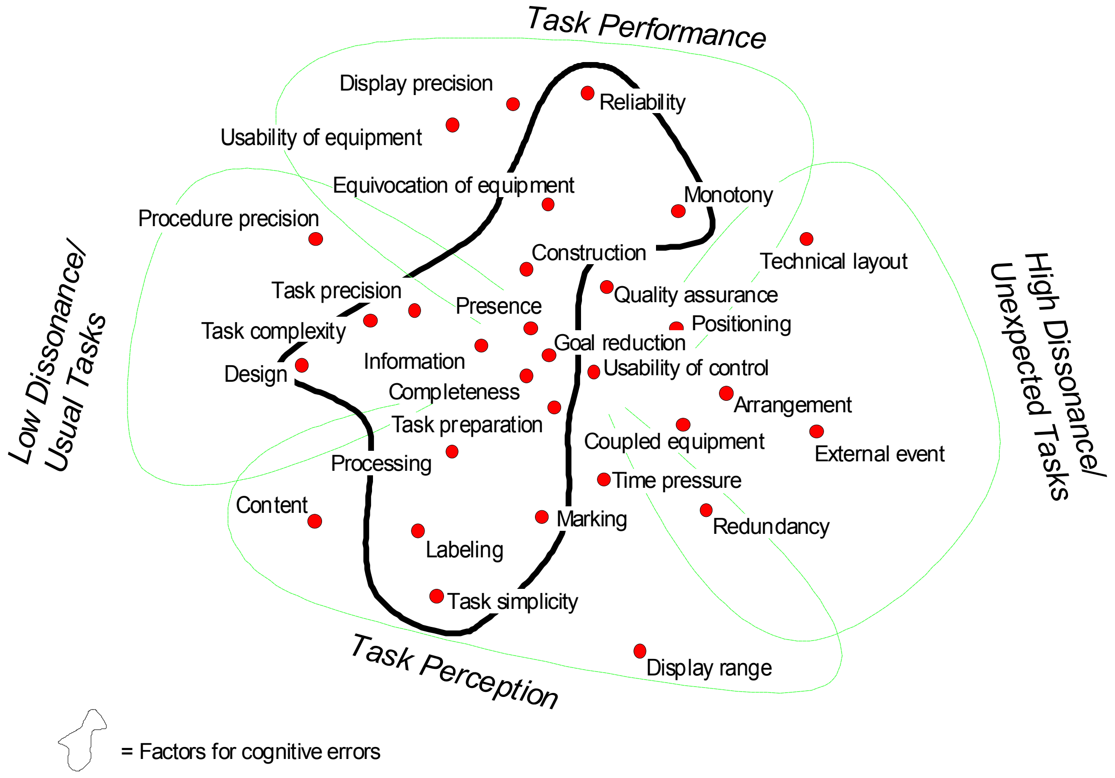

Figure 43 Non-Metric Multidimensional Scaling of Reciprocal Interactions Between Performance-Shaping Factors

Groupings here again were made according to content viewpoints. We can differentiate four indirect factors in the figure (broken lines): Task execution and task perception (personnel/organizational access) as well as habit and unexpectedness (situational access). Task execution and task perception can be characterized by incompatibilities between task and activity or task and feedback, that can be of organizational or personnel nature and that are also important in terms of work satisfaction. Habit is characterized in that the discrepancy between subjectively expected and required task assignment was not recognized consciously (no dissonance) and unexpectedness can be characterized by saying that the discrepancy between required task assignment and subjectively expected solution is too great (great dissonance).

The superordinate factors are of particular importance to the discussion of cognitive errors; this can be recognized already by virtue of the fact that the concept of dissonance can be used for the insertion of performance-shaping factors in non-metric multidimensional scaling. In the figure, the performance-shaping factors regarding the cognitive capacity of the individual are already anticipated: They are enclosed by a solid line and will be discussed in the next section together with system ergonomics.

5.2.6 System Ergonomics, Cognitive Errors, and Errors of Confusion

The discussion of performance-shaping factors clearly show that the relationship between situational facts and the information processing of the individual plays a decisive role in the generation of human errors, especially of errors of confusion. Another problem is to make predictions - from the observations - regarding the relationship between these internal courses and the above-discussed interrelationships. To solve this problem, it was proposed in Chapter 1 that the cognitive load and cognitive cope be described within the events.

System ergonomics classification was used to describe cognitive load (see Table 17, Chapter 3); a system ergonomics classification of the individual man-machine systems was performed on all 255 man-machine systems that were identified in the 165 observed events. Overall, it was thus possible to identify 76 man-machine systems with cognitively loading system ergonomics configurations.

To describe cognitive cope, we used the subdivision discussed in Chapter 1: information, processing, and goal reduction. All of these three factors are matched up with the man-machine system component called "person" and were obtained in the following manner from the event descriptions: in the event descriptions, we use the terms such as "mistakenly," "inadvertently," or "unintended" to describe cognitive errors. These terms point to errors in human information processing. When these terms are used to describe decision-making situations, we are dealing with a "goal reduction" according to the above-mentioned classification; if they were used to describe simple switching actions, then we are dealing with faulty "processing." The factor of "information" was put in when it emerged from the event descriptions that the acting person did not use information that was available mentally or in the form of reference stimuli (for instance, reference labels, displays) (see also Hacker, 1986). On the whole, we observe 24 man-machine systems in this fashion where corresponding indications were given regarding cognitive cope. The profiles in Figure 44 and Figure 45 show what error types and performance-shaping factors can be found by means of this procedure.

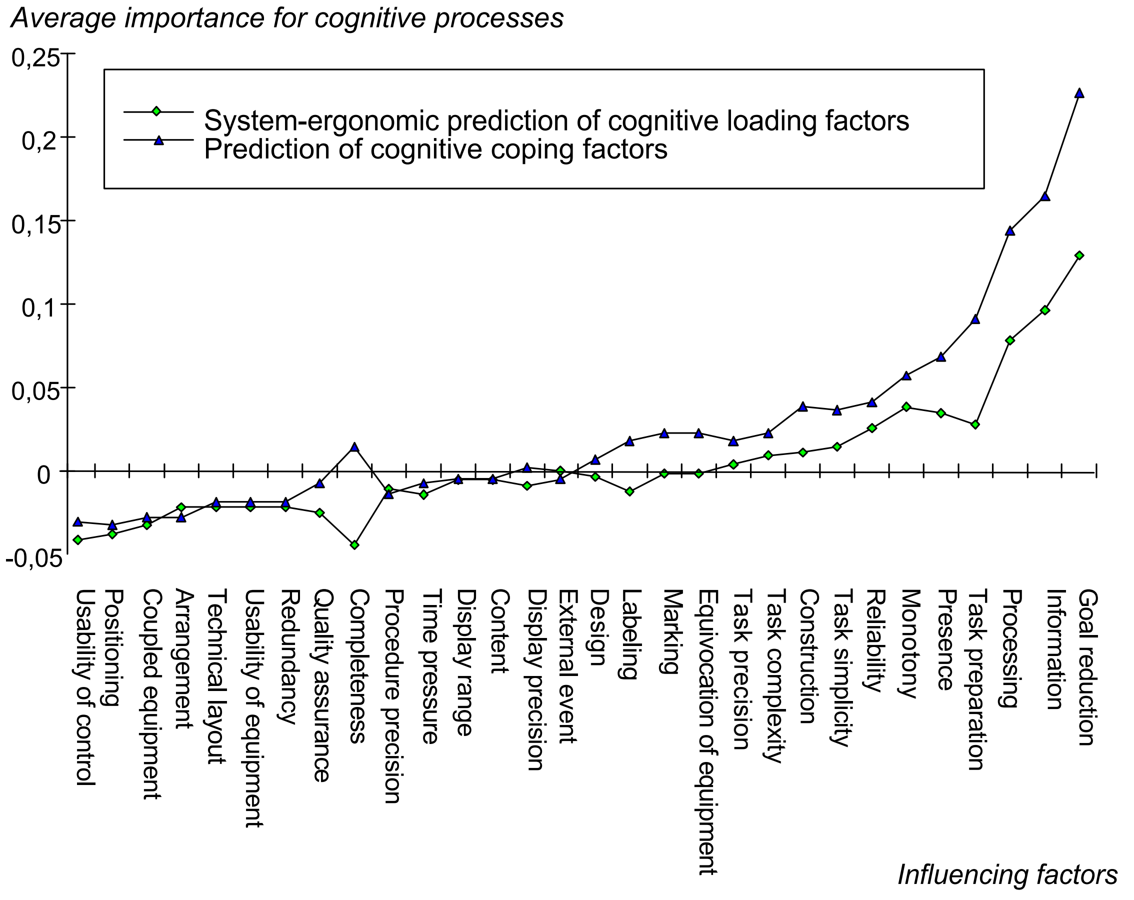

Figure 44 Profile of Significance of Performance-Shaping Factors With Relation to Cognitive Load and Cope

In the figures, the average significance of performance-shaping factors and error types is plotted in connection with cognitive processes. The average significance was determined in each case separately for events with and without cognitive load via the number of performance-shaping factors/error types, related to the number of events in which they occurred. Positive values give us the relative frequencies of cognitive processes; negative values give us the relative frequencies for non-cognitive processes. A distinction is furthermore made in the figures between the predictions of system ergonomics (cognitive load) and the cognitive performance-shaping factors (cognitive cope) that were mentioned in the events.

If one arranges the discovered cognitive performance-shaping factors from Figure 44 in the above presented Figure 43 of the non-metric multidimensional scaling of all performance-shaping factors, then cognitive errors occur only if the situation is neither completely accustomed, nor completely unaccustomed (factors that are enclosed by the solid line in Figure 43). In this area, we have little to average dissonance. In the extreme areas, in which very high dissonance prevails, we cannot find any cognitive performance-shaping factors. One may conclude from this that cognitive errors occur only when the given situation is not quite clear (lacking situation awareness, see also Meister & Hogg, 1995). In these situations it is thus neither clear as to whether the usual routine takes hold nor whether the given situation involves a completely new situation with corresponding need for action. Cognitive errors thus occur rather in undetermined situations and during the transition from clear situational requirements to accustomed behavior. Similar observations were also made during the interrogation of simulator trainers: Ullwer (1996) for example was able to show that errors by operators occur precisely when the trouble had been almost brought under control and when only customary intervention was required in order to correct the trouble once and for all.

One can make the following observations if one analyzes the meaning of the various error types in Figure 45 regarding cognitive processes: immediately after the rather cognitive error-describing error types (omissions of persons or false executions) come errors of time, faulty tasks and feedback. Other quantitative errors (such as "too much" or "too little") are less significant. Interestingly enough, the omissions of tasks or order dispatch has a rather subordinate meaning as cognitive error type. From this one can conclude that cognitively created errors are expressed in that the operator in some way wants actively to interfere in happenings (coping of disturbance) in order to prevent the occurred trouble (see Mosneron-Dupin, 1993).

It is precisely the identical curves of cognitive performance factors in Figure 44 that indicate that cognitive load and cognitive cope are interconnected. In order to examine this relationship more accurately, we correlatively compared to each other the absolute frequencies of performance-shaping factors and error types during cognitive loads and cope. Overall, we get the connection illustrated in Table 30. The correlation of r=1 between cognitive load and cope for instance indicates that the sequence of discovered performance-shaping factors is completely in agreement.

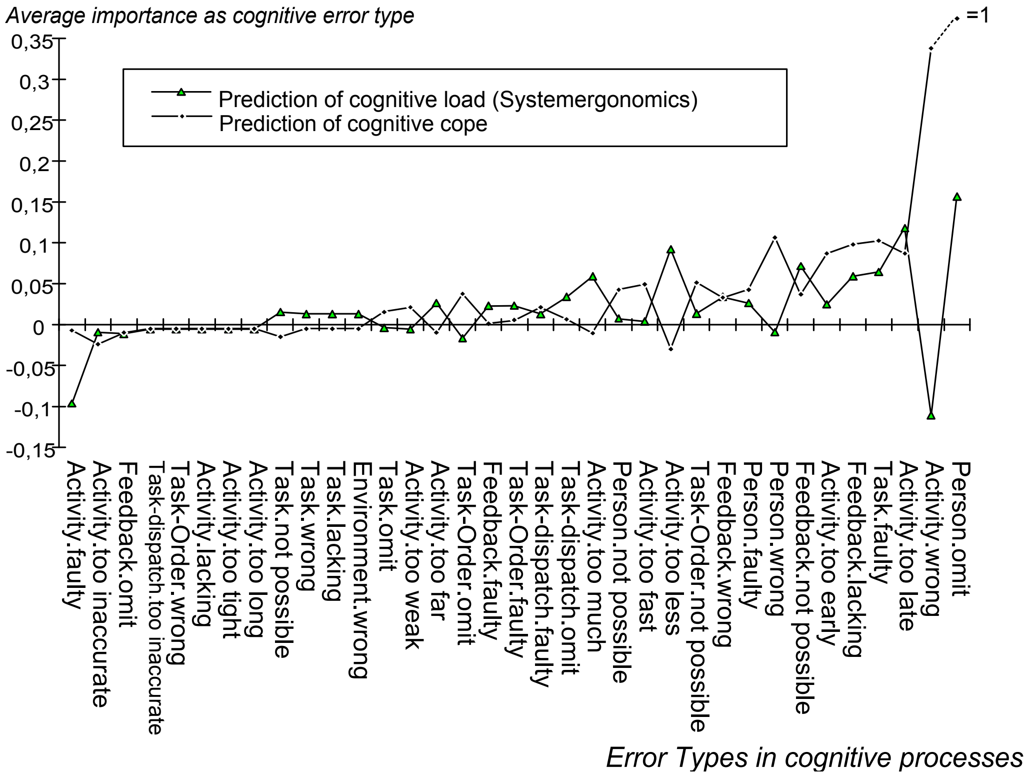

Figure 45 Profile of Meaning of Error Types in Connection With Cognitive Processes

If one looks at an individual comparison of the performance-shaping factors, then the cope factor of "goal reduction" can be observed primarily in conjunction with simultaneous multidimensional tasks and quantitative errors. The cope factor "information" is linked to monitive and dynamic tasks and leads to partly qualitative and partly quantitative errors. In the cope factor of "processing," on the other hand, we find almost exclusively qualitative errors and this is true in the case of the system ergonomics factor of inner compatibility. Here again, the errors in feedback make a greater contribution to the generation of error than in the other two cognitive coping factors. Earlier, we also identified the performance-shaping factor "equivocation of equipment" as a processing error and we discussed the role of compatibility and feedback for the generation of these errors. This means that qualitative errors, processing, and compatibility are definitely interrelated.

Table 30 Connection Between System Ergonomics and Cognitive Errors

(a) Correlation of sequence of error types in conjunction with cognitive load and cope in man-machine systems

	Cognitive Load	*Cognitive Cope*	*No Cognitive Load*	*No Cognitive Cope*
Cognitive Load	1			
Cognitive Cope	0.846955	1		
No Cognitive Load	-0.77492	-0.70749	1	
No Cognitive Cope	-0.71486	-0.48032	0.942643	1

(b) Correlation of sequence of performance-shaping factors in cognitive load and cope

	Cognitive Load	*Cognitive Cope*	*No Cognitive Load*	*No Cognitive Cope*
Cognitive Load	1			
Cognitive Cope	1	1		
No Cognitive Load	-0.08551	-0.08551	1	
No Cognitive Cope	0.074177	0.074177	0.963328	1

If one keeps in mind that the three cognitively coping factors in Chapter 1 were defined starting with the deviation (mismatch) of given and expected perception and via the extent of conscious control, then we can conclude that qualitative errors materialized primarily due to unconscious processes (missing dissonance), whereas quantitative errors occurred rather due to errors in conscious control. These processes are elementary, in other words, for example, they are not tied to the behavior level according to Rasmussen (1986) or to the subdivision in intentional and unintentional errors (Reason, 1990). This result also indirectly confirms the discussion on Table 6 in Chapter 1. In general, one can therefore conclude from this that the type of a cognitive error can be explained by the following two processes:

Missing Dissonance in Case of Deviation of Given Perception From Expected Perception: Concerning the performance-shaping factor of simplicity we already emphasized that people try to reduce the effort connected with conscious information process by means of subliminal processes. Subliminal processes run error-free until they are applied to situations in which minor deviations from learned behavior patterns appear. Furthermore, subliminary processes can interfere, something that was identified during the discussion of performance-shaping factors already as an essential initiator of errors of confusion. In the case of unconscious procedures, these effects can be explained neurologically by the synapse modification rule according to Hebb (1949) because practiced skills represent stronger cell connections and because, without conscious control, the activity fix the "easier route" via the stronger connections. This unconscious choice of the easier routes plays a role in the most widely varying ways of behavior of presence; this is true, for instance, in connection with decision-making procedures (for example, availability heurisms) or in the effects of stress or time pressure (for example, regression to practice behavior). In other words, it is not tied to the content of processing or to the processing stages according to Rasmussen (1986).

Faulty Conscious Control: As we can gather from the match-up of performance-shaping factors in Figure 43, we need a certain measure of dissonance so that an unconscious action will become accessible to conscious control. If a deviation of the perceived state from the learned behavior achieves conscious control, then the latter is applied to the problem that has arisen until one again attains a state in which the perception pattern can be worked without conscious control. This is why we find here rather errors of time (such as too early or too late) and hardly any setting errors (such as too much or too little) because the latter are based less on cognitive skills and more on motor skills. The role of feedback for these efforts at consonance was addressed already several times before. It is an essential factor in the generation and avoidance of errors because a feedback facilitates coordination and control in terms of time, in the first place. The entire process of the deviation of the given perception to the expected perception via conscious control all the way to a renewed state without conscious control thus takes the shape of a hysteresis (Figure 43).

5.2.7 Effectiveness of Optimization Measures

The performance-shaping factors we discussed and their action mechanisms also indicate what improvement measures would be most effective in response to an error that has occurred. To be able to estimate the effectiveness of past optimization measures, one may compare the discovered performance-shaping factors to the measures that were taken.

The various components within the man-machine system can for this purpose be subdivided on the whole into four areas: person (man-machine system component human being), equipment (man-machine system component: system and system output), ergonomics (man-machine system component task, activity, feedback, and environment), as well as organization (man-machine system components of order issue and order dispatch). Precautions were also mentioned in the event descriptions along with the identified performance-shaping factors. Agreement between the identified performance-shaping factors within the man-machine system components and the measures that were actually taking will show to what extent the improvement measures relate to the discovered weak points. The results on that score are shown in Figure 46.

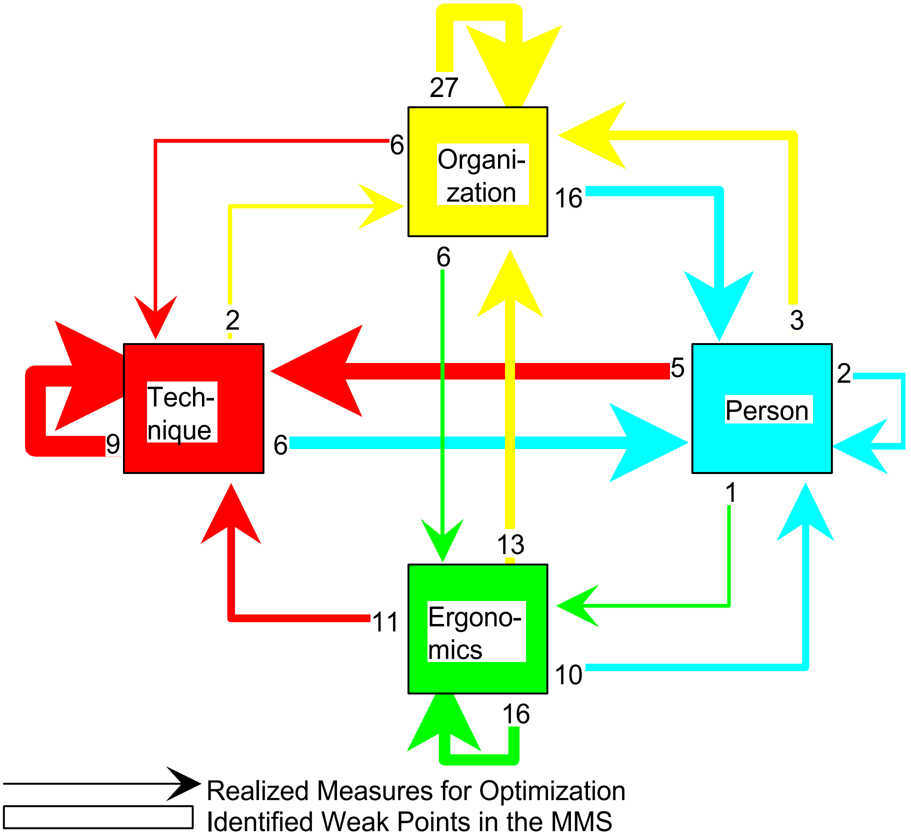

Figure 46 Identified Weak Points and Precautions Taken

The figure can be read similar to a voter migration diagram that is known from election reporting: the boxes represent the performance factors that were actually found; the arrows point to areas with which the measures taken must be matched up. The numbers indicate the absolute frequency of discovered measures (for example, a weak point was found in 16 events in the area of "organization" and a precautionary measure was taken from the area of "person"). The thickness of the arrows represents the relative share of measures (for instance, the 16 events related to all 35 weak points in the area of "organization"). Inside the figure, the arrows aimed at "organization" mostly represent measures regarding the change in or sublimination of instructions. The arrows pointing at the box "equipment" mostly represent locking or upgrading of technical components. As for the person, training courses were mentioned as improvement measures although it was less specified what exactly was taught. Whenever the training measure was described specifically, it mostly dealt with the errors that have occurred. The arrows aiming at "ergonomics" represent layout measures regarding signaling and arrangement or labeling of operating elements.

There are two aspects of this figure that should be emphasized: first of all, one can gather from the figure that a larger share of measures was aimed at the box labeled "person." One can conclude from this that training measures are often carried out although the acting person was not the direct condition. Accordingly, the precautionary measures (personnel training), initiated in the observed events, do not always appear to be the optimally most effective. Second, a small portion of measures points to the box labeled "ergonomics"; but many portions shoot off from it. This provides hints to the effect that ergonomic measures in the observed events were not carried out consistently although the ergonomics (as described above) is the most important factor in error avoidance for the acting person. The reason for this certainly presides in the fact that the choice of the best optimization measure is always a compromise between the risk potential of the occurred error (its meaning in terms of safety engineering), as well as the cause and effectiveness of the improvement measure.

This is why it is particularly important - for the sake of efficient error management - to take the most effective measures. It is especially the error pointing from the person to the equipment that, in the case of the analyzed events, indicates that error management so far is equivalent to the effort of avoiding individual errors. For example, if a precaution against leaving a valve open inadvertently involves locking the valve with lock and chain, then one can rule out precisely this error. If, from the ergonomic viewpoint, one encounters similarly positioned errors, such as, for example, leaving an electrical switch open, then again one can rule out precisely the error for the future. Such error management views human error as an individual error. It is precisely from the ergonomic viewpoint however that leaving a valve open or leaving an electrical switch open would be entirely comparable because human error mechanisms are independent of the technical system. That was noted clearly in the discussion of error types and performance-shaping factors. A human error thus can be considered as true individual error, from the ergonomic viewpoint, only in rare cases. This is why across the board, strategic error management (total quality management) is necessary with regard to ergonomic factors (see SVA, 1992).

Each box in the figure also represents the performance-shaping factors found in the man-machine system components; we can therefore furthermore see that error management can be further improved if the discovered performance-shaping factors are used to plan improvement measures. For example, training courses are appropriate only when inadequate knowledge was actually found (performance-shaping factor "information"). As was mentioned already in the discussion of the reciprocal interactions between performance-shaping factors, they are less appropriate when it comes to errors of habit (performance-shaping factor: processing). Here it would be better rather to use ergonomic measures.

5.3 Frequency Analysis-Based Predictions From Practical Operational Experience

Along with the qualitative indications regarding error possibilities and performance-shaping factors with respect to human reliability, another goal of event analysis is to obtain quantitative data on human reliability from the investigated events. In Chapter 2 we noted, among other things, which points are open within the human reliability analysis processes. They included essentially the validation of distribution assumptions as well as the validity of human reliability parameters that are used for evaluation purposes in human reliability analysis methods.

5.3.1 Assumptions as to Distribution

Two central assumptions as to distribution are made in connection with human reliability. They are logarithmic standard distribution (or, for short, log standard distribution) of human errors in the THERP method (see Swain & Guttmann, 1983) and the logarithmic-linear connection between time and success of diagnosis in processes with time-reliability correlation (see Hannaman & Spurgin, 1984a; Mosneron-Dupin et al., 1990). By regarding these two assumptions of distribution, we will examine in the following whether they can be verified with the help of practical operational experience. In conclusion, we will discuss an assumption of distribution combined from both of them.

- **Logarithmic Standard Distribution**

The assumption of logarithmic standard distribution is made in the course of the THERP process. It tells us that the error probabilities are distributed according to the following density function (see Reer, 1988):

$$f(p) = \frac{e^{-\frac{1}{2}\left(\frac{\ln(p)-m}{s}\right)^2}}{ps\sqrt{2p}} = \frac{e^{-\frac{1}{2}\left(\left(\ln(p)-m\right) \Big/ \frac{\ln(EF)}{1{,}645}\right)^2}}{p\frac{\ln(EF)}{1{,}645}\sqrt{2p}} \tag{25}$$

where:

p	*Probability*
m	*mean value of logarithmized probability*
s	*Scatter of logarithmized probability*
EF	*Error factor*

In terms of content, this formula tells us that the individual, in practiced work environments, for the most part, performs simple tasks and actions because, on the basis of effects of habit and practice as well as learning procedures, he or she reduces the subjectively perceived task complexity. Accordingly, in the case of simple tasks and actions, we would expect a correspondingly larger number of tasks and actions and thus also of errors (see Swain & Guttmann, 1983; Chapter 7). This means that the error probabilities are also shifted to the left with respect to a symmetrical distribution.

The number of sentences used in the description scheme regarding the man-machine system components of task, activity, feedback, order issue, and order dispatch is a measure taken from the description of the event which corresponds to the distribution parameter "practice" or subjectively perceived "task complexity." The reason for this assumption is that one may well assume that the description effort in these components is all the greater, the more likely the task in the described event is unpracticed as far as the operators are concerned. This operationalization seems plausible because the event descriptions are made by persons from the plant facilities. The authors of the event description thus are familiar both with work routine and local conditions and thus also with the idea as to whether the event situation is or is not a novel work situation as far as the operator is concerned. References to such interrelationships between description effort and mental representations can be found among others in Sträter (1994). The scope of the description effort contains in the event text thus to a certain degree also reflects the practiced nature of the situation - as subjectively perceived by the author of the event description - and thus also the task complexity that is subjectively perceived by the operator. The event descriptions furthermore were taken over unchanged and were converted only into several simple sentences; therefore, the work situation, as perceived by the author, was not altered by the analysis of the event.

One gets a distribution of events, related to the number of sentences according to Figure 47 if, on the basis of this hypothesis, one models the assumptions of standard logarithmic distribution as to how many sentences were used for event description with relation to the man-machine system components labeled task, activity, feedback, order issue, and order dispatch, and if one counts the number of error events with a certain sentence length. Here, sentences that contain information on written aids were not considered because written aids have a fixed description effort and do not represent the subjectively perceived complexity of the event.

Furthermore, the figure features a plot of the expected number of all sentences that would predict the standard logarithmic distribution according to equation 25 for 165 events. The parameters of the distribution were determined according to Reer (1988): the mean value is ì =2.35, the deviation is s=0.50. It thus corresponds roughly to the one that was determined according to Swain and Guttmann (1983) for uncertainties of HEP values (s_{THERP}=0.42). The correlation of the theoretical distribution with the one that was founded empirically amounts to r=0.87.

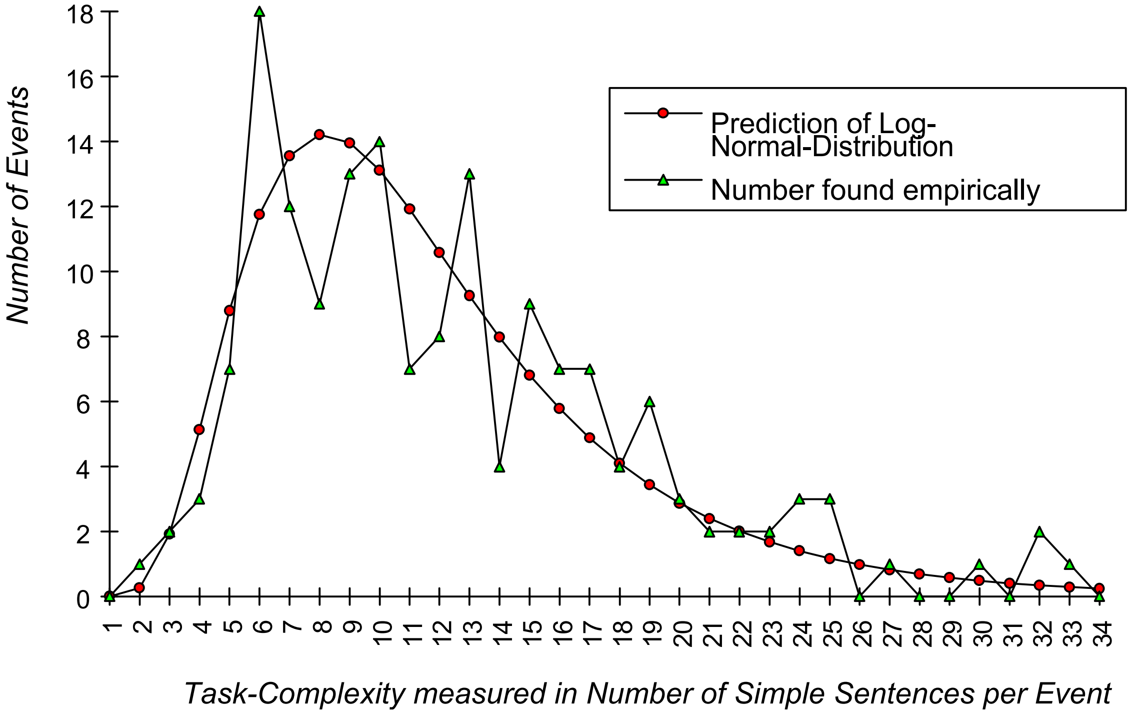

Figure 47 Standard logarithmic distribution operationalized by means of description effort

- **Time-Reliability Distribution**

Procedures that employ a time-reliability distribution to evaluate human reliability start with the following idea: as the available time grows, the probability of a human error decreases. If that is the case, then this simple assumption would have to be shown in the frequencies of the observed events for which a time indication was given.

To prove this distribution assumption, we determine, in a first step, all events where it is possible to interpret a time indication as time of diagnosis. From them, we designated the events where, after the given time, a human error (task error or execution error occurred). We performed a cluster analysis of the time data for the events thus found and we counted the frequencies of errors per cluster. Figure 48 shows the result.

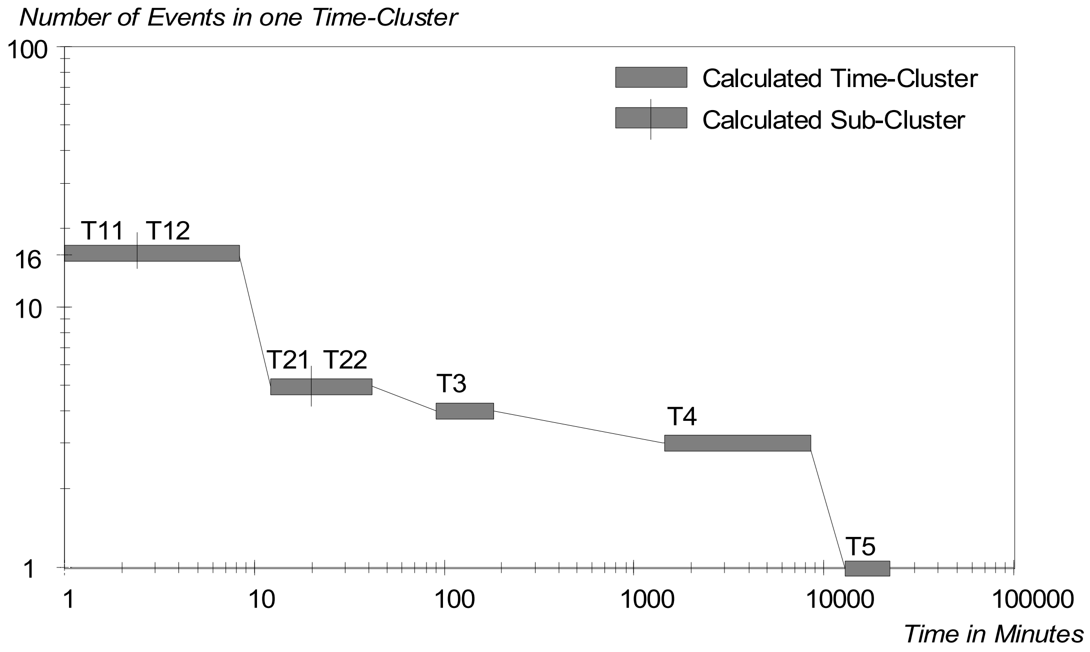

Figure 48 Logarithmic-Linear Connection between Time and Reliability

The pertinent inquiries addressed to the databank are given in Appendix 6. The monotonously descending curve in a logarithmically scaled coordinate system agrees with the curve of the THERP method and the PHRA method (see Chapter 2 and Appendix 5). We may thus assume that the assumption of distribution also applies within the observed events.

- **Joint Consideration of Both Distributions**

With the help of the available data from practical operational experience, it was possible in a summary fashion to confirm both assumptions of distribution. Additionally, with the available data set one can furthermore also determine to what extent the data on task complexity and time data are connected. For this purpose, we considered all events that entered into the time-reliability distribution. Their task complexity again was determined via the number of sentences needed for description. Figure 49 shows the results. To get a comparable yardstick, the figure gives the relative shares of errors, of task complexity (measured by the number of sentences), and of errors at given task complexity. From the figure we can gather a most extensive agreement between the curve of the number of errors made and the observed subjective task complexity. On the other hand, as the time increases, there is a rise in the number of errors made per sentence. We can conclude the following from this:

- From the agreement between the curve with the number of errors made and the observed subjective task complexity one can conclude that the potential for an error would appear to be determined rather by the complexity of the task than by the time. In most events, time and task complexity are merged (that is to say, during time intervals shortly after trouble arises there is a high degree of task complexity); therefore, procedures with a time reliability approach (such as HCR or PHRA) are sufficient to perform a simple evaluation of its situation. The uniform, almost parallel curve of error distribution and of task complexity however enables us to conclude that the task complexity is the actually determining magnitude for human reliability and not the time. Looking at it overall, one may conclude from this that a purely time-related evaluation of human actions - such as it is performed in the human cognitive reliability method - will not suffice. The connection found here on the other hand makes it obvious that the individual is capable of processing only a certain number of tasks at given task complexity.
- The number of errors for a given task complexity (measured in terms of sentences) rises with the time elapsed. This makes it obvious to conclude that (1) a calmed situation prevails after a long time and (2) that errors occur here rather for the reason that the trouble is unexpected (whereas, after a short time, errors occur on account of the high level of task complexity). The transition between the two states appears to be located at the point of intersection of the two opposite effects (about 90 minutes). This means that in this distribution, likewise, one can see something that was already discussed in connection with cognitive errors: diagnosis is characterized by two factors that were discussed already as cognitive factors: control over the complexity of the situation and dissonance regarding the need for action. If one investigates the type of errors that can be observed in connection with both factors, then here again we can confirm the hypothesis that was set up for the investigation of the cognitive errors: after a long time (in other words, if there is no dissonance), errors are rather of a qualitative nature and, after a short time (in other words, conscious control), they are rather of the time type.

Indirectly, by virtue of the uniform curve of errors with task complexity, there is also confirmation of the load/cope model that is customary in ergonomics and which assumes a most extensive dependence between human cope (measured here in terms of errors) and the load (measured here via task complexity). This hypothesis must certainly be investigated by means of additional, more detailed analyses of events, simulator experiments and basic experimentation. Approaches regarding their significance in the evaluation of human reliability however can also be found for instance in the experiments of the Halden Reactor Project (Kaarstad et al., 1995; Kirwan, 1994; Thelwell, 1994)

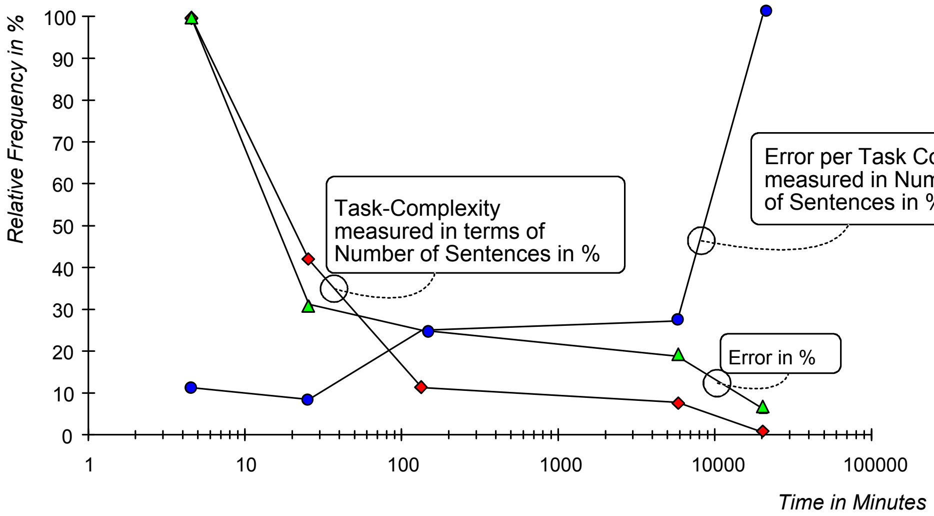

Figure 49 Connection Between Errors and Task Complexity

An evaluation of human reliability, oriented by task complexity, is worthy of discussion also for the reason that it offers advantages when compared to a time-dependent assumption of distribution. One disadvantage inherent in time-dependent models is represented by the fact that the success of diagnosis is reduced predominantly to the available time. Cognitive processes of the individual during the time of diagnosis or the complexity of the situation are not depicted or are depicted only inadequately (in the human cognitive reliability method, for example, this is done only via the levels of behavior and the time stretch-out). This reduced assumption is hotly disputed in psychology and in research on human reliability. Here, an assumption of distribution, oriented by the task complexity, could be an alternative for the evaluation of human reliability, in particular in connection with cognitive processes. But it must be kept in mind that the parameter of task complexity cannot be obtained by a simple objective measures (for example, number of actions). Task complexity instead is a subjectively perceived magnitude of cognitive cope of the individual behind which are hidden many fold experiences and habits. Just what objective factors influence this cognitive cope was discussed already in conjunction with system ergonomics (Section 5.2.6). System ergonomics thus represents a point of departure for an evaluation of human reliability oriented by task complexity.

5.3.2 Quantitative Predictions Based on Practical Operational Experience

The preceding section showed that it was possible to confirm central distribution assumptions with the help of the analysis model. This is followed by the question as to whether one can also gain quantitative data from the events that are suitable for checking the reliability parameters of which are used in different human reliability analysis methods used in determining human reliability. For this purpose, we will compare the data from practical operational experience to the following indications: with the data from the catalog by Swain and Guttmann (1983), that hereafter will be referred to as THERP data, and with the data of the PHRA method which are based on French simulator studies (Mosneron-Dupin, 1993).

Before this comparison can be performed, we must, however, clarify why observed frequencies from practical operational experience may at all be compared to probabilities because the human error probabilities of the human reliability analysis methods are claimed to be genuine probabilities according to the definition in Equation 2 (Chapter 2).

If, on the other hand, one tries to determine reliability parameters from practical operational experience, then one must note that a method, which is based on an analysis of practical operational experience, basically and in no case can supply the data for the calculation of error probabilities along the lines of the human error probabilities definition (Equation 2) because mostly only error actions are covered in practical operational experience. Error-free actions or erroneous actions below a certain identification threshold (for example, reporting threshold to the authority or the management of the power plant or faulty actions that are discovered by the person himself or herself and that are remedied again and thus did not have any effect on the plant) can of course accidentally be contained in or reported under the heading of practical operational experience; but they will in no case be covered completely. This circumstance leads to a general problem of determining human error probabilities from practical operational experience because, from practical operational experience, one can only determine limited frequencies having the following form:

$$h(\textit{erroneous actions of type } i \mid \textit{event above a certain reporting threshold}) \qquad (26)$$

This is a basic disadvantage inherent in all methods for the acquisition of practical operational experience and it is independent of by whom or how the events are recorded. According to the definition of human error probabilities, given already in Chapter 2, the basic totality, in other words, the actual number of actions of type i, must be known. On the basis of practical operational experience however one can determine only the number of errors connected with actions of type i and this can also be done only above a certain reporting threshold. This means that a comparison of data from operational experience with HEP values is permissible only if one can show that (1) the number of requirements in the collected events corresponds to those of the HEP values or (2) if one can show that the data from Swain and Guttmann (1983) or from the French simulator studies likewise are not "genuine" probabilities in the sense of human error probabilities according to Equation 2 but instead contain basically the same statistical information that can also be obtained from practical operational experience. Regarding these conditions, the following reasons would indicate that a comparison of frequencies of events with the probabilities of the THERP method is possible:

With respect to 1:

> Swain and Guttmann (1983, p2-11) give only values for rule-based behavior. This becomes particularly clear by virtue of the assumption of standard logarithmic distribution: within a technical system, by means of education and training, one may assume that the operators are well familiar with their tasks; therefore, the THERP method starts with the idea that the reliability parameters have a standard logarithmic distribution. With the help of this assumption of distribution, one anticipates the expected behavior level that a person takes up within the statistical average: THERP pertains mostly to rule-based behavior (the median of the HEP values is found within the range of rule-based behavior).
>
> The THERP method is restricted to rule-based actions; therefore, the HEP values in some way relate to the routine behavior of personnel. Accordingly, one may assume that, for all actions, one would have to get roughly identical basic totalities for the number of requirements because (as discussed earlier in Chapter 1), rule-based behavior is not connected with the idea that the operator has an instruction available in the form of a regulated procedure; instead, the idea is to find out how much he is familiar with the situation and how often he performs an action of type i (frequency of use).

The assumption of a standard logarithmic distribution is also found in practical operational experience with almost the same deviation as was used as basis in the THERP method; therefore, one may conclude that one can find similar basic totalities in the analyzed events. Occurrence-oriented frequencies can be compared to the HEP values from THERP. The basic totalities of the HEP values and frequencies of observation thus correspond to each other because the skill levels correspond to each other. This means that the number of requirements is comparable, although the absolute number of basic totality is unknown.

With respect to 2:

HEP values for errors in diagnosis are not determined by the number of errors related to the requirements of diagnosis; instead, we determine a relative frequency of the teams that perform the successful diagnosis. This applies to the experimentally obtained data in the French PHRA method. Accordingly, practical operational experience basically, for instance, compared to the data of the PHRA method, supplies comparable statistical information: number of observations with unsuccessful diagnosis as against number of observations with diagnosis.

The HEP values of Swain and Guttmann (1983) were partly also obtained via processes of estimation that go back to observations (and that's also to frequencies). They were also obtained without a precise knowledge about the number of requirements. Swain (1992) admits that himself. This means that foundations of estimation of the THERP method can be compared to the data that can be gained from practical operational experience.

In general, one can thus conclude from these considerations that one is justified in comparing the frequencies, observed in the course of practical operational experience, to the HEP values from the literature on the subject.

- **Comparison of Data on Human Reliability**

A series of data sources can be used as reference sources. The comparison is thus performed with the help of data on human error probabilities known from the literature and which are used in the THERP method and in the PHRA method. The individual HEP values of the THERP method are compiled in Appendix 5. The data for the PHRA method were presented already in Chapter 2. Additional sources (for instance, the nuclear computerized library for assessing reactor reliability databank) was not taken into consideration because these data are very heterogeneous and because the above-established conditions for comparability to the frequencies from practical operational experience do not exist. Estimates of experts that are accessible from literature were also skipped because they mostly are valid only for a specific situational context and (as discussed in Chapter 2) they are furthermore tainted by an unknown measure of uncertainties.

Frequencies were then determined for these inquiries with the help of the analysis model. The general procedure involved in the conversion of the THERP items into a situation-related inquiry is given in Swain and Guttmann (1983). Essentially, a differentiation is made there between data for task errors (omission) and execution errors (commission) as well as for system ergonomics (perception, operation, feedback) or administrative (organizational) error possibilities that in addition can be weighted with differing performance-shaping factors (Appendix 5). This means that the individual tables of the THERP catalog most intensively corresponds to the components of the man-machine system. A conversion of the items of the THERP catalog thus can also be accomplished in that error frequencies are determined in relation to the corresponding man-machine system components. For each item of the THERP method, corresponding situations were defined and were formulated as an inquiry addressed to the databank.

- **Determination of Absolute Frequencies**

Overall, we determined error predictions for 79 items in the THERP method. Appendix 6 is a combination of the inquiries addressed to the databank. In drafting the inquiries, they were worded in a way that they correspond to the situations that constitute the basis of the catalog of the THERP method. This can be done rather well for some items and to a lesser degree for other items. Some examples of conversion and an explanation - as to why the situational inquiry corresponds to the items in the THERP catalog - are given in Table 31.

Major difficulties are due to the effort to convert the correct abstract statements within the THERP catalog into specifically situation-related statements. For example, the THERP table 20-02 "Errors during a critical step within a rule-based action by control station personnel after diagnosis" is tainted with several uncertain concepts where there is a partly considerable interpretation leeway (among others "critical" or "rule-based"). In such cases, the situational inquiries were converted on the basis of estimates. A particular problem arose in connection with conversion for items in which neither the type of error, nor the conditions or performance-shaping factors - on whose basis the HEP values were arrived at - were precisely specified or do not clearly agree with those found in practical operational experience. Another difficulty resided in the fact that, for some items, it was necessary to find situational inquiries for which only inadequate information was available in the event descriptions. Such unclear tables in particular include the THERP tables 20-9, 20-10, 20-12 and 20-13.

Table 31 Examples of Modeling THERP (Technique for Human Error Rate Prediction) Items as Situational Inquiries to the Databank

THERP-Item	***Situational Inquiry***	***Description***
Item 20-02 (3): Error in a rule-based action without instructions	AND task.indication=[error] OR person.indication=[error] OR activity.indication=[error] AND NOT order issue.object= instruction	THERP describes errors relating to the performance of task steps; this is why communications errors are not considered. The fact of "rule-based action" was not considered because, on account of the verification of standard logarithmic distribution, it was already confirmed that one can observe mostly rule-based behaviors in the events.
Item 20-5 (1): Omission of a procedure step	AND task.indication=omit AND NOT Activity.indication=false AND order issue.object= instruction	The concept of instruction is used in the event description as synonym for procedure. By adding "AND NOT..." no consideration is given in this inquiry to errors of confusion.
Item 20-3 (2): False diagnosis within the first 10 minutes	AND task.indication=omit OR Person.indication=[error] OR Activity.indication=[error] AND Situation.time indication= [all times < 10 minutes]	All errors in connection with which a time indication was made are wanted here. A false diagnosis and the observed within the event descriptions only by means of task errors [omissions] and execution errors [commission]. In some events, the diagnosis thus contains also the time of action execution to an unknown extent.

Figure 50 shows the observed absolute frequencies in relation to the HEP values of the THERP catalog. The correlation is not high with a figure of r=33% so that one cannot draw any conclusions as to a direct link between observed absolute frequencies and the data from the THERP catalog.

It is known that absolute frequencies (in other words, a constant basic totality for all items) provide the worst estimated value for a probability; therefore, this result was to be expected. A better estimated value can be obtained by relative frequencies. With a sufficiently large observation universe, they supply a genuine estimate value for a probability. In the following section, we will accordingly form relative frequencies and compare them to the data of the analysis model.

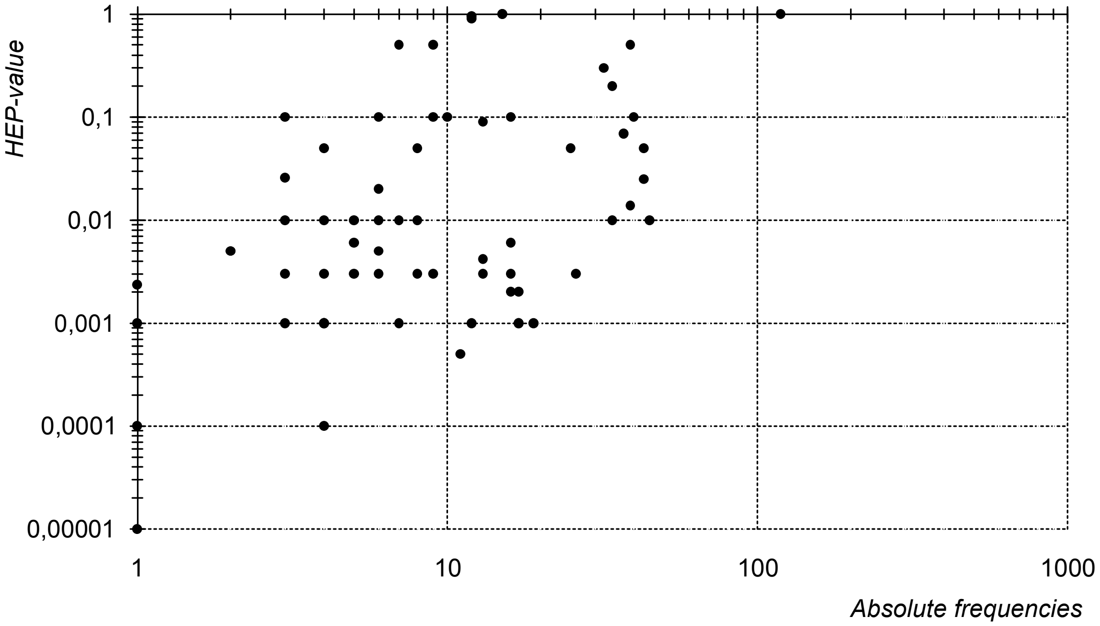

Figure 50 Distribution of Absolute Observation Frequencies in Comparison to the HEP Values From the THERP Catalog

- **Determination of Relative Frequencies**

Corresponding reference magnitudes for the discovered error frequencies were defined in order to form relative frequencies. They are noted in Appendix 6 in a commentary column on the items of the THERP catalog and the corresponding inquiries to the databank are given. One can immediately understand the procedure with the reference magnitudes if one visualizes the determination of relative frequencies for the time-reliability data:

On the whole, we observed n=32 events where it was possible to interpret any kind of time indication in the form of a time-dependent reliability. This means that the relative frequency for an error during time t - on the condition that a time indication was given in connection with an event - must be related to this number and not to the total number of all events. In order, from the relative frequency, to derive a measure that relates to m=165 events, one can extrapolate the expected frequency for an error of type i in m=165 events of type i by the factor of k=m/n-165/32. In general, an expected frequency n_i for an error of type 1 for an expected frequency of n'$_i$ in m=165 events of type i can be determined according to the following formula:

$$n'_i = k_i * n_i = m/m_i * n_i \tag{27}$$

where:

n'i *Extrapolated expected frequency for failures in operation i in m events*

ki *Multiplication factor in condition i*

ni *Absolute number of observed failures in condition i in events*

m *Number of all events*

mi *Number of all events with condition i*

The observed absolute error frequencies during condition i and the multiplication factor k$_i$ for each item are given in Appendix 6. The results shown in Figure 1 were thus achieved for the 79 data from the THERP catalog.

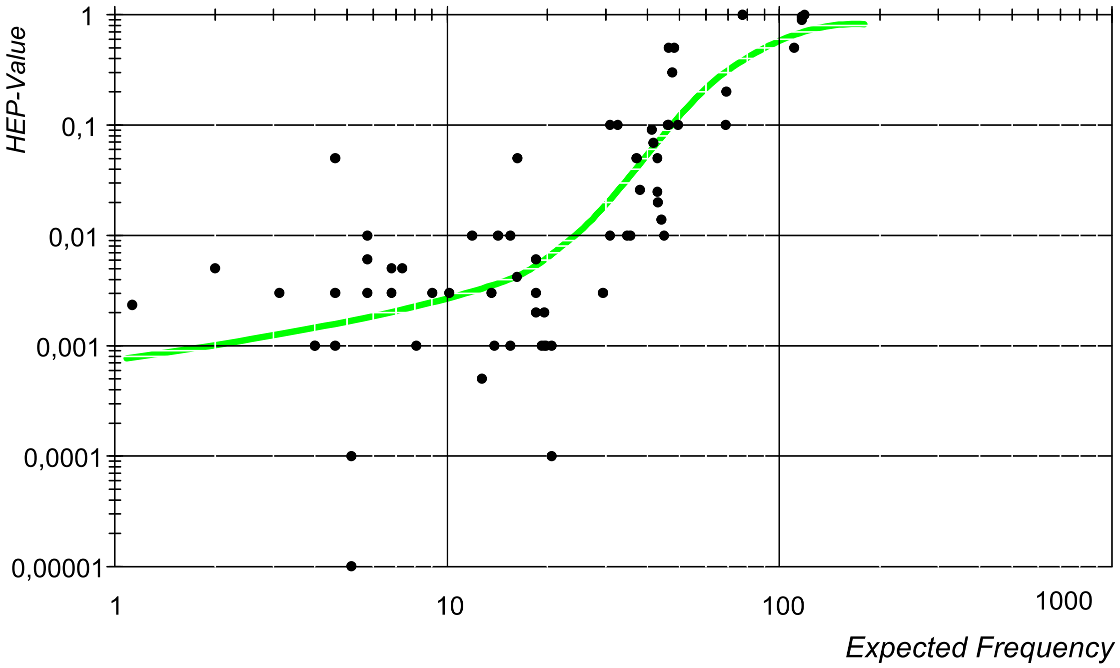

Figure 51 Expected Frequencies Compared to HEP Values of THERP

The correlation of the relative or expected frequencies for the HEP values of the THERP catalog is r=0.83 and is definitely higher than the absolute frequencies for the THERP data. One can thus conclude that the data of the THERP catalog can be found in practical operational experience.

If one moreover intends to make a numerical adjustment of the observed relative frequencies to the data derived from THERP, then the following possibilities may be considered:

1. Determination of a failure rate on the basis of the known period of observation,
2. Estimation of value for basic totality Ω,
3. Calibration of relative frequencies.

An estimate on the basis of a failure rate λ (the referenced magnitude here would be the time) does not come under consideration because a failure rate would not be comparable to the HEP values for the THERP catalog and because one would have to assume a distribution model for the purpose of calculating the probability. Estimating the value for Ω does not seem to make any sense because, as a result, uncertainties are injected via the process of estimation and they further accentuate the uncertainty in the observation. The route chosen below - performing a calibration of relative frequencies - thus appear to be the most suitable in establishing comparability and avoiding the injection of additional uncertainties.

Various functional interrelationships may be considered for calibration. The simplest ones are linear, exponential, or quadratic adaptations. One can also consider a probabilistic function as is made obvious by the distribution of dots in Figure 51. To clarify this assumption, the figure additionally shows an ogival curve with a gray line under it. It is characterized by a saturation in the upper and lower sections of the x-axis and points to a probabilistic connection.

Anticipating the next section, we might mention in the probabilistic model described below - as against linear, exponential, or quadratic adaptations - it is not only the approach for a calibration that is most conclusively justified in terms of content; it also achieves the best numerical agreement of the data from practical operational experience with the THERP data. Table 32 prepares the different approaches; the condition for the determination of the parameters in the formula was that the value range of the possible number of errors $(0 \leq n_i \leq 165)$ is depicted on the value range of probabilities $() \leq p_i \leq 1)$.

Table 32 Various Approaches to Calibration

Approach	***Formula***	***Hits in %=numerical agreement within the uncertainty bands of THERP***
Linear	$p_i = \frac{1}{165} * n'_i$	34%
Exponential	$p_i = e^{\frac{\ln(2)}{165} * n'_i} - 1$	39%
Quadratic	$p_i = \frac{1}{165^2} * {n'}_i^2$	56%
Probabilistic model according to Rasch	(described in the following sections)	75%

This comparison makes it obvious further to investigate and to calibrate the discovered connection with the help of a probabilistic model in order thus- in addition to the correlative connection - also to achieve an optimum numerical agreement. Just exactly how probabilistic models proceed and how they can be used, in order to determine estimated values for reliability parameters, will be covered in the following segment.

5.4 Estimated Values for Reliability Parameters From Practical Operational Experience With the Help of a Probabilistic Model

To calibrate relative frequencies, we can fall back on the model of Rasch (1960) that is known from psychological testing theory. Uses of the model of Rasch can be found among others in Wakenhut (1974) concerning the measurement of social political attitudes or in Köller et al. (1994) regarding the analysis of intelligence tests. Descriptions can among others be found in Fischer (1974), Rost and Spada (1978) or Wright and Stone (1979). The model is first of all presented and then used for a detailed comparison of practical operational experience with the data of the THERP catalog. The basic meaning of this procedure is discussed in conclusion (see also discussions on psychological scaling in Reer, 1993; p128 ff and Reer et al., 1996; p58 ff).

5.4.1 The Model of Rasch

The point of departure of the model is the psychological test theory. In general, methods of psychological test theory, also called scaling methods, try to depict the answer behavior of different persons in response to a common dimension. These methods are used mostly in intelligence research or psychological attitude research (summaries can be found among others in van der Ven, 1980). The main feature of the theory of testing is the illustration of the relationship between the true values or also present quantities (latent traits, hidden properties) and the specifically observable, manifest ways of behavior, such as, for instance, the number of problems solved in intelligence tests. Here, the mathematical relation between parameters and variables is labeled as syntactic area and the relationship between the mathematical magnitude (the test value) and the psychological construct is termed as a semantic area.

Concerning the connection between these two areas, conventional test theory simply presupposes the definition and existence of the property to be mentioned, in other words, we precisely lack the theory that defines the connection between the property to be measured and the observed variables. From this follows the approach - that is customary in conventional test theory - that the observed test performance X is equal to the true value of the person property T and that an error E is X=T+E. This presupposes that a person property can be estimated relatively clearly in statistical terms from a test. On account of this deterministic character, one can, in conventional test theory, estimate uncertainties in the statements above all only by sufficient random sample volumes as well as reliability and validity considerations. Conventional test theory makes no statements about the uncertainties that reside in the measurement itself.

The model of Rasch and the probabilistic test theory based on it tries to consider the statistical uncertainties that already reside in the measurements. For this purpose, the Rasch model starts with the assumption that a latent property (for instance, intelligence) is connected with a manifest behavior (for example, test values) in a probability functional manner, that is to say, the measured value is considered merely as an indicator of a latent property or dimension: (X=f(T). The latent property as a whole cannot be measured directly; instead, one can only measure behavior segments (indicators) of it. The consequence of this assumption is that, in probabilistic test theory, statements are made on the probabilities of occurrence of latent properties and not about latent properties as such.

- **Using the Rasch Model**

Starting with the probabilistic idea, the Rasch model makes the assumptions that are summarized in Table 33.

Table 33 Assumptions of Rasch Model

I) Reciprocal Independence

- Dichotomous events
- Local stochastic independence of person parameters (ability)
- Specific objectivity of item parameters (difficulty)

II) Probabilistic Test Theory

- Separation of latent dimension and observed variables (indicators)
- Unidimensionality (a latent dimension underlies all items)
- Exhaustive statistics

III) The Characteristic Curve Item

- Monotony
- Asymptotic approach
- Homogeneity
- Interval scaling

These assumptions or utilization prerequisites for the model of Rasch can also be used to explain why the model is better suited for determining probabilities from practical operational experience than a probability estimate oriented by conventional test theory, such as, for instance, the other solutions mentioned in Table 32. Accordingly, we will now describe them.

- **Reciprocal Independence**

As basic assumption I, Rasch postulated that the chance of a solving a problem is determined by two factors. That is first of all the difficulty of the task and besides the ability of the person. With a Chance of $C_{Success}$, both factors lead to solution of the problem; the chance for $C_{Failure}$ indicates that the problem could not be solved. The probability P of an event can be derived from the chance of this event; they are in a simple relationship. Equation 28 applies to their relationship in conventional test theory.

$$\begin{aligned} & C_{\text{Success}} = \frac{P}{Q} = \frac{P}{1-P} = \frac{X}{D} = \frac{1}{C_{\text{Failure}}} \\ \Rightarrow \quad & C_{\text{Failure}} = \frac{Q}{P} = \frac{D}{X} \end{aligned} \tag{28}$$

where:

C Chance of success or failure

P Probability of observation of successes

Q Probability of observation of errors

X Ability of the person

D Difficulty of task

The model of Rasch can thus be applied only to dichotomous events, as can be seen on the basis of the dichotomous distribution between success or failure. The error events observed in practical operational experience also involve dichotomous events (error or no errors); therefore, this prerequisite is given for the use of the Rasch model. That the considered human factor events reproduce the difficulty D of a situation was addressed already in the discussion on Table 15 (Chapter 3). Human factor relevant events consequently represent the abilities of the individual (X).

From this basic assumption follows the assumption as to the local stochastic independence, that is to say: the ability of the person is independent of the difficulties inherent in the tasks submitted to him or her and solved by him or her in the past. The concept of specific objectivity states the difficulty of an item cannot be influenced, in other words, it is independent of the person who has to solve the item. Reciprocal independence and specific objectivity are essential basic prerequisites for the Rasch model. With relation to the analysis of events, they expect that the frequency with which an error occurs is independent of which person makes the error. This assumption is also made in human reliability and can thus be considered as having been met with relation to an individual event. But dependencies can exist within one event. For example, it was found that actions from Type C are more situation degrading than actions from Type Ba. With regard to the analysis of events, this means that one must make sure that the frequency of an observed error of Type i is independent of the previously observable errors of Type i. This can be assured when an estimate is made on the basis of the number of events (m=165) and not on the basis of the man-machine systems observed in the events (I=255), because they are not independent of each other.

- **Probabilistic Test Theory**

Basic assumption II says in formal terms that the test values cannot directly estimate their underlying parameters, such as this is customary in conventional test theory (for example, via the formation of relative frequency). According to Equation 28, conventional test theory estimates the probability P and the chance C from the frequency n of the observation of event i, related to all m events in the following manner:

$$P \approx \hat{P} = \frac{n}{m} \Rightarrow C \approx \hat{C} = \frac{n}{m-n} \qquad (29)$$

where:

$\hat{P}$ *Estimate for P*

$\hat{C}$ *Estimate for C*

P *Probability for an event of Type i*

C *Chance of an event of Type i*

n *Number of all events of Type i*

m *Number of all events*

Rasch, on the other hand, assumes that the statistical uncertainty resides in the measurements themselves. It is not the relative frequencies that estimate the underlying parameter in an optimum fashion but rather a transformed value (the so-called Logits) which includes the statistical uncertainty of the data. According to Rasch, the chance thus is obtained not directly from the probability P but rather in that one considers the statistical uncertainty of the estimated values for P with the following formula:

$$C_{\text{Success}} = \ln\left(\frac{\hat{P}}{\hat{Q}}\right) = \ln\left(\frac{\hat{P}}{1-\hat{P}}\right) = \ln\left(\frac{\hat{X}}{\hat{D}}\right) = \ln(\hat{X}) - \ln(\hat{D}) = X - D \qquad (30)$$

This formula is also referred to as logistic transformation. *ln*$(\hat{X})$ and *ln*$(\hat{D})$ accordingly are called Logits. **This results in a separation of the latent dimension and the observable**

variables (indicators). The following should be noted regarding the choice of the logarithm:

- Rasch himself justifies the logarithm for the calculation of the Logits in terms of content by saying that this is an assumption that is often made in mathematics in order to consider uncertainties in the data, without having an explicit, mathematically conclusive justification for this (Rasch, 1980).
- As was seen earlier, the HEP values in the THERP procedure involves magnitudes with a standard logarithmic distribution; therefore, another interpretation possibility would be Logit $ln(\hat{P})$ gives the expected value of the logarithmized HEP value of P (see also Equation 25 and Reer, 1988).[13]

We will not go any further at this point into both of these explanations because the Rasch model, in this study, is to be used to calibrate the relative frequencies from practical operational experience with respect to the HEP values of the THERP catalog. Furthermore, a discussion of these assumptions would go beyond the scope of this study.

Unidimensionality is demanded as prerequisite for the separation of the latent dimension and the observable variables; in other words, all items can be interpreted on one dimension (by means of a psychological construct). The requirement that is leveled against data from this requirement is called exhaustive statistics; in other words, all items must relate to the same objective content that is given by the psychological construct. The assumptions of unit dimensionality and exhaustive statistics are given in that all analyses referred to the psychological construct of the human error.

- **The Item Characteristic Curve**

Basic assumption III finally says that the observed test value and the true value of a property are interrelated via a so-called item characteristic curve. The item characteristic curve is determined according to the following formula by solving Equation 30 for P:

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[13] Further discussions about the assumptions of the Rasch model, including the impact of the log-normal distribution, are given meanwhile in Reer et al. (1999).

$$\hat{P}_{\text{Success}} = \frac{e^{C_{\text{Success}}}}{1+e^{C_{\text{Success}}}} = \frac{e^{X-D}}{1+e^{X-D}}$$

$$\text{and} \qquad (31)$$

$$\hat{P}_{\text{Failure}} = \frac{e^{C_{\text{Failure}}}}{1+e^{C_{\text{Failure}}}} = \frac{e^{D-X}}{1+e^{D-X}}$$

Typical characteristics of the item characteristic curve are the monotonous rise and asymptotic approach to the limits $\hat{P}=1$ or $\hat{P}=0$. This means that this probabilistic function is in a position to transform data from practical operational experience into values that lie within the value range of probabilities. This is one reason why this probabilistic approach is particularly suitable for comparison to HEP values because the goal of calibration is to attain numerical agreement with the HEP values of the THERP catalog.

Another reason that can be gathered from Equations 30 and 31 is that $\hat{P}=1$ and $\hat{P}=0$ are not defined. Events, that lead to $\hat{P}=1$ and $\hat{P}=0$, do not point toward any kind of statistical uncertainty and must be taken out of the process of estimation. That applies both to the case for all persons are without fault (too capable) and also to a situation where all tasks are error-free (too easy). This probability is ideally applicable to practical operational experience because, as was hinted earlier, positive results, in which no errors occurred, are not reported and because practical operational experience as a result is always incomplete with respect to errors that did not occur. In probabilistic approaches, the latter had to be taken out anyway; therefore, probabilistic models are very suitable for analyzing information that is necessarily present incompletely in the practical operational experience.

Before we illustrate the application of this formula to events, we want briefly to address the remaining assumptions of homogeneity, monotony, and interval scaling. The item characteristic curve presupposes that there is homogeneity between the items, that is to say, all items cover the same characteristic and, in the persons considered, we are dealing with a homogeneous random sample. This assumption is met in that all events (items) relate to the characteristic of "human error." The homogeneity of the random samples was investigated already during the examination of the standard logarithmic distribution; it is insured according to Swain and Guttmann (1983) by training and education. Furthermore, the requirement for monotony says that the observed value and the probability are in a relationship via a strictly monotonously rising function. This is fulfilled mathematically by Equation 31. That the observed values are also empirically connected to the probabilities of THERP was demonstrated already by the high correlation between relative frequencies and the THERP data. The Rasch model furthermore assumes that ability parameters and difficulty parameters are interval-scaled. Interval scaling is insured in that the magnitudes obtained from practical operational experience are frequencies.

5.4.2 Estimating Parameters

In test theory, as a rule, one gets - from the observed solution probabilities - estimated values for the difficulty of the tasks or the ability of their person. There, the direction of the process of estimation thus is:

$$\hat{P} \longrightarrow \{X, D\} \tag{32}$$

The frequencies found in the course of event analysis however are estimates for the difficulty parameter and the ability parameter on whose basis one is supposed to conclude as to probabilities. This among other things can be gathered from the ogival curve of the dots in Figure 51 (the curve corresponds to that of the item characteristic curve). This means that the direction of the process of estimation here is thus:

$$\{\hat{X}, \hat{D}\} \longrightarrow P \tag{33}$$

Accordingly, one must exchange the estimated magnitudes and the estimated parameters in Equation 31. In other words, we estimate $\hat{X}$ and $\hat{D}$. The ability of the person - cannot be determined from the investigated events because, to do that, we would also have to analyze the human factor relevant events. One makes the smallest error when, in the following estimation process, one does not expect any contribution from the ability. This corresponds to an estimation of $\hat{X}=0$. Furthermore, ability can be viewed as being relatively constant, by virtue of education, within the considered technical system (power plants). $\hat{D}$, the parameter for the difficulty of a task, is estimated from the observations in the following manner:

$$\hat{C}_{Failure\ of\ Task\ \ of\ Type\ \ i} = \hat{D}_i - \hat{X}$$

and

$$\hat{X} = 0 \qquad (34)$$

$$\hat{D}_i = \frac{n'_i - m}{s_n}$$

where:

$\hat{D}_i$	*Estimate of difficulty of Task i*
$\hat{X}$	*Estimate of ability of presence*
n'_i	*Anticipated frequency of an error of Type i according to Equation 27*
μ	*Mean value*
s_n	*Anticipated deviation*

A possible Rasch distribution is obtained in that one estimates the difficulty of the task of i in that the error of frequencies, observed in the events, are norm for all observed events. This distribution is called a normalized Rasch distribution. The following factors were determined as standardization parameters which supply an optimum agreement between the relative frequencies of the events and the data of the THERP method:

$$\mu = m/2$$

and *(35)*

$$s_n » 12.5$$

where:

m	*Number of observations (all events with human error)*

The mean value m results from the assumption of the Rasch model to the effect that a mean chance of failure with an average individual ability leads to a failure probability of P=0.5. The deviation s_n was determined empirically (maximization condition was the highest possible agreement with the THERP data). For the Rasch model, we thus get the following connection of the chance $\hat{C}_{failure}$ as an estimate for the probability $P_{failure}$:

$$P_{Failure\ of\ Type\ i}=\frac{e^{\hat{C}_{Failure\ of\ Type\ i}}}{1+e^{\hat{C}_{Failure\ of\ Type\ i}}}=\frac{e^{\hat{D}_i}}{1+e^{\hat{D}_i}}=\frac{e^{\left(\frac{n'_i-m}{s_n}\right)}}{1+e^{\left(\frac{n'_i-m}{s_n}\right)}} \tag{36}$$

The formula supplies the probability with which occurs and error of Type i observed n times. It thus becomes possible to calculate a probability of occurrence from the relative frequencies. If one applies this formula to the m=165 observed events, then we get a distribution according to Figure 52.

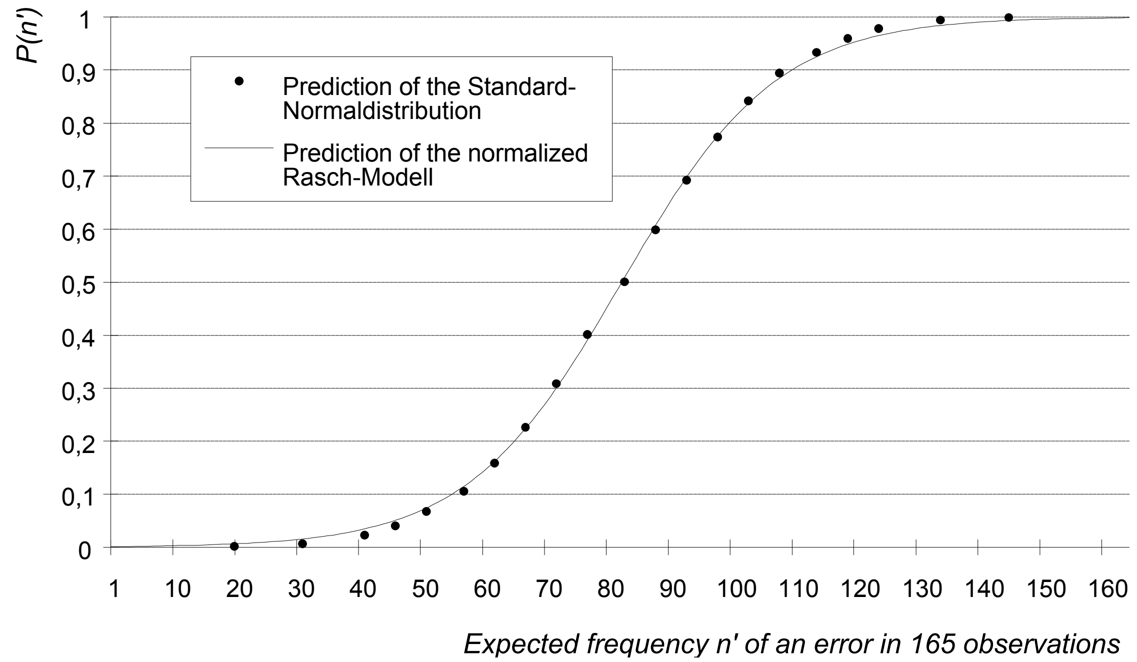

Figure 52 Probabilistic Model to Predict Occurrence Probabilities From Frequencies in Observation

From Equation 36 one can see that the Rasch model can be used only when not all observed errors are of the one and only Type i. One thus runs into problems of estimation when there is too little variation in the error types. For example, if in all events only two different error types were observed and if they were observed with equal frequency, then the model for both error types would determine a probability of P=0.5. Using the 165 analyzed events however it was possible to observe a sufficiently large number of different error types. For example, an error type, that was observed only in one event, supplies the value $P=f(\hat{D})\approx 0.0014$ with $\hat{D}=1/165$. This means that one can differentiate probabilities for a degree of resolution of $\Delta P\approx 0.0014$ from each other. The random sample offers sufficient variation so that it can be compared to the HEP values from the THERP method.

By means of the probabilistic functions, one can draw conclusions for probabilities from the difficulty parameter. Here, in other words, one estimates a probability from a rather qualitatively-oriented parameter (difficulty, operationalized by the number of errors of Type i observed in the events). With the help of this consideration one can establish a certain relationship between the item characteristic curve, set up here according to the model of Rasch, and the fuzzy set theory already addressed in Chapter 4 because the item characteristic curve corresponds to a membership function.

To the extent that one could show that (1) Equation 35 optimally estimates the difficulty parameter and (2) the item characteristic curve for the membership function correctly reproduces the connection between difficulty values and HEP values of THERP, one could - with relation to the question as to what kind of calculated probabilities one is dealing with here - even conclude that they are an estimate for "genuine" probabilities according to the HEP definition (Equation 2). But that remains in the realm of speculation because the origin of the HEP values in the THERP method is unknown. We will therefore not draw this conclusion here. Instead, a simpler statistical interpretation is possible on the basis of the formation of the difficulty parameter.

- **Statistical Interpretation**

In Figure 52, in addition to the item characteristic curve, we can also see the estimated curve of probability for some points, given by the standard normal distribution. The normalized Rasch curve agrees almost identically to the prediction of the normal distribution. In terms of statistics, the normalized Rasch distribution can thus be interpreted in the following manner: if one assumes that a dichotomous event (action or error of Type i) is constituted by a random distribution, then it is distributed binomially. The binomial distribution according to Bortz (1989), in case of $n\to\infty$, approximately blends into a normal distribution even in case of unequal probable alternatives. To determine how high is the probability of extracting at least one error of Type i from a given number of n events of Type i, one must determine the area under the normal distribution up to the z value which corresponds to the number n'_i of the observed errors of Type i.

From the agreement between the normalized Rasch model and the integral of normal distribution one may accordingly assume that Equation 36 estimates the probability of the appearance of an observation Type i. Figure 53 illustrates this connection from the perspective of the density function. The density function of the normalized Rasch distribution is illustrated in the figure in an idealized manner. The hachured surface then is the probability of observing at least one error of Type i within all observed events of Type i.

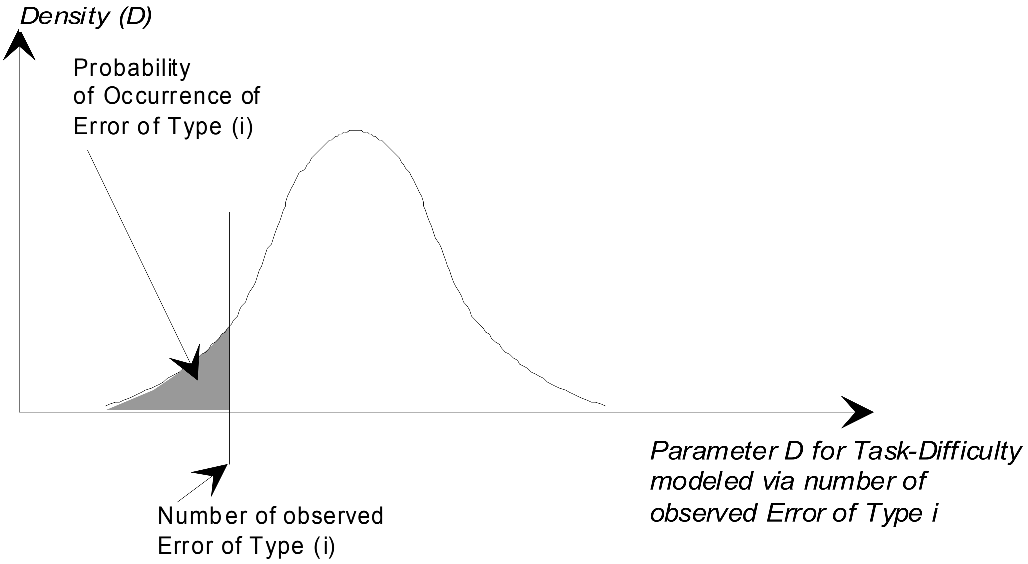

Figure 53 Density Function for Appearance of an Event of Type i as a Function of the Task Difficulty (D)

At this point we inevitably face the question as to why the logarithmic normal distribution is not assumed as a density function which was verified earlier. The normal logarithmic distribution however is a distribution of the person abilities and thus, in the sense of the Rasch model, it is a distribution of the ability parameter. But the latter was not considered because we only have error events in event analysis. The ability parameter requires that events be present with errors and performances (= no error). To be able to estimate the ability parameter, one would thus also have to analyze the existing human factor relevant events.

The normalized Rasch model thus makes it possible to come up with statements having the following form: if an event of Type i occurs then it will be an error in Type i with a probability of P_i. This means that the probabilities, calculated with this model, are not human error probabilities because, according to Equation 2, for a human error probability, we must know the number of requirements (or the basic totality). Earlier however we already discussed that this approach can be used to estimate the HEP values because the THERP method is related to rule-based behavior as emerges from the assumption of the normal logarithmic distribution.

5.5 Probabilistic Predictions From Practical Operational Experience

For the following probabilistic comparison, we determined probabilities with the help of the normalized Rasch model for the previously already determined anticipated frequencies. These values are then compared to the HEP data from the THERP catalog and the PHRA method. Along with an overall comparison, we also investigate individual model ideas of THERP: the diagnosis model, the dependency model, and the stress model. In conclusion, we discuss the comparison that was made.

5.5.1 Probabilistic Comparison of Practical Operational Experience With the Data of the THERP Method

The occurrence probabilities, calculated with the help of the Rasch model from the relative frequencies, were contrasted against 79 items from the tables of the THERP process. Along the lines of the developed databank CAHR (Connectionism Assessment of Human Reliability), they are also referred to as CAHR values for simplification purposes. Figure 54 shows the correlation between the THERP values and the CAHR values from practical operational experience. The correlation is r=0.83 for the HEP values and r=0.79 for the logarithm of the HEP values. The rise in logarithmized value amounts to $B_{xy} \approx 1.054$. This corresponds relatively accurately to a straight origin line.

If one considers the uncertainties (error factors) that were given with respect to the data of THERP, then about 73% of all observed CAHR values show overlaps with the HEP values of THERP. If, in addition, we consider the uncertainties in the CAHR values according to Equations 21 and 22 (Chapter 4), then about 94% of all items agree. A detailed compilation of the HEP values and uncertainties as well as overestimations and underestimations in the individual observations are illustrated in Figure 55 and Appendix 6. On the whole, we find good numerical agreement of the data from practical operational experience and the data from the THERP catalog.

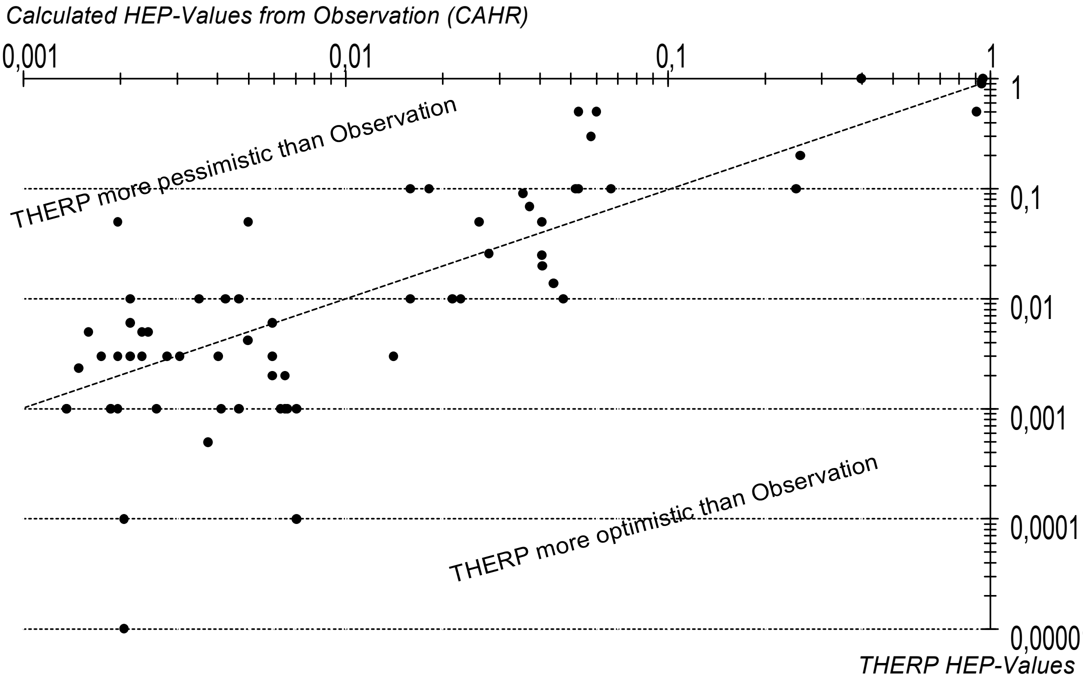

Figure 54 Linear Correlation Between HEP Values of THERP Compared to the Values Calculated From Observations With the Help of CAHR

Some mismatches, however, are outside the band of uncertainty given by THERP. They are discussed in Table 34. In the table, those items that are located both outside the uncertainty band of the THERP data and outside the uncertainties of the connectionism assessment for human reliability data are marked with *. As to whether major mismatches are due to an actual overestimation or underestimation of the conditions observed with the help of the THERP data or whether they can be traced back only to uncertainties in the data source is something that can be judged in that one subdivides the observed mismatches with respect to the following possible uncertainty sources:

1. Specific Mismatches: Specific mismatches can come about because there is inadequate agreement between the data from practical operational experience and those from the THERP catalog. That can be done in two ways: first of all by virtue of the fact

that the data from practical operational experience are not present in the form required for a modeling of the THERP items or, second, because the data of the THERP items are unclear. No further statements can be made regarding such mismatches. They are marked in the table with (d) for data inaccuracies and (i) for inaccuracies in the items in the THERP catalog.

2. Nonspecific Mismatches: This type of mismatches includes the unknown number of requirements (basic totalities) and the unknown person parameters. Both directions of mismatch can thus lead to an overestimation and to an underestimation. This is why items from a task area or with identical task descriptions must have approximately the same directions of mismatch because the basic totalities must be comparable within this delimitated area. If nevertheless one observes a mismatch in two differing directions, then the mismatch cannot be explained in the life of these uncertainty sources. In this case, the uncertainties are marked with (p) and have a certain meaning with regard to the HEP values given in the THERP catalog.

3. Another reason for a mismatch is noted in the table: (m) for methodological reasons. It means that, in these cases, no agreement was achieved because the THERP method does not give any uncertainties for HEP=1.

From the investigation of the mismatches in Table 34, one can thus discuss the following results with relation to the evaluation of human reliability:

- On the basis of the results pertaining to the diagnosis curve, one can propose using lower values for simple diagnoses than those that are given in THERP. When the time frame involved is long, one can furthermore observe a certain saturation at p=0.001. That seems to be below the limit of possible diagnosis errors, something that is also pointed out clearly by the results of the PHRA method.

- From the results concerning the THERP Table 20-06, one can conclude that there are differences in the handling of procedures. These differences can be caught in that, for Item 20-06 (3), one uses an error factor of EF=6 and for Item 20-06 (7) one rather employs the lower limit of the HEP value.

- The differences in results with respect to THERP Table 20-11 can be made up by raising the error factors EF=6 for Item 20-11 (2) and EF=4 for Item 20-11 (5).

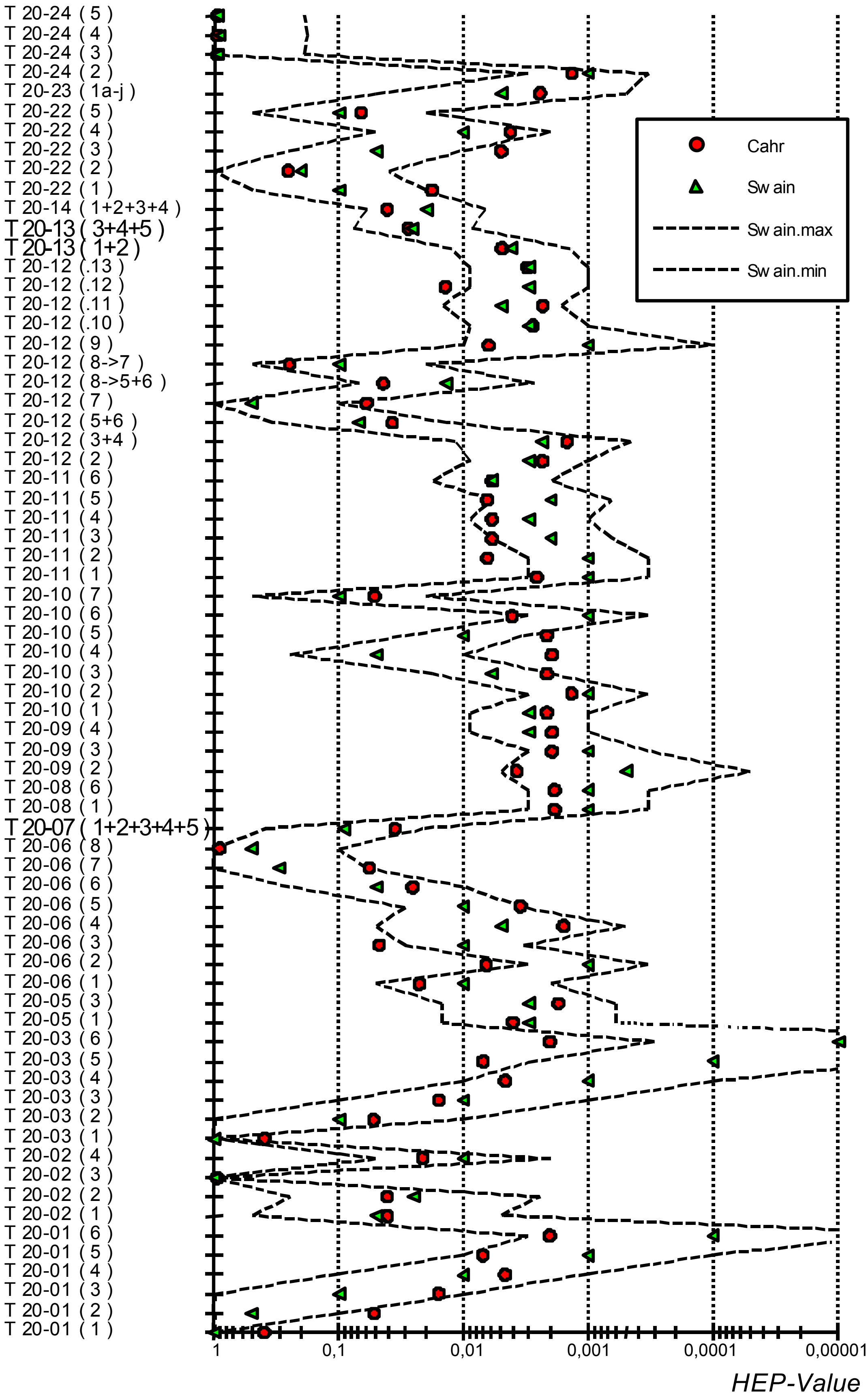

Figure 55 Illustration of Overestimations and Underestimations in Individual Observation

Table 34 THERP Items, Direction of Mismatched and Possible Reasons

THERP Item	***Direction of Mismatch***	***Possible Reason***	***Indi-cation***
Diagnosis Model (Screening and Nominal)			
20-01 (1)* 20-01 (2) 20-03 (1)*	THERP more pessimistic	Practical operational experience supplies only data for relatively simple diagnoses. There are no difficult diagnoses that occur in a complex trouble case.	p
20-03 (5) 20-03 (6)	THERP More optimistic	For a diagnosis, b=0.001 appears to be a lower limit. That is also indicated by the data from the PHRA method (Chapter 2).	p
Screening Model			
20-02 (3)	THERP more pessimistic	HEP for this item according to THERP is P=1. For these HEP values, THERP does not give any uncertainty band widths. The observed value does not lie exactly on the dot at P=1; therefore, it cannot correspond to the value of THERP. If one were to give uncertainties also for HEP values of P=1, then an error factor of EF=1.06 would suffice to place the observation within the uncertainties of the THERP item.	m
Administrative Control			
20-06 (2)	THERP more optimistic	The available event descriptions are not so detailed that one could describe a shift-dependent examination in detail. Accordingly, the modeling of this THERP item is possibly not fitting.	d
20-06 (3)*	THERP more optimistic	Item 20-06 (4) lies within the uncertainties and hardly deviates from the statement itself (error in the use of procedures); one can therefore conclude that this statement has a certain relevance for probabilistic investigations. This hypothesis is boosted by the fact that Item 20-06 (4) is assessed more pessimistically by THERP: that permits the plausible overall conclusion that procedures under normal conditions are handled differently when compared to disturbed system states.	p
20-06 (7)	THERP more pessimistic	With relation to Item 20-06 (3), one can conclude that this deviation also has a certain relevance for probabilistic investigations.	p
Errors of Commission During Quantitative Reading of Displays			
20-10 (4)* 20-10 (5)	THERP more pessimistic	The available event descriptions do not go into the types of displays in such detail that the modeling of these THERP items might possibly not be fitting.	d
20-10 (6)	THERP more optimistic	The available event descriptions are not sufficiently detailed.	d
Errors of Commission in Connection With Signal Displays			
20-11 (2) 20-11 (5)	THERP more optimistic	Performance-shaping factors relating to display layout were found in the event descriptions. Because the other items are both overestimated and underestimated by practical operational experience, there is a certain relevance here for probabilistic investigations.	p
Errors of Commission Involving Manual Operating Elements			
20-12 (7)	THERP more pessimistic	The available event descriptions are not sufficiently detailed.	d
20-12 (12)	THERP more optimistic	The item is so described ("performance-shaping factors are more favorable") that it is not clear which performance-shaping factors are to be considered.	i
Discovery of Errors of Others Through Supervision			
20-22 (1) 20-22 (3)	THERP more pessimistic	The available event descriptions are not sufficiently detailed.	d

5.5.2 Comparison With Individual Models of the THERP Method

THERP assumes certain models for some evaluation problems. They include the diagnosis model, the stress model, the dependence model, and the alarm reaction model. Models differ from the point values of the THERP catalog discussed so far in that they assume a functional connection between parameters and reliability parameters. It was possible to perform a comparison with these models except for the alarm reaction model for which the data were not adequately detailed.

- **Comparison to the Diagnosis Model From THERP and From the PHRA**

The diagnosis model of THERP represents a basic assumption as to human reliability. It says that the probability of making an error increases with the available time. Because the gradient and curve of the assumption here depends on the difficulty of the diagnosis situation, the French Electric Power Company performed its own experiments in order to get more specific data for differing situations, when compared to the generic diagnosis model of THERP (see Chapter 2).

It was possible to use 32 events from the investigated operational experience to validate the diagnosis model because corresponding time data were available for them. Conditions for the usefulness of an event to validate the diagnosis models called for the specified time to be interpreted as diagnosis time (for example, the operator noted the error after 10 minutes). Those man-machine systems were counted off where a human error (task error or execution error) could be found. In accordance with the modified Rasch model, occurrence probabilities were calculated for these data. Overall, we get a data distribution for the diagnosis model according to Figure 56.

In the figure, THERP.HEP represents the diagnosis model of THERP (according to THERP Table 20-01) and CAHR.HEP represents the predictions from practical operational experience (the HEP values for seven minutes were estimated on the basis of the values for t=10 minutes for THERP and CAHR). The PHRA method yields the curve P(1) for simple tasks diagnosing typical trouble (see Mosneron-Dupin et al., 1990). The layout of the curve calculated on the basis of practical operational experience here is most similar to curve P(1); the correlation here is highest (the correlation of the logarithmic values is r=0.97).

This result is plausible solely for the reason that, in practical operational experience, no serious troubles have so far been observed - such as they are assumed in the diagnosis curve of THERP.

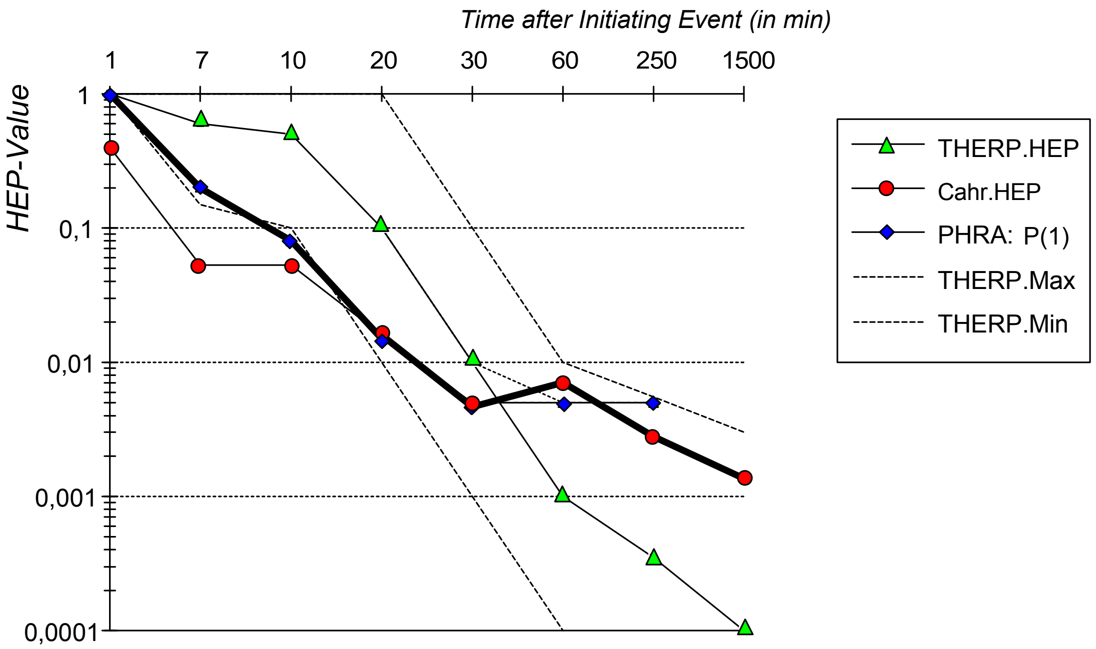

Figure 56 Comparison of Diagnosis Curves of THERP and PHRA With the one of CAHR

If one compares the curve to the one in Figure 48, then one first of all finds that one cannot recognize any monotonous descent here. This is due to the fact that, in this case, it was not the time clusters that were calculated from Figure 48 that were taken as basis but rather the time subdivisions specified by THERP (up to 10, 20, 30, 60, and more than 60 minutes). Accordingly, to form the diagnosis curve, the time data were pooled that came closest to the data of the THERP item. During 60 minutes, this produces an unexpected rise in the curve which contradicts the general assumption of the time reliability method (the monotonous decrease of error probability with time). This rise is based on the selected procedure of pooling the time data and thus, in the final analysis, it is based on the fact that too few data were observed.

From the results however one may conclude that the agreement of practical operational experience with curve P1 from the PHRA procedure can be taken as reference for the transferability and validity of other data of the PHRA method (the curves P1', P2, P3; see Chapter 2).

- **Comparison to the Stress Model From the Technique of Human Error Rate Prediction**

In the stress model, THERP gives multiplication factors by which one must multiply an existing error probability if a certain stress level prevails (see THERP Table 20-16 in Appendix 5).

These multiplication factors cannot be determined directly from practical operational experience; therefore, to compare practical operational experience to the stress model, it was assumed that a probability of P=0.0014 should be modified for the optimum state (optimal static, optimal dynamic) under different stress stages (P=0.0014 is the smallest value that can be achieved with the normalized Rasch model). The inquiries listed in Appendix 6 were used to model the various stress stages. For the different inquiries, we again calculated the expected frequencies and, from them, we calculated the probabilities with the help of the normalized Rasch model. Figure 57 shows the results.

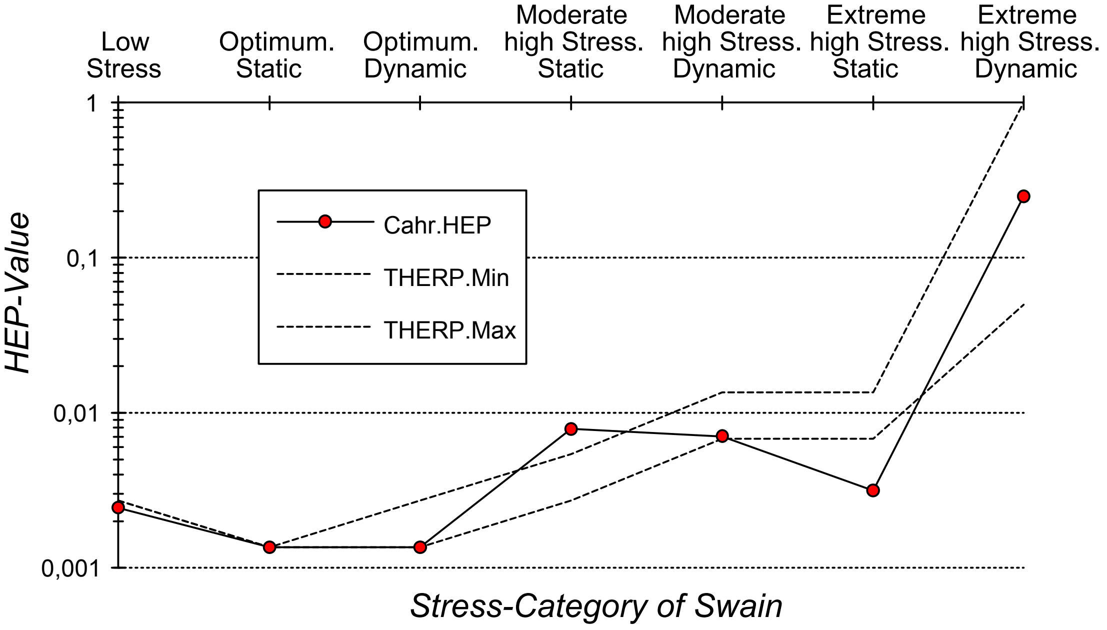

Figure 57 Comparison of Practical Operational Experience With the Predictions of THERP With Regard to Different Degrees of Stress

As one can see in the figure, the modeling made here agrees with the predictions in the THERP model rather nicely (the correlation of the logarithmized values is r=0.92). Because the dynamic tasks, under moderate stress, have a higher value than static tasks under extreme stress, the psychological construct of stress seems to be more complex than it can be modeled for the five different stages according to THERP (for example, Hockey, 1984). Essential factors that determine whether stress leads to human errors (negative stress) or whether stress releases performance reserves (positive stress) are not considered, for example by THERP.

Here again, system ergonomics appears to be a good help in modeling the meaning of stress in terms of human reliability. This is underscored by two reasons: 1) The modeling of the stress model performed here by means of the time window and the system ergonomics subdivision of the management type (in static and dynamic) agrees relatively well with the predictions of the stress model of THERP. 2) An essential factor as to whether the effects of stress are positive or negative is represented by control over the situation or feedback. Feedback was identified as an important factor for absence of error already in the analysis of the error types. System ergonomics thus investigates the essential factors that add up to the effect of stress.

- **Comparison to the Dependency Model From THERP**

Initial estimates on dependencies were already made in the investigation of the various action types in Table 55. A deterioration of the situation was observed for a Ba action in 16% of all cases. If one figures on the normalized Rasch model, that would correspond to an occurrence possibility of a situation deterioration of p=0.012 in case of Ba actions.

A subdivision on mutually corresponding persons, places and situations was already performed (Table 19) in Chapter 3, for a more extensive consideration of dependencies: accordingly, there is complete dependence when all three parameters are equal; there is high dependence when the situation and the person are equal; and there is average dependence when the person and the place or the place and the situation are identical. Low dependence exists when only one parameter is equal and independence exists when no parameter agrees. To verify the subdivision, we determined those results in which more than one man-machine system was mentioned. That, on the whole, was the case in 75 events. In the 75 events, an error generating man-machine system was followed by a situation deteriorating man-machine system in a total of 25 events. For these events, we made a count to find out how often it was possible to observe an identical place, an identical person, or an identical situation. From these frequencies we calculated the probabilities of occurrence of various constellations from Table 19.

From the observations, we determined dependencies between tasks directly from the relative frequencies of the events. The THERP method cannot do that; instead, it gives correction formulas for dependencies between tasks; therefore, to make a comparison, it was necessary to calculate the total probability, expected from THERP, for a situation with two mutually dependent tasks. To facilitate comparability with the observations, we chose the probabilities for the two dependent tasks (P_1 and P_2) in such a manner that they would correspond to those that underlie the observations: P_1 was determined in that the total number of 75 observed events with more than one man-machine system were related to all 165 events. P_2 results from the relationships between the 25 discovered situation degrading man-machine systems and all of the 165 events. Using the normalized Rasch model, we then get P_1=0.35 for the first task and P_2=0.009 for the second task. The total error probability was then calculated according to THERP Table 20-17. Furthermore, we assumed an error frequency=5 according to THERP Table 20-20 (Appendix 5). Overall, we thus get a distribution according to Figure 58 for the CAHR data and those of the THERP method (THERP Table 20-18). It was impossible to test THERP Table 20-19 because there were not enough data available.

With the help of the modeling performed here, we can find good agreement between the dependency model and the observations. The modeling of dependencies, done in Chapter 3, thus appears to be a realistic conversion of the subdivision performed in THERP. Moreover, it makes it possible to model dependencies in a manner oriented by the defined external conditions so that one can avoid uncertainties of the THERP model when this involves the choice of the dependencies in a situation that is to be evaluated.

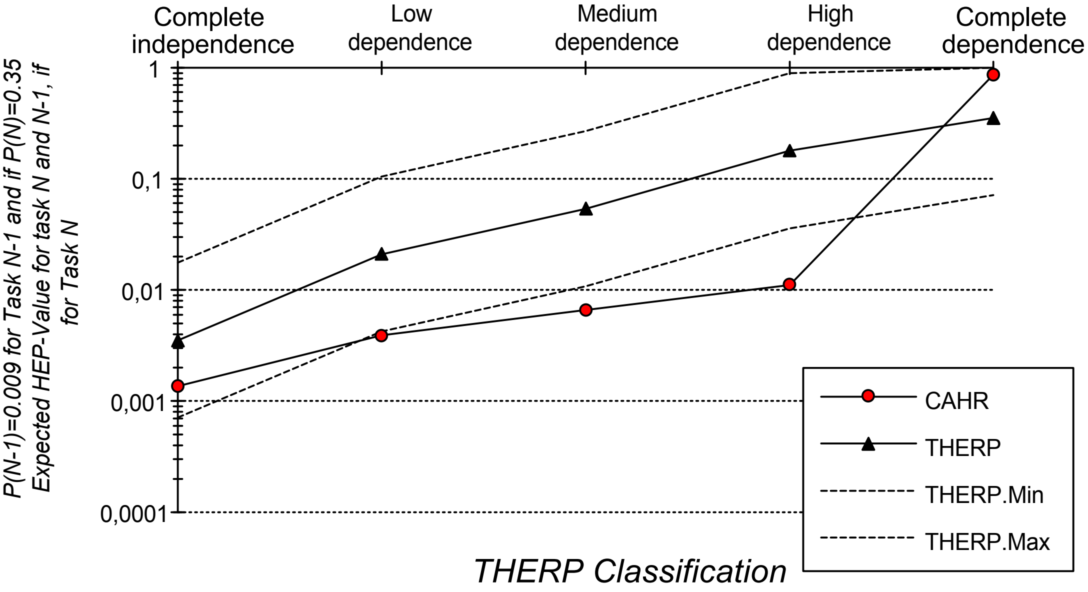

Figure 58 Comparison of Practical Operational Experience With the Predictions of THERP Regarding Different Degrees of Dependence

In numerical terms, the absolute HEP values only approximately correspond to this subdivision; therefore, it appears that there are still other factors for dependencies. In particular, the steep rise between great and complete dependence would indicate that, in the modeling performed here, there are no finer subdivisions of the dependencies. This is due to the fact that dependencies emerge between the individual tasks from the event descriptions only rarely; among other things, this can be gathered from the number of events that were found with several man-machine systems: the number of 75 events does not seem to yield a sufficiently realistic picture of the actual work procedures because, usually, it should be possible to observe at least two man-machine systems in each event: an error generating-man-machine system and an error-discovering man-machine system.

As far as content is concerned, one may conclude from the agreement that the basic procedure - of providing personnel redundancy by means of a second man who is employed next to the first one - seems to be the least effective possibility in the light of these findings. If there is effected personnel redundancy, then the independence of the persons and the situations must be insured in some form. For instance, two persons would be in a condition of only average dependence at the same place if they were to be assigned different tasks. With a clever selection of tasks, we would have better redundancy in terms of personnel than by means of having a second person merely present.

5.6 Discussion

In the first part of this chapter we were able to show that qualitative analyses on the information items gathered can be used to analyze interrelationships in error conditions and thus to optimize improvement measures or estimate their effectiveness. Furthermore, with the help of the procedure presented here, and in spite of inadequate data backup, it was possible to confirm central assumptions and data on human reliability (distribution assumptions, human error probabilities) from the THERP catalog for the sector of German nuclear power plants. The bands of uncertainty, given in the THERP method most extensively cover the observed mismatches of the tasks taken from practical operational experience. With the help of a more detailed analysis and wider use of the analysis method presented here, one would expect that the uncertainties in the data of THERP could be estimated even better. Here, likewise, it has so far not been possible to validate all items in the THERP catalog. For example, we did not have sufficient detailed information for the alarm response model.

In conclusion, there are two essential points of discussion that result from the agreement that was discovered in the course of quantification: (1) The significance of human error probabilities in connection with human reliability and (2) qualitative as well as quantitative statements concerning the fields of practical application of human reliability analysis for which so far it had been impossible to provide any secure indications.

5.6.1 Significance of Human Error Probability in Human Reliability

The good agreement between the data of the normalized Rasch model and the THERP values makes it obvious to conclude that the methods presented here can be used to estimate HEP values although no basic totalities are introduced in the estimation procedure, such as it is required in Equation 2 for human error probabilities. On the other hand, the estimation method presented here supplies only estimated values for occurrence probabilities and not for requirement probabilities. This procedure was necessary because the number of performed actions (the basic totalities) can never be determined from the event descriptions and because no HEP can be determined even with a knowledge of all erroneous actions and near erroneous actions because a residue of unobserved cases will always be missing. This means that good agreement also demands general considerations as to whether the "conventional" HEP definition - that treats the individual like a technical component that always functions equally - does at all correspond to the nature of human processing and human error mechanisms (see also Discussions in Adams, 1982; as well as Heslinga and Arnold, 1993).

An essential problem of the "conventional," component-related approached regarding human action is this: the complexity of human performances and learning ability leads to a situation where this definition basically can lead to any kind of numerical results, depending on which level of abstraction the tasks of Type i are defined or perceived by the individual or processed by the individual. Why this is so is illustrated by the following considerations that relate to human performances in information processing, perception, and action.

- **Problem of Determining a HEP Value for the Field of Diagnosis**

It is precisely the quantification of human diagnosis abilities via the diagnosis model that one can clearly see that the indication of "genuine" human error probability is basically problematical. This is shown by the following consideration: People have the ability to learn and automate uniform stimulus response patterns (see Schneider & Shiffrin, 1977). Complex problems solution processes can also be automated (Rasmussen, 1986), so that, in the case of identical information stimuli, a diagnosis of the information no longer takes place; instead, there is an automatic reaction to the information pattern. This means that human information processing is a rather continuously occurring process (see Wickens, 1984). When it comes to quantification, it thus follows that the number of requirements, needed for genuine human error probability, can be determined neither theoretically nor empirically. Here are the main reasons: (1) The information processing procedures for a narrowly circumscribed diagnosis task of Type i are processed mentally in different ways and can thus be viewed from the angle of the operator not as a mental representation of Type i that can always be called up equally, as is required by the definition of HEP. (2) The number of mental requirements of diagnoses of Type i cannot be determined because the diagnosis itself is a rather continual processing procedure. HEP values in a diagnosis of Type i - that are based on the number of requirements of the diagnosis - thus, at best, have a theoretical value; but they do not correspond to the properties of the individual in terms of information processing.

- **Problem of Determining a HEP Value for the Field of Perception**

The same problem can also be observed in the field of perception. For purposes of illustration, let us take a calculation example where 10 errors were observed during the processing procedures and where a total of 1000 procedures had to be handled during the same timespan. Furthermore, in an idealized fashion, we assume that all 10 errors came about because a letter within the procedural step was misread (for example, turn on TH 999 instead of turn on TK 999) and all procedures are identical. One could thus think that all indications, required according to Equation 2, for the determination of a HEP value for errors during the processing of a HEP procedure are present and that a HEP value can be determined. But the individual is in a position to read, not letter by letter, but entire words, sentences, or even paragraphs in one processing step, as demonstrated by memory experiments and reading experiments (for instance, in Wickens, 1984). If one tries to determine a HEP value, then one finds that it depends on the definition of the task that one gives as reference magnitude. If one now assumes that each procedure contains 10 procedural steps, each procedural step contains 10 individual instructions, and each individual instruction contains 10 letters, then one gets the following HEP calculations for one and the same observation:

$$HEP_1 = \frac{Errors\ during\ processing\ of\ procedures}{Number\ of\ procedures\ to\ be\ processed} = \frac{10}{1000} = 1,0 * 10^{-2}$$

$$HEP_2 = \frac{Errors\ during\ processing\ of\ procedures}{Number\ of\ procedural\ steps\ to\ be\ processed} = \frac{10}{1000} = 1,0 * 10^{-3}$$

$$HEP_3 = \frac{Errors\ during\ processing\ of\ procedures}{Number\ of\ words\ to\ be\ processed} = \frac{10}{1000} = 1,0 * 10^{-4}$$

$$HEP_4 = \frac{Errors\ during\ processing\ of\ procedures}{Number\ of\ letters\ to\ be\ processed} = \frac{10}{1000} = 1,0 * 10^{-5}$$

We can thus say that a HEP value does not represent an unambiguous quantification of a human perception error. This applies even if all necessary information, that is required by the definition of HEP, is known. The level of what is assumed to be an action of Type i must be determined by the analyst with the help of estimates.

- **Example of Determination of a HEP Value for the Field of Actions**

The following thought experiment is intended to show clearly that no uniform HEP values can be determined also for action execution, strictly speaking: let us assume that one is given the narrowly outlined task of Type i="type A text." If one knows the number of typos and the number of all letters that were typed, then, according to the HEP definition, we would get the following HEP value for this task:

$$HEP = \frac{Number\ of\ typos}{Number\ of\ letters\ typed}$$

Experiments however have shown (among others, those by Rummelhart & Norman, 1982) that typos (letter reversals, word supplementations and reductions) are made with respect to sentences, words, or paths of the word. As a result, the central theorem of the probability calculation is violated because it presupposes that the possible states (letters that were typed) must be independent of each other. Strictly speaking, there would be any number of HEP values for this simple action (for example, one would get two HEP values for one typo, either error per letter type or error per syllables typed). The number of requirements here always depends on what is considered to be a unit of action. One may well say that no unambiguous human error probabilities can be given even for actions although all parameters may be present according to the definition of HEP.

- **Conclusion**

In summary, we may conclude that the definition of human error probabilities - looking at it from the viewpoint of ergonomics or psychology - is very problematical. To quantify any human performance (for example, perception, cognition, memory, action), one must consider the situational context so as to take into account human variability, flexibility, and creativity. This clearly shows something that was already touched on during the discussion of error definitions in Chapters 1 and 2: The individual cannot be described as a simple system component and therefore human errors, strictly speaking, cannot be described with the conventional HEP definition. Giving failure probabilities for any human performance is a big problem and that applies even when all indications according to the HEP definition are available. The main problem resides in the determination of the unit of action and the number of requirements of this unit of action. This problem is independent of the human reliability analysis method that was chosen. From this one may conclude that HEP values according to Equation 2, in the final analysis, do not constitute any meaningful measure for the quantification of human errors.

Conversely, one may conclude from this that - the HEP values obtained with the help of the normalized Rasch model - in case of a question as to their applicability, cannot be exposed to any greater criticism than values that correspond to the "conventional" HEP definition. To integrate human actions in probabilistic safety analysis studies however one must give probabilities for human error actions; therefore, the approach presented in this study - gaining estimated values for human error actions from practical operational experience - would appear to be a possible solution for this basic problem of HEP values. Probability statements are calculated, independently of the number of mental requirements, with the help of the method presented here. They are thus independent of the mechanisms of information processing that cause problems of practical application connected with conventional HEP definition.

5.6.2 Predictions on Human Reliability With the Help of a Situational Evaluation Approach

If one attempts a summary derived from all of the error types, performance-shaping factors, and error mechanisms covered in this chapter as well as from the possibilities of quantification, then the following becomes clear: the procedure chosen here for validation conversely can also be used as a situational evaluation approach to the evaluation of human reliability. The following reasons support that:

- The man-machine system, being a fundamental approach, is in a position to describe errors and performance-shaping factors both for a qualitative and a quantitative evaluation in a systematic manner. Here, the problem of evaluating human reliability is not reduced to a simple relationship between error and performance-shaping factor but instead one considers reciprocal interactions and situational conditions. It thus represents a context-related approach that considers ergonomic, organizational, and cognitive factors.

- The system ergonomics approach, connected with the approach of the man-machine system, can be used for prediction in connection with cognitive errors, in central distribution assumption, as well as in modeling approaches of the THERP method (for example, stress model).

- Occurrence probabilities can be calculated for the context-related approach by means of quantification using the normalized Rasch model.

With the help of the context-related evaluation of human actions, presented here, one can determine, for instance, HEP values for situations for which in the past there had been no evaluation indications. This includes, among others, data on the evaluation of non-full power states, accident management, or evaluation of cognitive errors. Errors of confusion were identified as essential cognitive error type; therefore, by way of example, we might give some values, among others, for errors of confusion:

• Errors of confusion, general	$p(25/165)=0.0099$
• Errors of confusion connected with maintenance tasks	$p(10/54)=0.0154$
• Errors of confusion when labeling is in effect	$p(2/7)=0.0558$
• Errors of confusion when clarity is in effect	$p(1/3)=0.0997$
• Errors of confusion when arrangement is in effect	$p(1/6)=0.0121$
• Errors of confusion when time pressure is in effect	$p(1/7)=0.0088$
• Faulty response to the occurrence of a latent error	$p(8/48)=0.0121$
• Faulty quality control in connection with maintenance activities	$p(4/54)=0.0036$
• Activities on several redundancies as error initiators	$p(5/116)=0.0023$

6 Concluding Discussion on the Results of This Study

In this study, we developed and applied a method for the analysis of events with view to the aspects of human reliability. Such a development was necessary because past methods for event analysis permit only simple analyses and evaluations whereas, on the other hand, the data from evaluation procedures so-called human reliability analysis methods, are inadequately or hardly validated. In this study, we were able to achieve the following results whose significance will now be discussed in conclusion:

1. A method for the systematic description and analysis of events with a view to human reliability (description model).

2. A method for the analysis of information from events with a view to qualitative and quantitative aspects of human reliability (analysis model).

3. The application of the method to 165 events taken from German power plants, resulting in the procurement of findings about some human error mechanisms (for example, for cognitive errors, and performance-shaping factors). It was also possible to verify quantitative data on human reliability (such as those of the technique for human rate prediction method).

- **Discussion of Description Model**

In contrast to past methods for event analysis, the process developed in this study is an analytical and not a classifying method. In the method, an event is systematically broken down, analyzed, and described for the purpose of a qualitative error and cause determination. The analysis method proceeds from general questions to substantive information that was observable during the event, and, via actions it moves on to error indications and performance-shaping factors. This object oriented procedure facilitates the analysis especially when initially only little information is available about the event. Although the method developed here also employs known taxonomies from literature for support during analysis, it is not tied to any fixed, predetermined descriptors; it is, in other words, an open procedure. In that way, the approach makes it possible to preserve also the original information of the events and makes the analysis of an event replicable in general. Besides, there is no compulsion to categorize an event in a certain classification scheme that might possibly not reproduce actually observed aspects correctly and that could thus lead to misinterpretations.

Another reason for choosing an open and analytical method had to do with the enormous complexity with which a human error is treated through different questions (such as, for example, evaluation of a human error analysis, event analysis, organizational aspects, cognitive aspects, safety engineering aspects, etc.). Beyond that, questions and performance-shaping factors are subject to change. Openness and flexibility are thus necessary in order to be able to depict all of these and future aspects equally. In this approach we specify only the generic element for the analysis of human errors or the question structure: the man-machine system.

On the whole, the description model thus is a general instruction for the evaluation and analysis of events because it asks all questions that are relevant for the evaluation of human reliability and because, due to a knowledge based system, which can be constantly expanded on the basis of new findings, it offers possible answers for selection (Appendix 1). The method thus is also a generally valid procedure for analyzing events and it can be transposed to other technical fields, among others, transportation, the processing industry/chemical industry, medical technology).

- **Results Concerning the Analysis Model**

By means of this kind of open description, the classification job however is also shifted from data input to data analysis. To analyze events, an analysis model was therefore developed of which can qualitatively and quantitatively analyze the information acquired via the description model. Within the collected events, the method makes it possible to determine frequencies of any concept combinations as well as interrelationships between various concepts. For this purpose, a connectionism algorithm was developed which offers a series of advantages with regard to approaches based on structure query language (see Chapter 4). By virtue of its network structure, the method is for instance in a position to establish fuzzy relationships between the information items and to depict similarities between different events. This can be used, first of all, in order to interrogate quantitative data for an evaluation of human reliability or to depict the interrelationships of different information items (performance-shaping factors or error types).

Within the field of research on artificial intelligence, this approach represents a connection between simple processing and associated systems. It can therefore be used for a large number of similarly-positioned analysis problems (for example, systems of experts for medical diagnosis, counseling systems for technical events or trouble, finances). The approach however is also in a position to imitate typical properties of human information processing (parallel and serial processing as well as explicit or conscious conclusions as compared to implicit or unconscious conclusions as compared to implicit or unconscious conclusions); it thus also offers a possibility of modeling human cognition within cognitive psychology.

- **Discussion of Results on Human Reliability**

By applying the analysis method to 165 events with human errors, it was possible to identify various performance-shaping factors and mechanisms involved in human error actions and to derive some possibilities for error avoidance. Furthermore, it was possible to investigate optimization measures in terms of their effectiveness and to confirm essential statements of probabilistic evaluation of human actions for the field of German nuclear power plants. This includes central distribution assumptions (standard logarithmic distribution, time-reliability distribution), data from the THERP catalog by Swain and Guttmann (1983) and data from French simulator studies (Mosneron-Dupin, 1993).

As for the qualitative analysis of events, it was possible to trace errors of confusion back to an interference effect of cognitive sub-skills. Also found in the system ergonomics approach according to Bubb (1992) was a possibility of modeling cognitive errors within a cognitive load and cope model. The cognitive errors, that could not be evaluated so far, here are important to modern technologies (for instance, computerized control rooms) because the share of cognitively loading activities for the operators there - and thus also the share of cognitive error actions - increases (Sträter et al., 1995). Two elementary cognitive processing modes were identified along with the interference effect: actions without dissonance lead mostly to qualitative errors; actions with conscious control lead mostly to errors in terms of time sequence. With the help of event analysis, it was possible to identify, from practical operational experience, also 30 performance-shaping factors that influence human reliability. They represent an expansion of the factors mentioned in the literature regarding the aspects that are important to human reliability within the technical system called "nuclear power plant."

Regarding probabilistic analysis of practical operational experience, we developed a model that facilitates an estimation of human error probabilities derived from practical operational experience. Using this model, we calculated occurrence probabilities on the basis of practical operational experience for 79 items in the technique for human rate prediction catalog and we compared them with the latter. On the whole, we found good agreement between predictions derived from practical operational experience and the data taken from the technique for human rate prediction. With the help of a more detailed analysis and wider use of the analysis method used here, one would expect that the uncertainties in the data of the technique for human rate prediction method can be estimated even better. Also, not all items of the technique for human rate prediction catalog could so far be validated.

The good agreement of the data from practical operational experience with the technique for human rate prediction method by Swain and Guttmann (1983) furthermore makes it possible to draw the opposite conclusion to the effect that the method presented here makes it possible to derive more accurate or more realistic estimated values for human error probabilities from practical operational experience or to gain indications on human reliability, on which Swain and Guttmann provided no statements. That includes, among others, data on the evaluation of non-full power states, on accident management, on the relevance of human errors in terms of safety, or on the evaluation of cognitive and organizational errors. The estimation process proposed here could be further improved if also the events - in which the individual intervened in the system in a faultless manner (labeled in this study as human factor relevant events) - were to be analyzed systematically and used for estimating quantitative data.

- **Concluding Considerations**

In general, we find in this study that a single concept on error avoidance and increasing the reliability of the individual will not suffice. Enhancing human reliability can only be an integral task. The human error here must be so analyzed that progress in findings about error mechanisms will become possible independently of the question of culpability and legal consequences because this question terminates a systematic causal analysis in that the (presumably) guilty person is found. On account of the multi-causal character of a human error, such a procedure is not appropriate for effective error avoidance and it does not prevent the occurrence of grave consequences. Here are essential aspects of an integral error analysis that were identified in this study:

- Ergonomic aspects regarding "conventional" factors of work environment and system ergonomics aspects;

- Consideration of properties of human information processing in the design of technical systems;

- Consideration of organizational aspects that influence the acting person.

The method developed here supplies meaningful information for all aspects because (1) it is not one-sidedly focused on one of these aspects and (2) it makes it possible to depict and analyze complex interrelationships. Looking at it in conclusion, the root of the system ergonomics approach, taken in this study, turns out to be a suitable method for analyzing and evaluating human errors in the most complete possible fashion and without any question as to any guilty person.

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Appendix

Appendix 1: Illustration of CAHR Databank System

Appendix 2: Taxonomies to Describe Human Actions and Errors

Appendix 3: Example of an Event Description With the Description Model

Appendix 4: Approaches to the Analysis Model from Artificial Intelligence

Appendix 5: Extract of Chapter 20 of the THERP Handbook

Appendix 6: Criteria for the Selection of Human Factor Cases, Inquiry Results of CAHR on the THERP Tables

Appendix 1: Illustration of CAHR Databank System[16]

The CAHR databank system is a tool for analyzing breakdowns that are caused by access of personnel or by organizational factors. Available for analysis is a generic knowledge base that is expanded independently by the events that are put in. The knowledge base contains data for the description of the system state, of the tasks, as well as the error possibilities and performance-shaping factors. Figure 1-1 shows the rough structure of the databank.

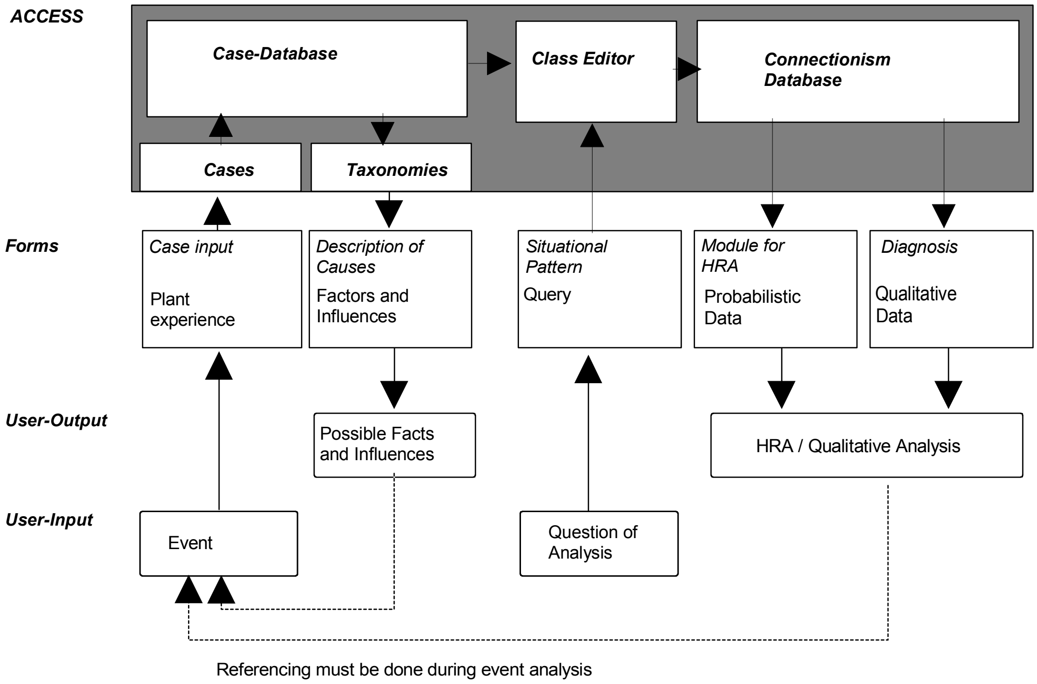

Figure 1-1 Structure of the CAHR System

- **Event Input**

Here we put in all relevant information on the event regarding general characteristics of the plant and of the system state (Figure 1-2). By simply clicking on the arrows, one can quickly enter all necessary characteristics of the procedure. The contents of characteristic input can also be expanded.

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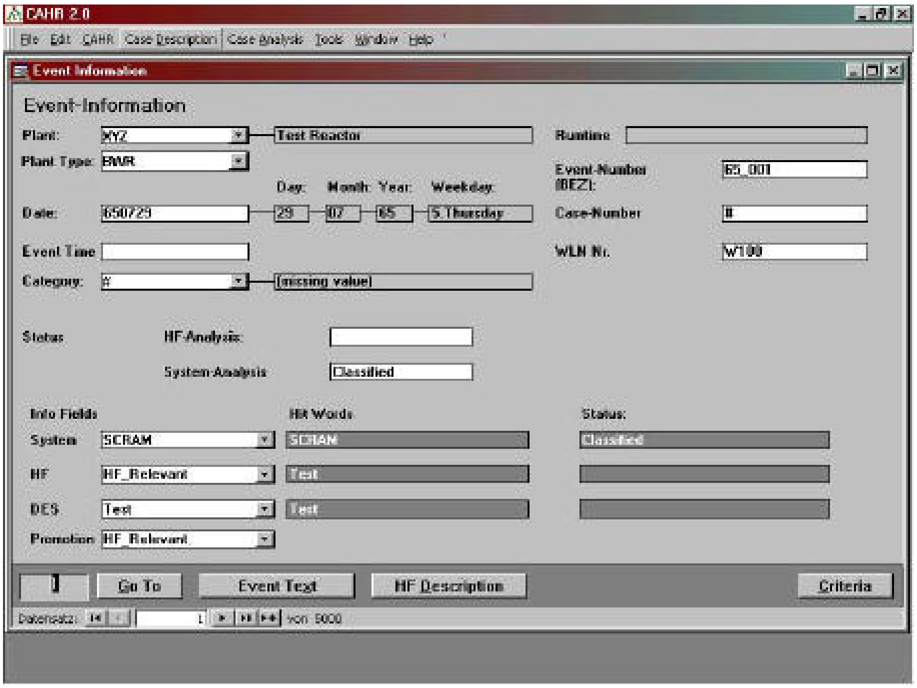
[16] on "www.lfe.mw.tum.de/forschung/mms/cahr" you can download a demonstration of CAHR.



Event-Information

Plant:	XYZ	Test Reactor	
Plant Type:	BWR		
Date:	650729	Day: 29, Month: 07, Year: 65, Weekday: 5 Thursday	
Event Time			
Category:	#	(missing value)	
Runtime			
Event-Number (BEZ):	65_001		
Case-Number	0		
WLN Nr.	W100		

Status HF-Analysis:

System-Analysis: Classified

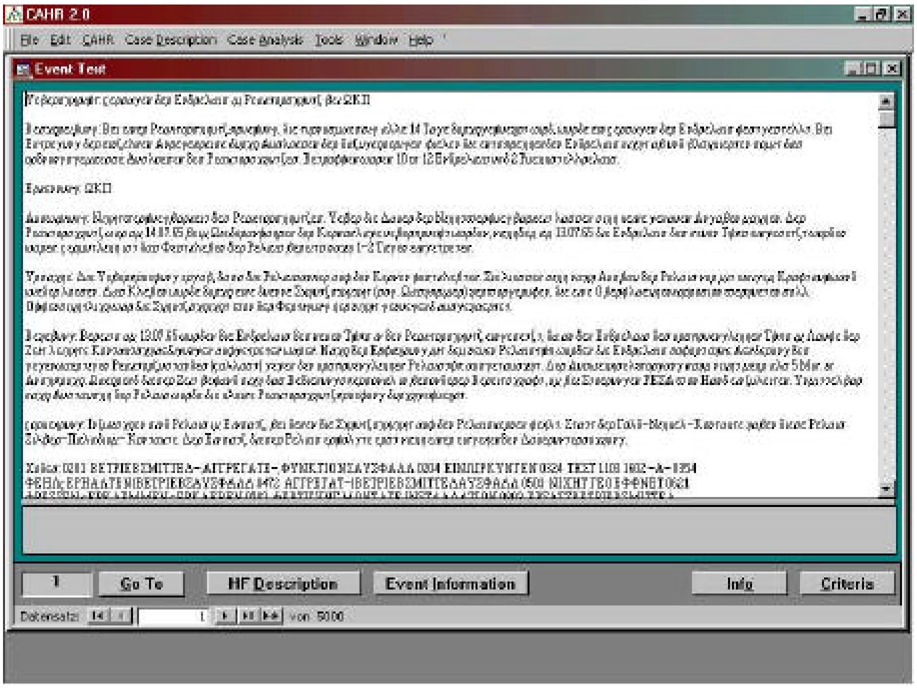
Info Fields		Hit Words	Status:
System	SCRAM	SCRAM	Classified
HF	HF_Relevant	Test	
DES	Test	Test	
Promotion	HF_Relevant		

Datensatz: 1 von 5000

Figure 1-2 Put in Characteristics into the Databank

- **Input of Event Descriptions**

The event descriptions are filed in a text field and a commentary field (Figure 1-3). The fields can be searched for certain concepts by means of full text search.

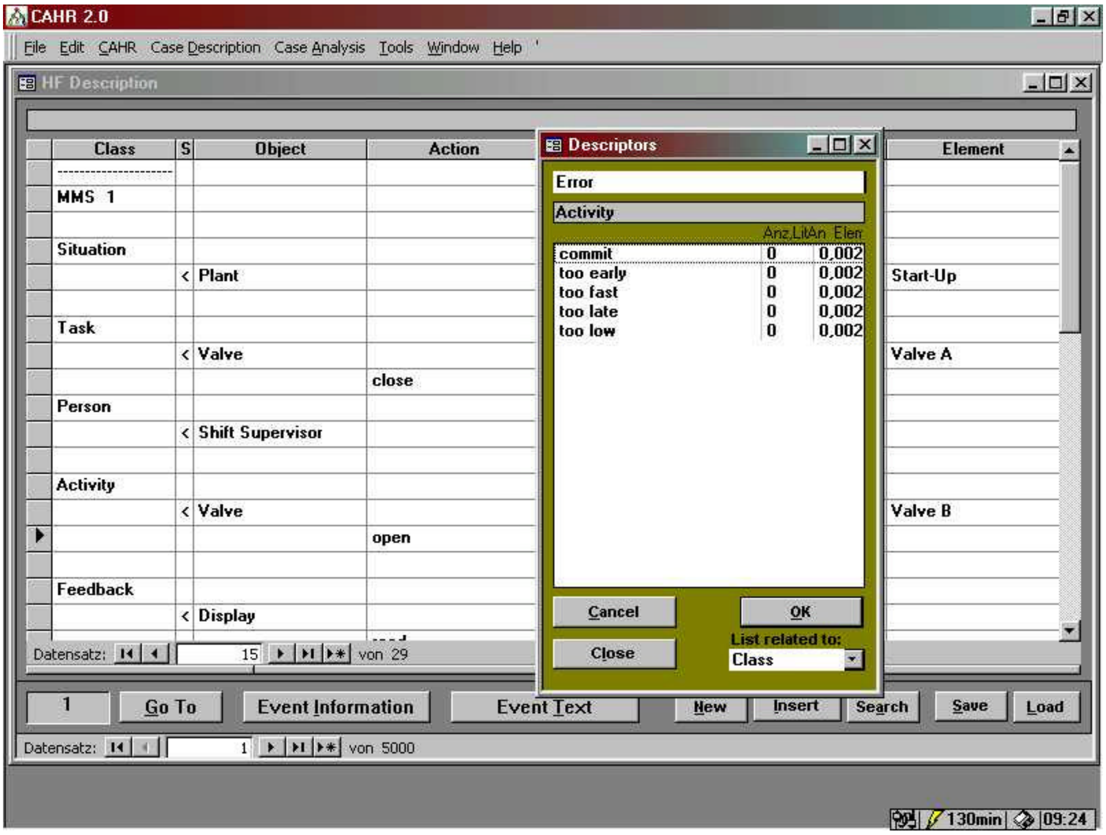


Datensatz: 1 von 5000

Figure 1-3 Event Description in the Databank

- **Input of Relevant Event Information**

All relevant information concerning human actions is put in interactively. Figure 1-4 by way of example shows the input into the databank for the sub-taxonomy object-person. In event analysis, one builds up the input of general questions on information items that were observable during the event (object, action) into error data and performance-shaping factors. This is done in an implicative way, that is to say, for example, one may enter only one error in the "indication" column if an object and an action have already been stated. The same applies to the performance-shaping factors in the column "property." In that way one can make sure that the effectiveness relationship between actions, errors, and performance-shaping factors will be illustrated so that it is determined what the performance-shaping factor acted on.



Class	S	Object	Action	Element

MMS 1				
Situation				
	<	Plant		Start-Up
Task				
	<	Valve		Valve A
			close	
Person				
	<	Shift Supervisor		
Activity				
	<	Valve		Valve B
			open	
Feedback				
	<	Display		

Datensatz: 15 von 29

Error

Activity

	Anz,LitAn	Elen
commit	0	0,002
too early	0	0,002
too fast	0	0,002
too late	0	0,002
too low	0	0,002

List related to: Class

1

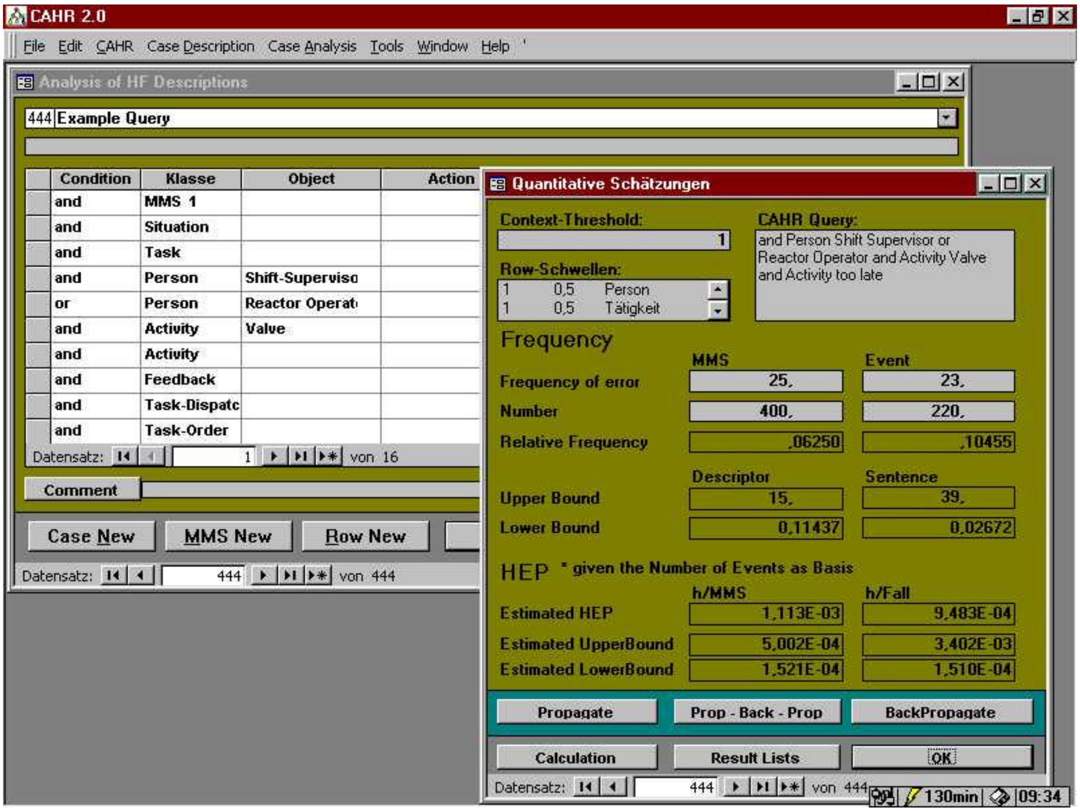
Datensatz: 1 von 5000

Figure 1-4 Input of Human Factor Information Into the Databank

This object oriented procedure facilitates the analysis of events because one starts with information that was observable on the technical system. In addition, it avoids allocation of culpability because the event is analyzed by starting with the error situation and not by starting with the persons who are involved. By offering decision making aids during concept selection to the person who wants to describe an event with the help of this procedure, the concepts are sorted according to frequency of use.

- **Analysis of Events**

The connectionism approach allows qualitative and quantitative analyses of data in a uniform model. In that way it becomes possible to supply both information for the evaluation of human reliability and for the optimization of the technical system in a uniform database. First of all, one can interrogate frequencies of interrelationships of any concepts within the data structure (for instance, relationships between errors and performance-shaping factors). Permissible logic tie-ins between concepts here are AND, OR, AND NOT, related to the various classes of the man-machine system and the various description stages (object, action, indication, property). With the help of the connectionism approach, one can implement all of these analysis possibilities on any degree of detailing of the event description (for individual concepts or general classes).



444 Example Query

Condition	Klasse	Object	Action
and	MMS 1		
and	Situation		
and	Task		
and	Person	Shift-Superviso	
or	Person	Reactor Operat	
and	Activity	Valve	
and	Activity		
and	Feedback		
and	Task-Dispatc		
and	Task-Order		

Datensatz: 1 von 16

Datensatz: 444 von 444

Context-Threshold: 1

Row-Schwellen:

1	0,5	Person
1	0,5	Tätigkeit

CAHR Query: and Person Shift Supervisor or Reactor Operator and Activity Valve and Activity too late

	MMS	Event
Frequency of error	25,	23,
Number	400,	220,
Relative Frequency	,06250	,10455
	Descriptor	**Sentence**
Upper Bound	15,	39,
Lower Bound	0,11437	0,02672

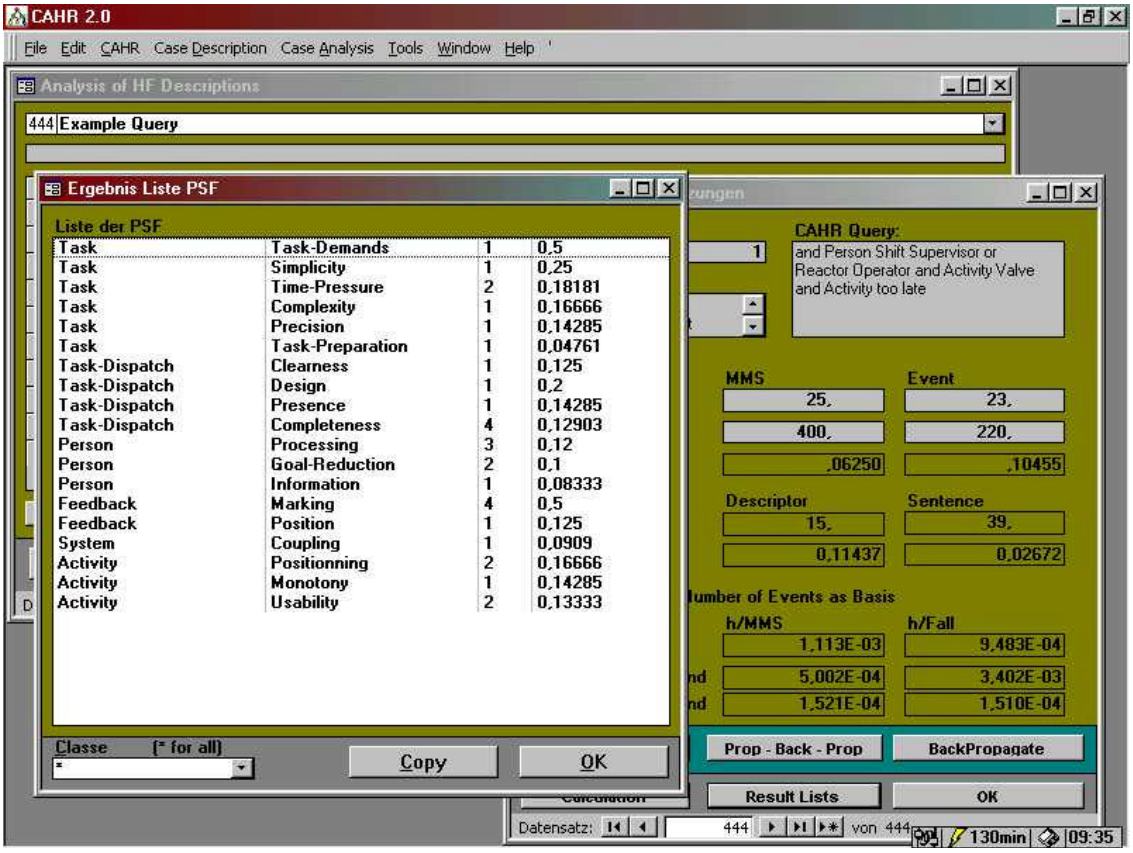
* given the Number of Events as Basis

	h/MMS	h/Fall
Estimated HEP	1,113E-03	9,483E-04
Estimated UpperBound	5,002E-04	3,402E-03
Estimated LowerBound	1,521E-04	1,510E-04

Datensatz: 444 von 444

Figure 1-5 Illustration of a Quantitative Inquiry in the Databank System

For each interrelationship, that was observed with a frequency of more than 0, one can determine qualitative interrelationships on the basis of all cases of available information observed so far. A typical inquiry to the collective data is for instance: "How many errors of confusion were observed, what performance-shaping factors were observed, and what precautions were initiated against repetition?" Figure 1-6 and Figure 1-7 show this inquiry within the databank. It is answered by the databank system with the help of various lists; information items gained can be traced back all the way to the individual cases.



444 Example Query

Liste der PSF

Task	Task-Demands	1	0,5
Task	Simplicity	1	0,25
Task	Time-Pressure	2	0,18181
Task	Complexity	1	0,16666
Task	Precision	1	0,14285
Task	Task-Preparation	1	0,04761
Task-Dispatch	Clearness	1	0,125
Task-Dispatch	Design	1	0,2
Task-Dispatch	Presence	1	0,14285
Task-Dispatch	Completeness	4	0,12903
Person	Processing	3	0,12
Person	Goal-Reduction	2	0,1
Person	Information	1	0,08333
Feedback	Marking	4	0,5
Feedback	Position	1	0,125
System	Coupling	1	0,0909
Activity	Positionning	2	0,16666
Activity	Monotony	1	0,14285
Activity	Usability	2	0,13333

Classe (* for all): *

CAHR Query: and Person Shift Supervisor or Reactor Operator and Activity Valve and Activity too late

MMS	Event
25,	23,
400,	220,
,06250	,10455

Descriptor	Sentence
15,	39,
0,11437	0,02672

Number of Events as Basis

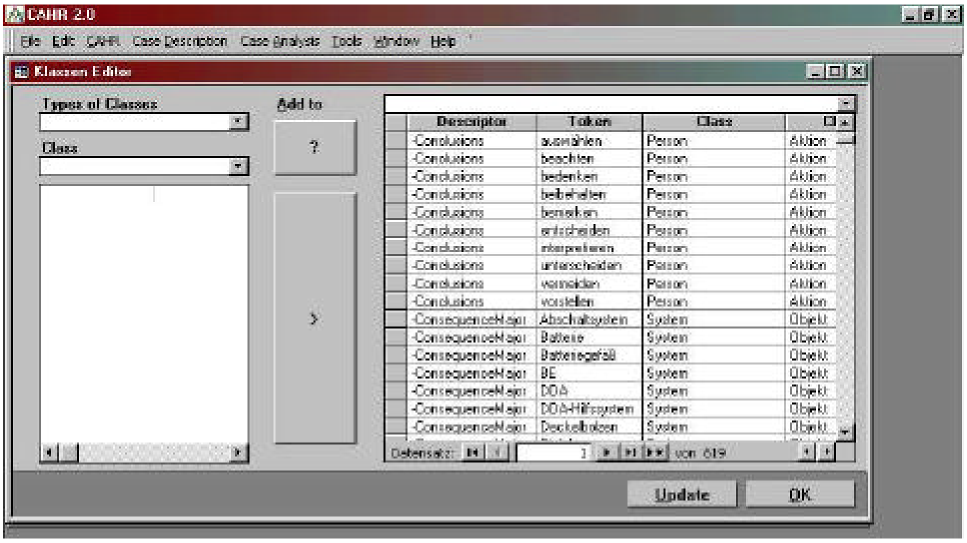
	h/MMS	h/Fall
	1,113E-03	9,483E-04
nd	5,002E-04	3,402E-03
nd	1,521E-04	1,510E-04

Datensatz: 444 von 444

Figure 1-6 Illustration of a Qualitative Inquiry in the Databank System

- **Class Editor**

New generic concept and sub-concept relationships for any concepts can be established by means of a class editor and can be used in the event analysis as if they had been mentioned themselves (Figure 1-7).



Descriptor	Token	Class	
-Conclusions	auswählen	Person	Aktion
-Conclusions	beachten	Person	Aktion
-Conclusions	bedenken	Person	Aktion
-Conclusions	beibehalten	Person	Aktion
-Conclusions	bemerken	Person	Aktion
-Conclusions	entscheiden	Person	Aktion
-Conclusions	interpretieren	Person	Aktion
-Conclusions	unterscheiden	Person	Aktion
-Conclusions	vermeiden	Person	Aktion
-Conclusions	vorstellen	Person	Aktion
-ConsequenceMajor	Abschaltsystem	System	Objekt
-ConsequenceMajor	Batterie	System	Objekt
-ConsequenceMajor	Batteriegefäß	System	Objekt
-ConsequenceMajor	BE	System	Objekt
-ConsequenceMajor	DDA	System	Objekt
-ConsequenceMajor	DDA-Hilfssystem	System	Objekt
-ConsequenceMajor	Deckelbolzen	System	Objekt

Figure 1-7 Illustration of Class Formation

- **Tables for Diagram Preparation**

Data can be processed in another way by inquiries and cross reference tables to illustrate simple interrelationships or reciprocal relations in the form or tables or diagrams. Inquiries are styled interactively and are stored. The data can be processed graphically in various ways. All possibility from the customary WINDOWS PRODUCTS are available to vary the graphic processing (for example, copy the graphs and tables in Text Processing or Table calculations).

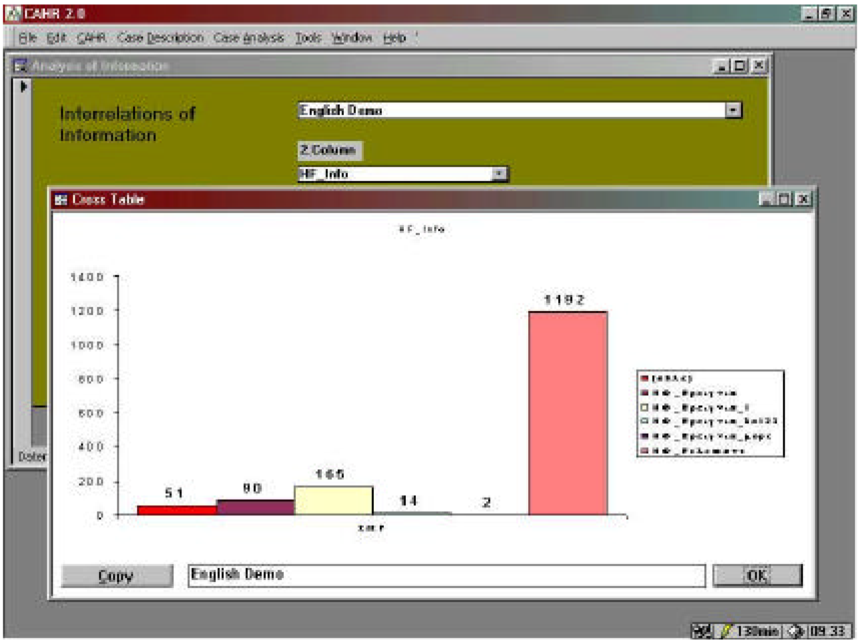


Figure 1-8 Analysis of Characteristics in the Databank System

Appendix 2: Taxonomies to Describe Human Actions and Errors

Below we are compiling different taxonomies to describe human factor events from the literature on the subject. They were used in the databank system, illustrated in Appendix 1, for analysis support and are subdivided accordingly over the various components of the man-machine system. The following sources were used for drawing up a total taxonomy to describe human errors:

- BuS Seifert and Brauser (1987)
- HRP Taxonomy of the Halden Reactor Project to design automatic procedures (see Handelsby et al., 1992)
- Fujita Fujita (1992)
- GLaw Design laws (for example, in Guski, 1989)
- HSYS Harbour and Hill (1991)
- S Seifert (1992)
- TAG/ Task Action Grammar, such as they are used, for example, in the GOMS model according to Kieras and Polson (1985)

A series of additional descriptor lists are being used by different operators and government agencies (for example, French Electric Power Company, use nuclear regulatory commission, Rhinish-Westphalian electric power utilities). They are not listed here explicitly but can be inserted in the predetermined structure of the man-machine system without problems and are used in the databank program. Regarding these descriptor lists, see also Wilpert et al. (1994).

Class	Object	Action	Property	Indication	Element	Source
Task			Number of stimuli	Too much	Stimuli per channel	HSYS
Task			Task requirement	Too high		HSYS
Task			Task organization		Task grouping	HSYS
Task			Task organization		Task placement	HSYS
Task			Task organization		Task sequence	HSYS
Task			Task assignment		Information	HSYS
Task			Task assignment		Precision	HSYS
Task			Type of event	Surprising		BuS
Task			Type of event	Overlapping		HSYS
Task			Type of event	Foreseeable		BuS
Feedback			Grouping		Function	HSYS
Feedback			Grouping		Frequency	HSYS
Feedback			Grouping		Sequence	HSYS
Feedback			Grouping		Importance	HSYS
Feedback			Grouping		Importance	HSYS
Task			Frequency	Accustomed		BuS
Task			Correctability	Possible		BuS
Task			Correctability	Not thought of		HSYS
Task			Correctability	Not used		HSYS
Task			Correctability	Not well solved		HSYS
Task			Correctability	Not anticipated		HSYS
Task			Correctability	Certainly possible		BuS
Task			Correctability	Impossible		BuS
Task			Risk factor	Moderate		BuS
Task			Risk factor	No risk		BuS
Task			Risk factor	Poor		BuS
Task		Select				BuS/TAG
Task		Decide				BuS
Task		Remind				BuS
Task		Recognize				BuS
Task		Identify				BuS
Task		Note				BuS
Task		Calculate				BuS
Task		Estimate				BuS
Task		Search				HSYS
Task		Transform				BuS
Task		Compare				BuS
Task		Select				BuS
Task		Move to goal				TAG
Task	Acceleration					BuS
Task	Size/value					BuS
Task	Force					BuS
Task	Menu					TAG
Task	Position					BuS
Task	Rate/ frequency					BuS
Order issue	Instruction				Control stand	HRP
Order issue			Remuneration structure		Quality	HSYS
Order issue			Remuneration structure		Quantity	HSYS
Order issue			Management activities			Fujita
Order issue			Hierarchy levels		Superiors/ subordinates Relationship	Fujita
Order issue			Instructions	Not as necessary		BuS

Class	Object	Action	Property	Indication	Element	Source
Order issue			Instructions	Inadequate		BuS
Order issue			Instructions	Present		BuS
Order issue			Communication			HSYS
Order issue			Coordination	Deficient		HSYS
Order issue			Management policy			HSYS
Order issue			Personnel		Conflict of relations	Fujita
Order issue			Personnel		Coordination	HSYS
Order issue			Personnel		Peer groups	HSYS
Order issue			Personnel		Peer status	HSYS
Order issue			Personnel		Overtime	HSYS
Order issue			Personnel		Makeup	Fujita
Order issue			Personnel		Cooperation	HSYS
Order issue			Personnel		Matching	HSYS
Order issue			Personnel selection		Selection criteria	HSYS
Order issue			Personnel selection		Degree of detailing	HSYS
Order issue			Personnel selection		Accuracy	HSYS
Order issue			Personnel selection		Information	HSYS
Order issue			Personnel selection		Number of qualified applicants	HSYS
Order issue			Personnel selection		Personal abilities	HSYS
Order issue			Personnel selection		Personal character	HSYS
Order issue			Personnel selection		Hiring	HSYS
Order issue			Personnel selection		Procedure	HSYS
Order issue			Personnel selection		Quality	HSYS
Order issue			Personnel selection		Completeness	HSYS
Order issue			Training			Fujita
Order issue			Training		Meaning of assignment to training	HSYS
Order issue			Training		Criteria for passing	HSYS
Order issue			Training		Formats	HSYS
Order issue			Training		Contents	HSYS
Order issue			Training		Instructions	HSYS
Order issue			Training		Criteria	HSYS
Order issue			Training		Possibility for training	HSYS
Order issue			Training		Motivation	HSYS
Order issue			Training		Simulator experience/practice	HSYS
Order issue			Training		Procedure	HSYS
Order issue			Training		Procedure	HSYS
Order issue			Training		Quantity	HSYS
Order issue			Training		Legal requirements	HSYS
Order issue			Training		Switching actions	HSYS
Order issue			Training		Test procedures	HSYS
Order issue			Training		Tests	HSYS
Order issue			Training		Training plant	HSYS
Order issue			Overtime	Too much		HSYS
Order issue	Shift plan					HSYS
Order issue	Regulations		Violation			HSYS
Order issue	Instruction				Terminate	HRP

Class	Object	Action	Property	Indication	Element	Source
Order issue	Instruction				Start	HRP
Order issue	Instruction				Check	HRP
Order issue	Instruction				Gosub	HRP
Order issue	Instruction				Go to	HRP
Order issue	Instruction				Manual action	HRP
Order issue	Instruction				Manual check	HRP
Order issue	Instruction				Monitor	HRP
Order issue	Instruction				Notice	HRP
Order issue	Instruction				Return	HRP
Order issue	Procedure				Attention-text	HSYS
Order issue	Procedure				Work instruction	S
Order issue	Procedure				Description	HRP
Order issue	Procedure				Operating guideline	S
Order issue	Procedure				Conditions	HSYS
Order issue	Procedure				Limitations	HSYS
Order issue	Procedure				Operating handbook	S
Order issue	Procedure				Operating document	S
Order issue	Procedure				Operating regulations	S
Order issue	Procedure				Checklist	S
Order issue	Procedure				Documentation aids	S
Order issue	Procedure				Decision-making logic	HSYS
Order issue	Procedure				Flow chart	HSYS
Order issue	Procedure				Free switch catalog	S
Order issue	Procedure				Graphics	HSYS
Order issue	Procedure				Action step reference	HSYS
Order issue	Procedure				Emphasis technique	HSYS
Order issue	Procedure				References	HSYS
Order issue	Procedure				Instruction	S/HRP
Order issue	Procedure				Punctuation	HSYS
Order issue	Procedure				Assembly instructions	S
Order issue	Procedure				Emergency handbook	S
Order issue	Procedure				Operating handbook	S
Order issue	Procedure				Planning documentation	S
Order issue	Procedure				Testing instructions	S
Order issue	Procedure				Testing regulations	S
Order issue	Procedure				Margin settings	HSYS
Order issue	Procedure				Margin visibility	HSYS
Order issue	Procedure				Step	HRP
Order issue	Procedure				work permission sheet	S
Order issue	Procedure				Spacing	HSYS
Order issue	Procedure				Symptom oriented	HSYS
Order issue	Procedure				Tables	HSYS
Order issue	Procedure				Typography	HSYS
Order issue	Procedure				Overview	HSYS
Order issue	Procedure				Vocabulary	HSYS
Order issue	Procedure				Warnings	HSYS
Order issue	Procedure				Attendants handbook	S
Order issue	Procedure		Break-off criteria	Inadequate	Recognizing procedure break-off	HSYS
Order issue	Procedure		Break-off criteria	Inadequate	Instructions for the next action	HSYS

Class	Object	Action	Property	Indication	Element	Source
Order issue	Procedure		Break-off criteria	Inadequate	Prerequisite not met	HSYS
Order issue	Procedure		Ability to find	Missing	Agreement among quantitative boundaries	HSYS
Order issue	Procedure		Calculations		Information input	HSYS
Order issue	Procedure		Calculations		Spacing/layout of aids	HSYS
Order issue	Procedure		Calculations		Technical guidelines	HSYS
Order issue	Procedure		Calculations		Validation and verification	HSYS
Order issue	Procedure		Calculations			HSYS
Order issue	Procedure		Identifiability			HSYS
Order issue	Procedure		Relationship to practice			HSYS
Order issue	Procedure		Check automatic actions			HSYS
Order issue	Procedure		Check conditions			HSYS
Order issue	Procedure		Check immediate action			HSYS
Person				Poor		HSYS
Person				Inadequate		HSYS
Person			Action options	Unknown		HSYS
Person			Attention			HSYS
Person			Attention		Speed	HSYS
Person			Attention	Average		BuS
Person			Attention	Very little		BuS
Person			Attention	Very high		BuS
Person			Attention	Overloaded		HSYS
Person			Experience	Average		BuS
Person			Experience	Very little		BuS
Person			Experience	Very high		BuS
Person			Fatigue			HSYS
Person			Ability		Procedure	HSYS
Person			Processing		Figurative similarity	GLaw
Person			Processing		Helplessness	Fujita
Person			Processing		Information focusing/ tunnel effect	Fujita
Person			Processing		Intellect	Fujita
Person			Processing		Tendency toward good shape	GLaw
Person			Processing		Understand	HSYS
Person			Processing		Perception speed	HSYS
Person			Processing		Timely meeting	GLaw
Person			Processing		Goal conflicts	HSYS
Person			Compatibility		Task to activity	HSYS
Person			Performance prerequisite		Age	Fujita
Person			Performance prerequisite		Experience	Fujita
Person			Performance prerequisite		Fatigue	HSYS
Person			Performance prerequisite		Ability	HSYS
Person			Performance prerequisite		Individual capacity	HSYS
Person			Performance prerequisite		Boredom	HSYS

Class	Object	Action	Property	Indication	Element	Source
Person			Performance prerequisite	Inadequate	Performance orientedness	Fujita
Person			Performance prerequisite	Missing	Availability of resources	HSYS
Person			Performance prerequisite		Knowledge	HSYS
Person			Motivation			HSYS
Person			Motivation	Rejecting		BuS
Person			Motivation	High		BuS
Person			Motivation	Moderate		BuS
Person			Personality		Alcohol/Drugs	HSYS
Person			Personality		Anxieties	Fujita
Person			Personality		Depression	Fujita
Person			Personality		Ambition	Fujita
Person			Personality		Sickness	HSYS
Person			Personality		Opportunism	Fujita
Person			Personality		Personal background	Fujita
Person			Personality		Physical qualities	Fujita
Person			Stress			Fujita
Person			Stress		Work related	HSYS
Person			Stress		Work environment	HSYS
Person			Stress		Task related	HSYS
Person			Stress		Task overload	HSYS
Person			Stress		Perceived	Fujita
Person			Stress		Person related one	HSYS
Person			Understanding		Person inadequate	HSYS
Person			Understanding		Procedure poor	HSYS
Person			Understanding		Steps unknown	HSYS
Person			Understanding		Understanding of steps and procedures	HSYS
Person			Knowing		Required knowledge	HSYS
Person			Knowing		Individual capacity	HSYS
Person			Knowing		Personnel selection	HSYS
Person			Knowing		Personnel training	HSYS
Person			Knowing		About action consequences	HSYS
Person			Knowing		About action options	HSYS
Person			Knowing		About correctness of procedure	HSYS
Person			Knowing	Inadequate	About input signal/cue	HSYS
Person			Knowing	Inadequate	About search area	HSYS
Person			Knowing	Inadequate	About search area	HSYS
Person			Knowing	Inadequate	About alternate explanations	HSYS
Person			Knowing	Inadequate	About criteria	HSYS
Person			Knowing	Inadequate	About priorities	HSYS
Person			Goal conflicts			HSYS
Feedback; activity			Situation	Unfavorable		HSYS
Feedback; activity			User friendly		Design	HSYS
Feedback; activity			Quantity	Too much		HSYS

Class	Object	Action	Property	Indication	Element	Source
Feedback; activity			Quantity	Too little		HSYS
Feedback; activity			Availability		Work resource status	HSYS
Feedback; activity			Availability		Information status	HSYS
Feedback; activity			Availability		Capital status	HSYS
Feedback; activity			Availability		Personnel status	HSYS
Feedback; activity			Availability		Time state	HSYS
Feedback; activity			Maintainability			HSYS
Feedback					Numerical sequence	BuS
Feedback					Number	BuS
Feedback				Missing		HSYS
Feedback			Commensurateness			HSYS
Feedback			Display/Control Integration		Control/feedback ratio	HSYS
Feedback			Display/Control Integration		Layout of console	HSYS
Feedback			Display/Control Integration		Grouping	HSYS
Feedback			Display/Control Integration		Compatibility/ consistency	HSYS
Feedback			Unambiguousness		Display resolution poor	HSYS
Feedback			Unambiguousness		Display poor	HSYS
Feedback			Unambiguousness		Signal intensity too weak	HSYS
Feedback			Recognizability	Not possible		HSYS
Feedback			Recognizability	Poor	Meaning of input	HSYS
Feedback			Recognizability	Too low	Knowledge about alternatives	HSYS
Feedback			Recognizability			HSYS
Feedback			Coloration			BuS
Feedback			Malfunction			HSYS
Feedback			Layout		Delimitations	HSYS
Feedback			Layout		User definition	HSYS
Feedback			Layout		Coloration/shading	HSYS
Feedback			Layout		Label/coding	HSYS
Feedback			Layout		Human physical limitation	HSYS
Feedback			Layout		Population stereotypes	HSYS
Feedback			Layout		Control desk contents	HSYS
Feedback			Layout		Spacing	HSYS
Feedback			Layout		Control stand layout	HSYS
Feedback			Reference stimuli		Auditory	HSYS
Feedback			Reference stimuli		Kinesthetic	HSYS
Feedback			Reference stimuli		Tactile	HSYS
Feedback			Reference stimuli		Visual	HSYS
Feedback			Identifiability			HSYS
Feedback			Presentation	Inadequate		BuS
Feedback			Presentation	Very little		BuS
Feedback			Presentation	Disturbing		BuS
Feedback			Presentation	Inadequate		HSYS
Feedback			Input output frequency	Too low		HSYS

Class	Object	Action	Property	Indication	Element	Source
Feedback			Characterization		Quality of printout	HSYS
Feedback			Characterization		Legibility	HSYS
Feedback			Characterization		Scaling	HSYS
Feedback			Consequences	Not acceptable		HSYS
Feedback			Number of stimuli	too high		HSYS
Feedback			Sensor/display cue	Missing		HSYS
Feedback			Differentiability			HSYS
Feedback			Process engineering behavior			HSYS
Feedback			Foreseeability	Inadequate		HSYS
Feedback			Time behavior		Input/output frequency too low	HSYS
Feedback			Time behavior		Access speed	HSYS
Feedback			Access speed	Too slow		HSYS
Feedback			Reliability			HSYS/Fujita
Feedback		Here				BuS
Feedback		Read				BuS
Feedback		Perceive				BuS
Feedback	Display				Bar indication	S
Feedback	Display				Digital indication	S
Feedback	Display				Circle arc indication	S
Feedback	Display				Lamp	S
Feedback	Display				Lamp field	S
Feedback	Display				Loud speaker	BuS
Feedback	Display				LCD field	S
Feedback	Display				LED field	S
Feedback	Display				Signal flag	BuS
Feedback	Display				Needle instrument	BuS
Feedback	Display screen				Menu	BuS
Feedback	Display screen				Multifunctional	BuS
Feedback	Display screen				Optical	BuS
Feedback	Display/control		Separability			HSYS
Feedback	Reporter				Noise	BuS
Feedback	Reporter				Ear phones	BuS
Feedback	Reporter				Sound	BuS
Feedback	Reporter				Sound sequence/melody	BuS
Feedback	Reporter				Switch field	BuS
Feedback	Control desk				Switch position	BuS
Feedback	Control desk					HSYS
Feedback	Control desk		Boundary lines			HSYS
Feedback	Control desk		Displays of division			HSYS
Feedback	Control desk		Recognizability	Poor		HSYS
Feedback	Control desk		Coloration			HSYS
Feedback	Control desk		Identifiability			HSYS
Feedback	Control desk		Spacing			HSYS
Feedback	Control desk		Separability			HSYS
Situation	Control desk		Time budget	Barely sufficient		BuS
Situation			Time budget	With reserve		BuS
Situation			Time budget	Too little		HSYS
Situation			Time budget	Too short		BuS
Situation	Time indication				Action selection	HSYS

Class	Object	Action	Property	Indication	Element	Source
Situation	Phase				Action planning	HSYS
Situation	Phase				Recognition	HSYS
Situation	Phase				Understanding	HSYS
Situation	Phase				More than 6 hours	BuS
Situation	Phase				Around 4 hours	BuS
Situation	Phase				Less than 2 hours	BuS
System			Reliability	Little		BuS
System			Reliability	High		BuS
Activity				Inappropriate		HSYS
Activity			Function			HSYS
Activity			Quality			HSYS
Activity			Support			HSYS
Activity			Presence	Missing		HSYS
Activity			Presence	Not found		HSYS
Activity			Presence	Not purchased		HSYS
Activity			Access			HSYS
Activity		Activate				BuS
Activity		Type in				BuS
Activity		Sense				BuS
Activity		Go to				BuS
Activity		Look to				BuS
Activity		Copy				TAG
Activity		Erase				TAG
Activity		Adjust				BuS
Activity		Write				BuS
Activity		See				BuS
Activity		Speak				BuS
Activity		Feel				BuS
Activity		Control				BuS
Activity		Search				BuS
Activity		Type				TAG
Activity		Rename				TAG
Activity		Draw				BuS
Activity		Show				TAG
Activity	Unit	Move				TAG
Activity	Button	Click				TAG
Activity	Data file					TAG
Activity	Desktop					TAG
Activity	Rotary switch					BuS
Activity	Level					BuS
Activity	Lever switch					BuS
Activity	Joystick					BuS
Activity	Button					BuS
Activity	Crank					BuS
Activity	Light pointer					BuS
Activity	Mouse					BuS
Activity	Microphone					BuS
Activity	File folder					TAG
Activity	File folder					TAG
Activity	Wastebasket					TAG
Activity	Pedal					BuS
Activity	Poti				Rotary poti	BuS
Activity	Poti				Linear	BuS
Activity	Wheel					BuS
Activity	Writing style					BuS
Activity	Button field				Simple	BuS
Activity	Button field				Multifunctional	BuS
Environment					Corridors	HSYS
Environment					Stairs	HSYS

Class	Object	Action	Property	Indication	Element	Source
Environment			Anthropometrics			HSYS
Environment			Work resource	Poor		HSYS
Environment			Workplace layout	Inadequate		HSYS
Environment			Work station layout	Inadequate		HSYS
Environment			Work environment			HSYS
Environment			Equipment	Missing		HSYS
Environment			Equipment	Does not work		HSYS
Environment			Equipment	Cannot be found		HSYS
Environment			Equipment	Not available		HSYS
Environment			Quantity of equipment	Not adequate		HSYS
Environment			Illumination		Display screen	HSYS
Environment			Illumination	Not commensurate		BuS
Environment			Illumination	Normal		BuS
Environment			Illumination	Very poor		BuS
Environment			Acceleration	Barely tolerable		BuS
Environment			Acceleration	Moderate		BuS
Environment			Acceleration	Intolerable		BuS
Environment			Acceleration	Low		BuS
Environment			Mobility			HSYS
Environment			Biomechanical design			HSYS
Environment			Poor design strictness			HSYS
Environment			Distractors		Other persons	HSYS
Environment			Distractors		Work environment	HSYS
Environment			Distractors		Scope	Fujita
Environment			Distractors		Design	HSYS
Environment			Distractors		Visual	HSYS
Environment			Distractors		Auditory	HSYS
Environment			Attainability	Impossible		HSYS
Environment			External threat	Little		BuS
Environment			External threat	No		BuS
Environment			External threat	Very strong		BuS
Environment			External threat	Strong		BuS
Environment			Danger of explosion	Dangerous		HSYS
Environment			Climate factors	Not commensurate		BuS
Environment			Climate factors	Normal		BuS
Environment			Climate factors	Very poor		BuS
Environment			Contamination	Bearable		BuS
Environment			Contamination	None		BuS
Environment			Contamination	Noticeable		BuS
Environment			Contamination	Intolerable		BuS
Environment			Noise			HSYS
Environment			Noise	Bearable		BuS
Environment			Noise	Strong		BuS
Environment			Noise	Noticeable		BuS
Environment			Performance support			HSYS
Environment			Air humidity			HSYS
Environment			Air flow/ventilation			HSYS
Environment			Physical factors		Illumination	HSYS

Class	Object	Action	Property	Indication	Element	Source
Environment			Physical factors		Hazard conditions	HSYS
Environment			Physical factors		Noise	HSYS
Environment			Physical factors		Temperature/air humidity	HSYS
Environment			Protected devices			HSYS
Environment			Vibrations	Noticeable		BuS
Environment			Vibrations	Not noticeable		BuS
Environment			Vibrations	Very dangerous		BuS
Environment			Vibrations	Disturbing		BuS
Environment			Safety/danger of accident	Dangerous		BuS
Environment			Safety/danger of accident	Great		BuS
Environment			Safety/danger of accident	Moderate		BuS
Environment			Safety/danger of accident	Inadequate		BuS
Environment			Safety systems			HSYS
Environment			Supports	Poor		HSYS
Environment			Accessibility		Entrance	HSYS
Environment			Accessibility		Attainability	HSYS
Environment			Accessibility		Grouping	HSYS
Environment	Operators room					HSYS

Appendix 3: Example of an Event Description With the Description Model[17]

As an example, we might take a typical event from a technical plant where a series of ergonomic, cognitive, and organizational shortcomings were identified. In our example, a drain valve was unintentionally left open and the following course of events and the end was based on the fact that this open drain valve was not recognized and that, as a result, the mixture of two chemicals (A and B) became critical. Rather than illustrate the entire plant, Figure 3-1 shows only a basic diagram of the technical systems to clarify the event. The circuitry of the drain valve is considerably more complicated and covered in the process as a whole.

In the technical system, two chemicals A and B are to react with each other in a tank. Medium A is hot, Medium B is cold. The higher the temperature or the greater the concentration of Medium B, the greater will be the chemical reaction in the tank. If there is between Medium B and Medium A is greater than 2, double concentration of B as against A, then a bonding medium C is fed in so as to prevent an over-reaction. But, as a result, the product and the tank is useless.

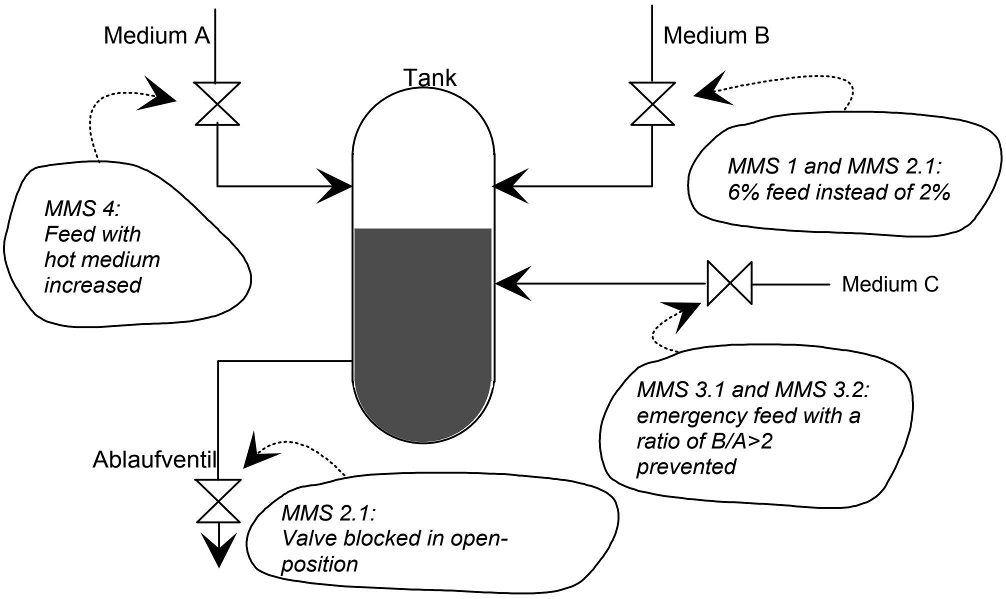


Figure 3-1 Basic Diagram of Technical Systems that Were Important in the Event

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[17] Meanwhile, another example of using the CAHR-method for event analysis is published in Reer et al. (1999). There, the Davis-Besse event was analyzed.

Figure 3-1 shows the technical and human errors in italics: in the course of the event, first of all prior to the performance of a test A, it was overlooked that Medium B was being fed into the reaction tank at 6% instead of 2%. During the performance of the test, the drain valve was inadvertently left opened. As a reaction to the disturbed state, automatic emergency feed of Medium C to bond the chemicals was prevented and instead hot Medium A was added, as a result of which, quite unintentionally, an overreaction was almost triggered (due to temperature rise). This gives us a course of the event as illustrated in Figure 3-2.

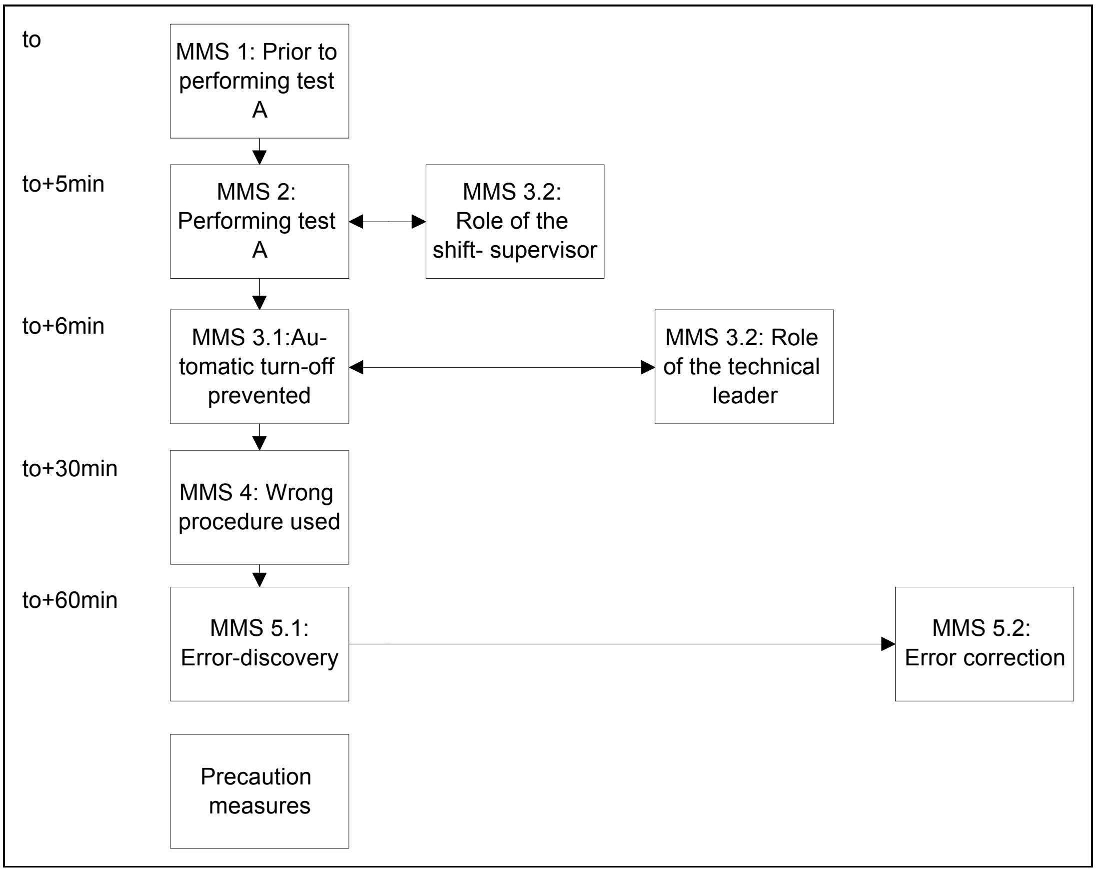

Figure 3-2 Course of Event

In the following, we will describe the man-machine systems and, in conclusion, the precautions taken for the entire event for each step of the course of the event. The table 3-1 basically should be read like a written text. Each man-machine system represents a separate section. Each line, that starts with the symbol"<", is a new sentence that describes the event with relation to the man-machine system component labeled by the symbol on the left or in the upper left-hand corner, i.e. like a structured bullet list.

Table 3-1 Example for an Event Description

Class	Sen	Object	Verb	Indication	Property	Element
Prior to Performance of Test A						
MMS 1		Type AO				
		Tasks	Monitive			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	One			
		Compatibility	Internal			
		Control	Static			
Situation	<	Time indication				t0
	<	Time indication				Shortly before shift change
	<	System	Turned off			Since several months
	<	Management	Orders			Test performed on a valve
	<	Process magnitude				to 6%
						Test demands 2%
Task	<	Test				Preliminary test
						Results
		Results	Wait			
				Omit	Time pressure	
	<	Test	Carry out			Follow-up test
			Test			Preconditions
				Faulty	Time Pressure	
Person	<	Control room personnel				Novice
			Think	Omit		Meaning of preliminary test
					Information	Knowledge about meaning of preliminary test
					Goal reduction	Test to be completed prior to shift change
Activity	<	Follow-up test	Started	Too early		
Feedback	<	Process magnitude				Is at 6%
						Not at 2%
			Identify	Omit		
					+Marking	+2% and 6% not differentiated
					Reliability?	Display unreliable?
			Take out?	Not possible?		By means of other displays with this process magnitude?
Order dispatch	<					
Order issue	<	Instruction	Follow	Time Pressure		
					Completeness	Incomplete illustration of preconditions/validity criteria
					Design layout	No unhook positions
Environment	<	Control room				
System	<	Process medium				B
						Concentration
		Concentration	is	Too high		Possibility of unintentional reactions

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Performance of Test A						
MMS 2.1		Type A				
		Tasks	Active			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	One			
		Compatibility	External			
		Control	Static			
Situation	<	Time indication				t0+5 min
Task	<	Valve				Drain valve
			Open			
		Pump				Feed pump
			Test			Functional effectiveness
	<	Valve				External valve
			Close	Faulty		
					Time-Pressure	
Person	<	Test personnel	Think			That valve can lock
				Omit		
					Processing	Expectation that valve is closed
Activity	<	Valve				External valve
			Closed	too little		
					Position-ability	Inadequate
Feedback	<	Valve				Signal
		Signal				In control room
			Identify			That only 50% closed
				Not possible		
					Display accuracy	Position indication
					Display accuracy	Represents only open or closed state
					Display accuracy	No signal means open
					Reliability	Was repaired recently
					Reliability	Caused problems several times in the past
Order dispatch	<	Control room personnel	Inform			About completion of work
Order issue	<	Instruction	Follow			
Environment	<	On site				
System	<	Valve				External valve
			Block	Wrong		In 50% open position
			Open	Wrong		
	<	Process medium				A and B
						Temperature
			Leak	Wrong		
		Temperature	Up	Wrong		

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Role of Shift Leader						
MMS 2.2		Type C				Degrading
		Task	Monitive			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	One			
		Compatibility	Internal			
		Control	Static			
Situation	<	Time indication				t0+5 min
Task	<					
Person	<	Shift leader	Note			That process magnitude B is too high
	<	Process magnitude	Recognized			That process magnitude B is at 6% instead of 2%
				Too late		Already super critical concentration
Activity						
Feedback	<					
Order dispatch	<	Operator	Inform	Too late		Process magnitude B to be reduced
Order issue	<					
Environment	<	Control room				
System	<	Process medium				A and B
						Temperature
			Leak	Wrong		
		Temperature	Up	Wrong		

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Automated Shot-Down Prevented						
MMS 3.1		Type O				Degrading
		Task	Monitive			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	Several			
		Compatibility	Internal			
		Control	Dynamic			
Situation	<	Time indication				t0+6min
Task	<	Shut down				Automatic shut-down
						would render product unusable
			Wait	Omit		
					Task preparation	Primary goal is production and not safety oriented shut-down
					Time Pressure	High
Person	<	Shift personnel	Thought	Wrong		Having situation under control because a reason for faulty course of test was found (process magnitude 6% instead of 2%)
					Goal reduction	Save chemical product
					Processing	Confidence in own diagnosis (temperature rise because process magnitude B too high)
					Information	Reason found checks with learned measures
Activity	<	Shut down				Automatic shut-down
			Prevented	Wrong		
Feedback	<					
Order dispatch	<	Technical chief	Inform			About problem
						By phone
Order issue						
Environment	<	Control room				
System	<	Process medium				A and B
						Temperature
			Leaked	Wrong		
		Temperature	Rose	Wrong		

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Role of Technical Chief						
MMS 3.2		Type C				Degrading
		Task	Active			
		Operation	Simultaneous			
		Presentation	Compensation			
		Dimension	Several			
		Compatibility	Internal			
		Control	Static			
Situation	<	Time indication				t0+6min
Task	<	Control room	Goal	Omit		
					Complexity	Was busy with other tasks
					Task preparation	Had been transferred to other department and was no longer responsible
Person	<	Technical chief				
			Thought	Wrong		That shift personnel could handle it by themselves
					Goal reduction	To subjectively more important tasks
Activity	<					
Feedback	<					
Order dispatch	<	Shift personnel	Proposed			Look for reason for temperature rise
			Offered	Wrong		That he is coming to the control room
			Informed	Goal		That he has other things to do
					Responsibility?	Not defined?
					Responsibility?	Deputy not provided for?
Order issue	<					
Environment	<	In his office				
System	<	Process medium				A and B
						Temperature
			Leaked	Wrong		
		Temperature	Rose	Wrong		

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Wrong Procedure Used						
MMS 4		Type C				Degrading
		Task	Monitive			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	Several			
		Compatibility	Internal			
		Control	Dynamic			
Situation	<	Time indication				t0+30min
Task	<	Technical chief				Arrive
		Arrive	Wait	Omit		
					Time pressure	
Person	<	Shift leader	Think	Omit		That process magnitude at 6%
					Goal reduction?	No better solution available?
					Information?	Missing about meaning of deviation (6% instead of 2%)
Activity	<	Valve				Additional feed valve
			Open	Wrong		
Feedback	<					
Order dispatch	<					
Order issue	<	Instruction				Event-oriented diagnosis instruction
			Follow	Omit		
					Availability?	Two-time consuming?
					Design layout?	Too complicated to use?
					Completeness?	Criteria of application not defined?
	<	Instruction				Shut-down procedure for normal conditions
			Followed	Wrong		
Environment	<	Control room				
System	<	Process medium				A
						Hot medium
			Fed	Wrong		
	<	Process medium				A and B
						Temperature
		Temperature	Risen	Wrong		Even more intensely than before

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Discovery of Error						
MMS 5.1		Type C				Degrading
		Task	Active			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	Several			
		Compatibility	Internal			
		Control	Static			
Situation	<	Time indication				t0+60min
Task	<					
Person	<	Shift leader	Search			For other possibilities that might account for the error because the system state has still not improved.
			Find			Solution due to imbalance between feed and evacuation
			Ignored	Wrong		Alarm
					Goal reduction?	Because he had found a solution?
Activity	<					
Feedback	<	Imbalance				Between feed and evacuation
			Recognized			
			Recognized			
Order dispatch	<	Technical chief	Inform	Omit		
		Operator	Instructed			To test the position of the drain valve, and possibly to close it
Order issue		Instruction				Event-oriented diagnosis instruction
Environment	<	Control room				
System	<	Process medium				A and B
						Temperature
		Temperature	Risen	Wrong		

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Error Correction						
MMS 5.2		Type C				Improving
		Task	Active			
		Operation	Sequential			
		Presentation	Sequence			
		Dimension	One			
		Compatibility	Internal			
		Control	Static			
Situation	<	Time indication				t0+60min
Task	<	Valve				Position
		Position	Test			
					Time pressure	
Person	<	Operator				
Activity	<	Valve				Drain valve
			Closed			
Feedback	<					
Order dispatch	<	Shift leader	Inform			That the valve was open and was closed
						Telephone
Order issue	<					
Environment	<	On site				
System	<	Process magnitude	Normalized			

Table 3-1 (cont)

Class	Sen	Object	Verb	Indication	Property	Element
Precautions						
Precaution	<	Personnel	Train			Not to prevent emergency feeds
	<	Personnel	Train			To master complex situations
	<	Control room	Improve			Sound alarm
	<	Instruction	Improve			Check preconditions for a test

Appendix 4: Approaches to the Analysis Model from Artificial Intelligence

The following methods are discussed in literature available on artificial intelligence in an effort to solve problems arising during the development of a model for the analysis of event descriptions:

- Expert-Systems,
- Fuzzy-sets,
- Probabilistic networks,
- Neuronal and connectionism networks.

These methods - all of which have different performance characteristics regarding the coding and retrieval of information - will in the following be investigated in terms of points of approach that can be used for a method to analyze information from the description model.

A.4.1. Systems of Experts

- **Introduction**

The goal of expert-systems is to summarize and process available knowledge about a particular condition or situation, called domain, in such a way that they can be employed by potential users in solving a problem (see Zimolong & Rohrmann, 1988). This means that this technology can be used to make available the knowledge - that is contained in the events - for the purpose of making a judgment concerning human reliability. Figure 4-1 illustrates the structure of a system of experts.

Expert-systems are frequently differentiated according to whether the knowledge base is constructed on the foundation of observed cases or on the foundation of generally valid knowledge. The former are referred to as case-base system and the latter are described as rule-based system (in terms of "fixed rules").

Rule-based and case-based systems of experts can be differentiated essentially regarding the method used in formulating the basis of knowledge and formulating the mechanism of inference. In the rule-based design, one formulates both the knowledge base and the inference mechanism by means of rules. In the object-oriented design, the basis of knowledge and the mechanism of inference are formulated via generic concept/subgenera concept structures (for example, Heuer, 1992).

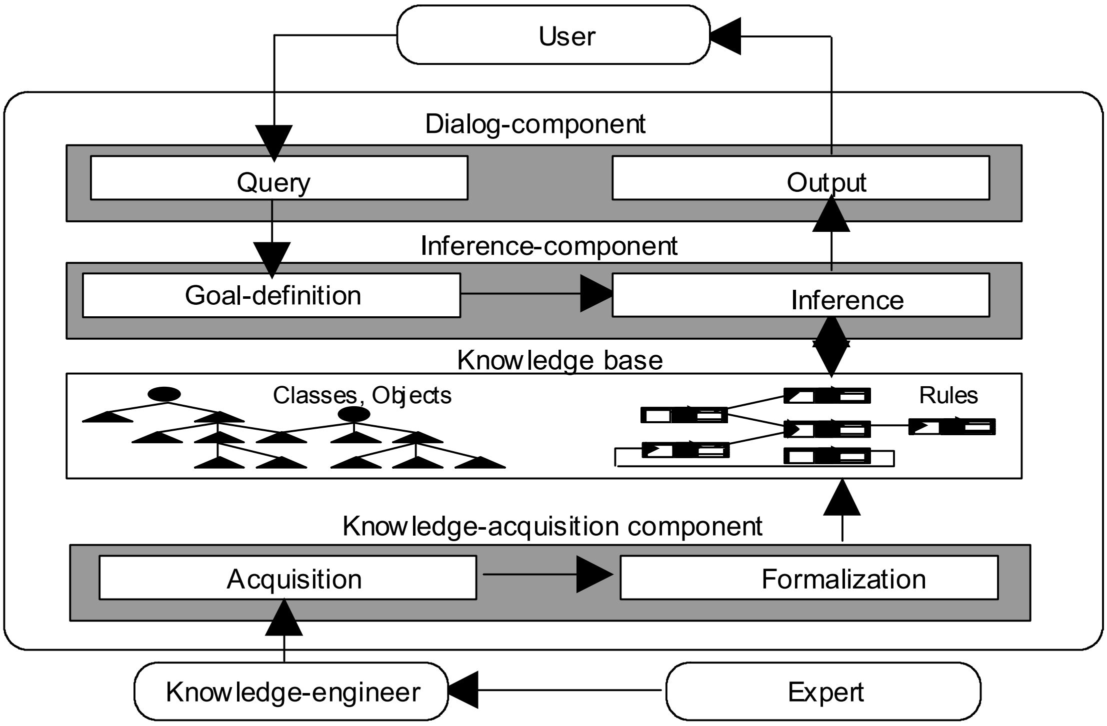

Figure 4-1 Principal construction of an expert system

- **Rule-based design**

In rule-based design, knowledge is organized into more or less abstractly formulated rules. The basis of knowledge is represented as a network of rules, and the inferences of the inference components are drawn by means of available rules. Consequently, a rule in association with the network of rules of the basis of knowledge permits the following inference, for example:

IF [object] = 'Ford Taunus'
THEN [object] = 'Ford Taunus' belongs to the [class] = 'automobile'
THEN [object] = 'Ford Taunus" has [property] = 'four wheels'

Rules generally consist of a left side antecedent, also called Left Hand Side (conditio), a right side hypothesis and a right side action part, or also called Right Hand Side (conclusio)

(Figure 4-2). Several conditions can be presented in the antecedent and be logically connected (usual operators are AND, OR AND NOT). Rules of inference indicate with which priority the rule is to be processed. A fixed value can be assigned to the categories of inference, but they can also be dynamically confirmed. The hypothesis is then always given the value assignment „is true“ or „is not true“ if the conditions are fulfilled, or not fulfilled. A further possibility of indicating the correctness of hypotheses consists in allocating them probability values in the event that the conditions are met (for example, in MYCIN, Shortliffe, 1976). If the hypothesis is true (or within a certain interval of confidence), objects or characteristics of objects can be assigned values in the action part.

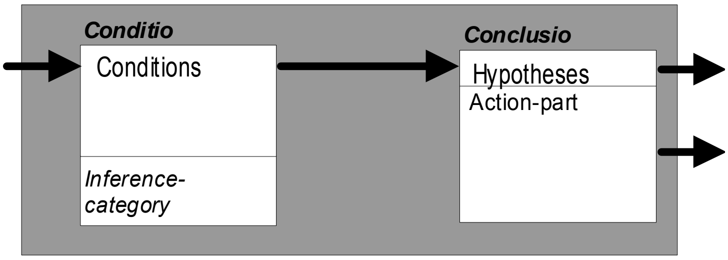

Figure 4-2 General structure of a rule in experiment systems

If hypotheses of established rules are indicated in the antecedent of a rule, then a network of rules arises. Figure 4-3 illustrates such a network of rules. Simple chains are here connections of only two rules. This is represented by the arrow a) in the Figure. Multiple chains are several rules which lead to a hypothesis. In the figure, this is represented by the arrow b) and c); they form an OR gate. In this case, the rules of inference establish the sequence in which the rules which comprise the OR gate are to be processed. If categorically b is numerically greater than category c, then first Rule 4 and then Rule 5 is processed.

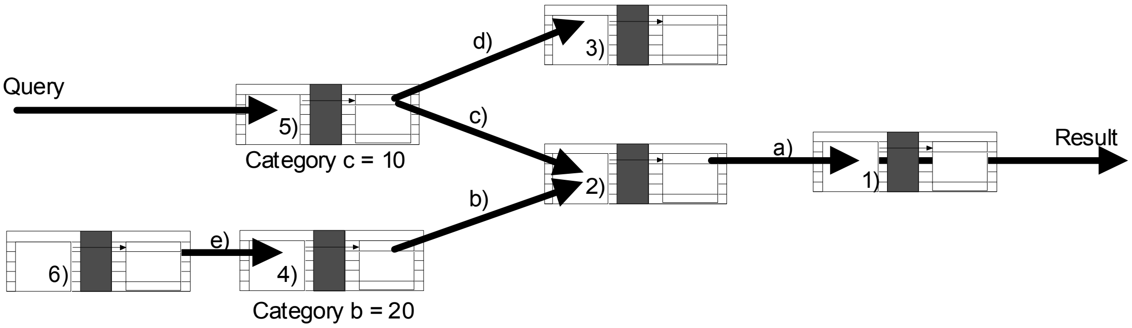

Figure 4-3 Possible connections of rules in expert systems

In processing a network of rules, **exhaustive inference** means that all rules of an OR gate are processed, whereas with non-exhaustive searching, the processing of the OR gate is interrupted already when a hypothesis proves correct. The remaining hypotheses are no longer processed (NEXPERT, 1990).

It is furthermore distinguished whether rules are processed depth first or breadth first. In the figure, depth first search means that, for example, with processing of rule 2, rule 4 and rule 6 are processed first, and only then rule 5. With a breadth first search, rule 4 is processed first and then rule 5, since both form an OR gate.

- **Object-oriented design**

With object-oriented design, knowledge is represented in that concepts or objects are embedded in categories or classes. Classes and objects can once again possess features which are attributed to them as properties (also called attributes). Classes serve to group different objects with common features. Formation of a class is in other words appropriate whenever several objects have the same properties. Classes, objects and features or properties are designated as concepts or entities in this context (cf. also Mandl & Spada, 1988; Harmon & King, 1986).

To be able to draw conclusions (inferences) looking at the object oriented design, one needs certain conventions according to which the attributes are ascribed to different objects. They are: inheritance, polymorphism, and encapsulation (see among others also Gerike, 1991; Heuer, 1992). Inheritance means that a class or also an object may pass on the attributes belonging to it to subordinate classes or objects. Polymorphism refers to the possibility of assigning an object to several classes. Encapsulation means that an attribute passed onto an object may take on a specific configuration which applies only to that object. Encapsulation in other words is necessary if a class has passed an attribute onto an object and if this object takes up the inherited attributed with a value that is applicable only to it. The process of value placement is called instantiation.

A typical network, that is in a position to draw an inference via inheritance is shown by way of example in Figure 4-4.

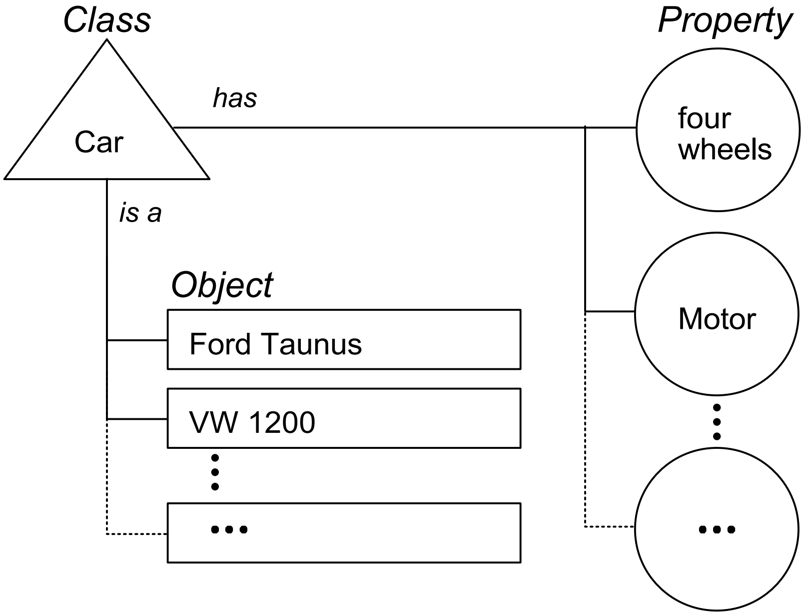

Figure 4-4 A Simple Object Network

The attributes, shown in the figure, are assigned to a class called "car". The class can pass or inherit these [attributes] to subordinate objects. This means that the example shown in the figure permits the following inferences:

[Class] = `Car' has [attribute] = `four wheels'
[Object] = `Ford Taunus' belongs to [class] = `Car'
¾> *[Object] = `Ford Taunus' has [attribute] = `four wheels'*

In this example, polymorphism means that the term for `motor' can be assigned both to the object "Ford Taunus' [sic] or to the object `VW 1200.' In other words, valid associations are as follows:

[Object]$_1$*.Motor = `Ford Taunus'.Motor*
[Object]$_2$*.Motor = `VW 1200'.Motor*

In this case, encapsulation is required when both objects take up one attribute with different values. For example, the following applies:

[Object]$_1$*.Motor = `Ford Taunus'.Motor = `Engine with in-line cylinders'*
[Object]$_2$*.Motor = `VW 1200'.Motor = `Opposed cylinder engine'*

In complex hierarchies, one differentiates in the object oriented design (as in the rule base design) between search in-depth and search in-breadth. In the depth search, one inherits attributes in the concept hierarchy, branch by branch, down to the lowest stage; in breadth search, the attributes are first of all passed on to heredity to all objects of a hierarchy stage before one continues on a lower hierarchy stage. Exhaustive search here also means that all objects of the hierarchy are processed. Priorities concerning processing can also be given in object oriented design by specifying that the objects get priority weights.

- **Discussion Relating to the Analysis Model**

In terms of graph theory, expert-systems try - regardless of whether they proceed with rule-based or object oriented - to reduce the search by means of directed graphs (see also, among others, Schefe, 1987). In both cases, the search space consists of nodes (entities or conditions and the conclusions part) and relations (connections between entities or rules). This means that both design approaches are identical in terms of the formal content because a rule can be formulated adjusted well as a relation between two entities, the way a relation can be formulated between entities as rule. The knowledge basis and the inference mechanism of a system of experts can thus be built up equally in a rule-based manner (for example, with Petri networks) or in an object oriented manner (for example, with semantic networks) (see also Bonato, 1990). For instance, the relations (edges) between objects of an object hierarchy can always be construed as simple rules having the following form:

[Class] = `Car'-g-> [Attribute] = `four wheels'
corresponds to
IF [Class] = `Car' THEN [Attribute] = `four wheels'

[Class] = `Car'-g-> [Object] = `Ford Taunus'
corresponds to
IF [Class] = `Car' THEN [Object] = `Ford Taunus'

The difference between the two procedures resides in the fact that object oriented design makes it possible to establish a relation between two objects although this relation is not explicitly present but rather is formed only by the process of inheritance. This relation can be determined only while the inference process is in progress; therefore this behavior is described as a dynamic bond. For the above example, this relationship looks like this:

[Object] = `Ford Taunus'-g-> [Attribute] = `four wheels'

This is not possible in this form in the rule based design. There, every relationship must be stated explicitly. Here, the association of an object is performed by processing a rule:

IF `Ford Taunus' THEN `four wheels'
IF `VW 1200' THEN `four wheels'
etc.

Knowledge is imaged implicitly in rules within the rule based design. If an attribute changes, then all rules must be investigated to determine the extent to which this attribute is contained in the rule. If, for instance, all cars would suddenly get three wheels, then each rule for each car would have to be revised.

Object oriented design is closer to the graph theory illustration and turns out to be a more concentrated and clearly observable form of representation when compared to rule based formulations. This clear overview offers the advantage that expansions in the knowledge base can be achieved in the object oriented design by widening the object hierarchy. Knowledge is thus represented as being explicitly accessible here.

The class of `car,' as taken from the above examples, for instance, can be formed by observation of two cases and by determining the common features of the entities observed there and need not be determined a priori, in other words, it need not have to be specified prior to observation of the cases:

Case 1: [Object] = `Ford Taunus' has [attribute] = `four wheels'
Case 2: [Object] = `VW 1200' has [attribute] = `four wheels'
=> [Object] is identical with respect to [attribute] = `four wheels'
=> [Object] is labeled as [Class] = `Car'

In addition, it is also possible to associate an observed Case 1 directly with an already existing class:

[Class] = `Car' has [attribute] = `four wheels'
Case 1: [Object] = `VW 1200' has [attribute] = `four wheels'
=> [Object] = `VW 1200' corresponds to [Class] = `Car'
with regard to [attribute] = `four wheels'
[Object] = `VW 1200' belongs to [Class] = `Car'

The circumstance that, in the case of the object oriented design, there are conclusion (inferences) due to assignment of attributes to classes, results in better coding of knowledge and easier expendability of the knowledge base because here one need change only one attribute of a class instead of having to search all rules as to whether they must be expanded by this new attribute.

By means of an exhausting search within an object hierarchy, it becomes possible to compare patterns of different objects in that one specifies an object A with an attribute X and looks for the pertinent class for which this object/attribute constellation applies. Once this class has been found and if another object B belongs to the same class, then both objects (A and B) are similar with respect to this attribute X. Such inferences cannot be drawn in the rule based design. Summarizing, one thus gets the following conclusions:

1. Rule based design is suitable only when the existing data material is highly standardized and when it can be summarized in a few fixed rules. If that is not the case (as in most practical applications), then one gets a combinatory explosion of the rules that must be contained in the knowledge basis. This combination oriented explosion is also referred to as relation-problem. In the worst case, each combination of relations would have to be formulated as a rule and we would thus require the following number of rules:

   $$\binom{\binom{n}{k}}{l} \tag{4-1}$$

   where
   n *Number of individual facts that are to be combined*
   k *Number of conditions that are to be formed from the individual facts*
   l *Number of conditions that are used in one rule*

   Rule based design has a series of additional inadequacies that render this design useless for the analysis of practical operational experience: As noted earlier, rules represent knowledge implicitly. As a result, one often encounters the problem of insufficient flexibility because a knowledge base that changes often or grows cannot be expanded by newly formulating a few rules. In most cases, many and, at worst, all rules must be adapted to the new conditions. The inference mechanism must also be constantly adapted so that all newly established rules will be considered during the processing procedure (see also Schult, 1992).

This is why the technology of rule based systems of experts so far has yielded only practical applications for narrowly limited areas of knowledge. Typical practical applications were prepared among others in medical diagnosis or narrowly limited disease pictures (for example, MYCIN; Shortliffe, 1976). An analysis of complex problems (for example, a general system for medical diagnosis of differentiated disease pictures) could not be put together with these means for the reasons given. They are thus also unsuitable for the analysis of events because they, too, have a high degree of variability and complexity and simply cannot cope with rule based design.

2. The object oriented design offers the advantage that there is no effort in terms of rule formation. This is why it is superior to the rule based design.

   The information gathered can be used in the object oriented design in a more flexible manner and is the case with the rule based design because access to the collected data is possible via class formation. Within a base of knowledge one can thus draw conclusions to the effect that objects with identical attributes are combined to form classes. In the rule based design, on the other hand, the similarity between two objects must be formulated explicitly in a rule. Exceptions are hybrid systems that permit object oriented and rule oriented procedures (for instance, NEXPERT, 1990).

Overall, an object oriented design for the analysis of practical operational experience is to be preferred because the events involve a knowledge base that keeps changing or growing. Furthermore, the events derived from practical operational experience involves case based data. In terms of the technology of system of experts, this means that a case based system is to be preferred over the object oriented design when it comes to analyzing the data of the description model.

Within the expert system technology of course there is no suitable method for gaining, from an object network, quantitative information about the individual cases (events), such as this is required to analyze the events with a view to human reliability. Fuzzy-sets seem to be suitable for this purpose.

A.4.2 Fuzzy-Sets

- **Introduction**

The Fuzzy-sets setup offers the possibility of interrelating generic concept and sub-concept structure and obtaining quantitative data from this relationship of semantic concepts. This attribute makes the Fuzzy-Set very interesting when it comes to the analysis of practical operational experience because, in this way, one can obtain both qualitative (in other words, semantic) and quantitative data from the collective events. The Fuzzy-Set theory is described comprehensively in Zimmermann (1990).

Practical applications of the Fuzzy-Set theory are mainly known from the control of technical and physical processes (among others, Pedrycz, 1989; Altrock, 1991; Abel, 1991). For example, the subway in Tokyo is run without conductor by means of a Fuzzy-Set control (see Preuss, 1992). To associate semantic concepts with quantitative magnitudes, the Fuzzy-Set approach uses, as central assumption, the so-called membership function.

- **Membership Function**

The way a membership function works in Fuzzy-Set theory can be illustrated in the simplest way with the help of the subway case, as explained by the following little example: each membership function needs an underlying dimension X (for example, stopping area), that is present in several configurations i (for instance, too far, good, too close). In this case, the intensity, in other words, the measure of membership of underlying dimensions can be determined by the weighting value $\mu_i(x)$.

Figure 4-5 shows a simple membership function $\mu_i(x)$ that may apply to this situation (the determination of the membership function will be discussed below). The parameter x here represents the stopping area that is given at the subway station in the form of centimeters or meters. The three different possible configurations i of the dimension called stopping area are subdivided into "too close" (i=1), "good" (i=2), and "too far" (i=3). The shaded areas of the membership function represent overlap areas of the various configurations.

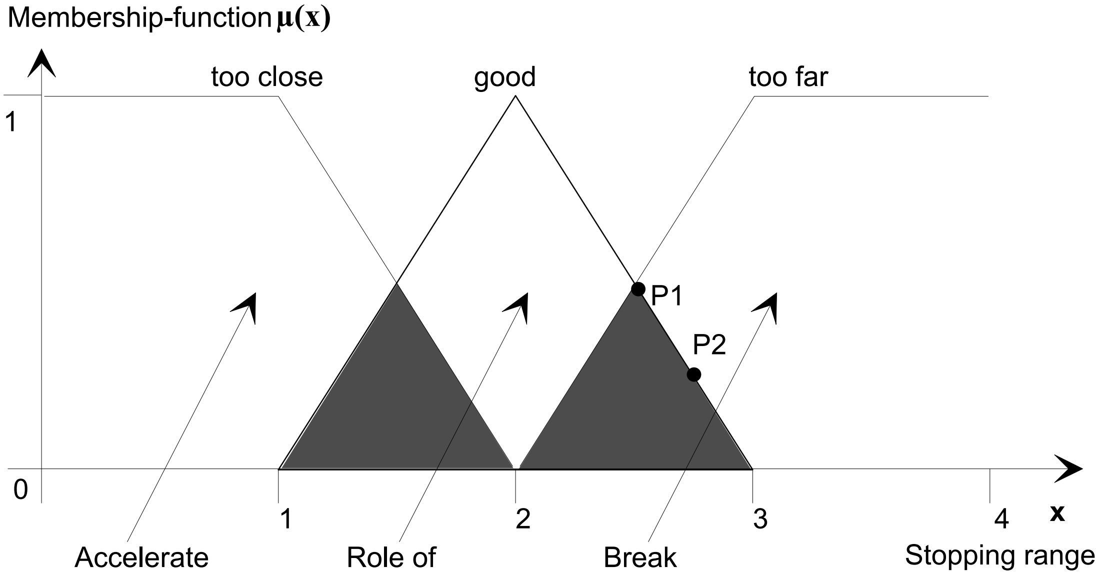

Figure 4-5 A Simple Membership Function to Determine the Stopping Area of a Subway

If now the current position x is measured by a signal detector, then a fuzzy set control does not proceed in such a way that, for instance, braking is done as a position x=1, so that the subway will come to a halt precisely at Point x=2, as is the case with conventional controls. A Fuzzy-Set control regulates the braking force on the basis of the membership function and in the process exploits the circumstance that it is immaterial whether the subway comes to a halt at x=1 or at x=3. The current values x on the dimension called stopping area are given to determine the braking force. If the current value is within the area "accelerate," then the Fuzzy-Set control - with a certain force, that depends on $\mu_1(x)$ - provides for an acceleration. If the current value lies in the area called "roll-out," then no force whatsoever is mustered (neither for acceleration, nor for deceleration). If the current value is in the area "brake," then the Fuzzy control brakes with a certain force that again depends on $\mu_3(x)$.

The actual output of the Fuzzy-Set control resides in areas in which it is clear whether one should accelerate, roll-out, or brake. Function values of the membership functions $\mu_i(x)$ are accounted with each other by the overlapping configurations in these overlap areas. In the figure, one must brake more forcefully for instance at Point P2 and then at Point P1. Usually, the functional values of the two membership functions are accounted for by forming a mean value, in other words, for Point 2, we average the portion of membership for the configuration "break" $\mu_{\text{too far}}(P2)$ with membership for the configuration "roll-out" μ_{good} (P2); more on the different calculation method can be found in Zimmermann (1990).

If one looks at the process of mean value formation over different time stages t, then one can clearly see wherein lies the advantage of Fuzzy-Set control. The required value of a Fuzzy-Set control at point in time t+1 is calculated by the mean value of the actual value and the required value at point in time t. This means that the distribution of the required values over that span of time takes on an exponentially decreasing curve of half values. The required value approaches the actual stopping point in an asymptotic manner. This is why Fuzzy-Set controls brake considerably "softer" than it is possible by means of conventional controls.

A membership function $\mu_i(x)$ however cannot be considered only as distribution function; it also represents a measure with which an attribute belongs to a certain class. If one interprets the membership functions as probability distributions, then, in the example, Point P2 can be classified both as "good" (with probability μ_{good} (x) = 0.25) and as "too far" (with probability $\mu_{\text{too far}}(x)=0.75$). Accordingly, one can depict a Fuzzy-Set connection also as a network (see Zimmermann, 1990). This was done in Figure 4-6 for the above membership function. Membership in a class (deceleration or acceleration) is expressed by the activation of the relations that spring from an attribute. The attribute again gets activation by means of the actual value x that are being put in.

As the figure shows clearly, one can model a combined frequency of two configurations (in other words, the cut or the overlap area of two membership functions) by having a superordinate node take care of activations of both configurations.

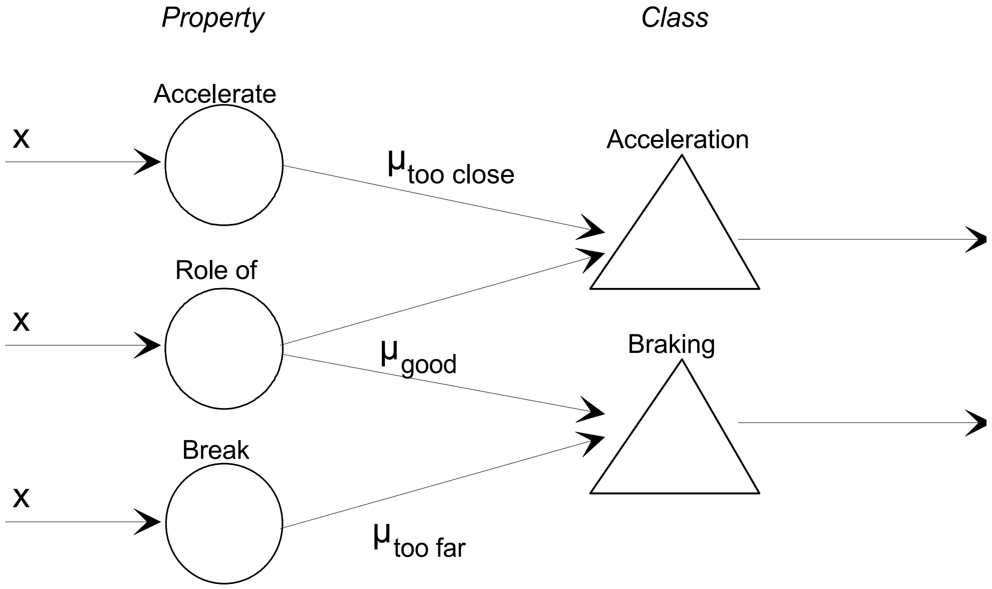

Figure 4-6 Illustration of a Membership Function as Network

Generalizing, one can model the cut of n configurations by having a node take care of activations of all n configurations. The current value of a node results then by calculation of input signals, something which, for instance, can be done according to the following equation:

$$h\left([Class]_j\right) = \frac{\sum_{i=1}^{n}\left(f\left(g_{ij}\right) * m[Property]_i\right)}{n} \tag{4-2}$$

where:

n *Number of all relations included in the class*

$$f\left(g_{ij}\right)\begin{cases} o & if\left([Property]_i - g_{ij} \rightarrow [Class]_j \leq 0\right) \\ 1 & if\left([Property]_i - g_{ij} \rightarrow [Class]_j > 0\right) \end{cases}$$

Compared to rule oriented or object oriented systems, the Fuzzy-Set theory thus of course does not solve the relations problem touched on above because the number of required relations to form all possible combinations of inquiries is not reduced. But because only certain relations were observed, there is a possibility of getting around this problem in that the relations are assigned certain weights. If, in a given inquiry (x), the weight of the relation $g_{ij}=0$ then attribute i does not make any contribution via the relation $Property_i - g_{ij} \rightarrow Class_j$.

The decisive problem connected with the Fuzzy-Set approach is the determination of the membership function that correctly calculates the frequencies for the classes at a given value x. The problem is more difficult to solve when, for combination of parameters, one must give correct frequencies with the help of the membership function. As shown in the above example, the membership function supplies frequencies in that, at a given value x, the shares of different function values $\mu_i(x)$ are figured with each other. This procedure works very nicely for the regulation of unidimensional physical magnitudes. But application to multidimensional magnitudes become a problem and that also goes for application to the analysis of events because they, as was emphasized already in Chapter 1, are always conditioned in a multifactorial manner.

This problem - of applying the Fuzzy-Set theory to multidimensional magnitudes - can be explained in the simplest fashion if one looks at the construction of membership functions. For multidimensional magnitudes, the curves of the membership functions must supply correct frequencies for all conditions that are relevant during analysis. All $\mu_i(x)$ and their overlap areas must therefore be coordinated with each other in a way that one can provide correct data for all possible combinations of inquiries. This problem of coordination clearly explains a minor change in the above example: one might want to derive how significant the performance-shaping factor of "control stand design" is. The performance shaping factor here resides in the configurations "poor," "average," and "good." In this case likewise the Fuzzy-Set theory assumes that membership in the fundamental dimension of "control stand design" can be determined by the weighting values $\mu_i(x)$. Figure 4-7 shows such a membership function $\mu_i(x)$.

In the figure, the parameter i represents the three configurations "bad" (i=1), "average" (i=2), and "good" (i=3). While a person with respect to the above example might feel that a configuration of x=2.5 is a "good control stand design," that might turn out to be "average" Point (P1) for another person. The configuration itself remains x=2.5; but it can be matched up with two different configurations: first of all, with the configuration "good" with intensity $\mu_1(2.5)=0.5$ and the configuration "average" with intensity $\mu_2(2.5)=0.5$. If the configuration migrates to a higher value of x=2.75, then the share of the "good" configuration increases and the share of the "average" configuration decreases (Point P2).

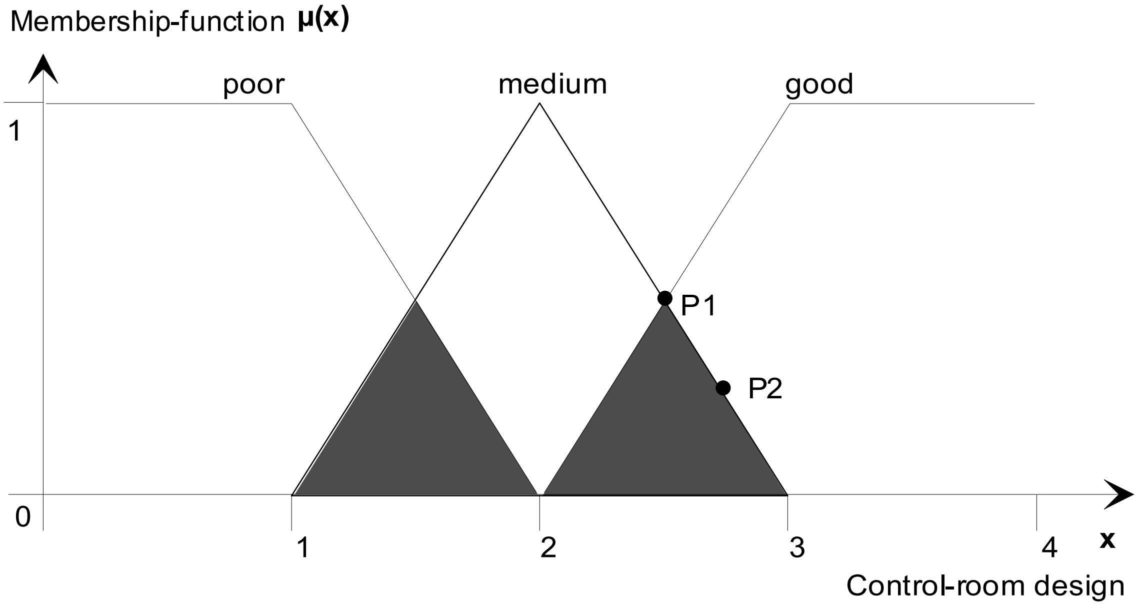

Figure 4-7 A Simple Membership Function of the Dimension "Control Stand Design"

This means that the correctness of a Fuzzy-Set statement depends on that (1) the dimension x is actually generally valid and can be subdivided into classes that underlie the membership functions and (2) the functional curve of the membership functions is known for all values of x. One employs heuristic assumptions and scaling procedures to determine these parameters:

In the case of heuristic assumptions, the form of distribution of the membership function is anticipated and one merely determines the overlap area of different functions. For the sake of simplification, triangles were assumed in the distributions of the above examples. This assumption suffices for simple technical regulating tasks but it encounters the limits of prediction accuracy when the dimension, underlying the membership function, is not a physically measurable magnitude but rather constitutes a semantic magnitude or a psychological construct.

The simplest way to construct membership functions for semantic magnitudes is known from the psychological decision-making theory as signal detection theory: according to the signal detection theory, there are four possibilities of matching a concept on with another one (Table 4-1).

Table 4-1 Decisionmaking Table to Determine a Membership Function

Factual Configuration ***Association of Configuration by Experts***	***Average***	***Good***
Average	Agreement (Hit) with configuration = average F(Hit)=n%	New agreement (false alarm) with configuration = average F (False Alarm) = (100-n)%
Good	Wrong answer (miss) concerning configuration = average F(Miss)=m%	Correct rejection of configuration = good F(Correct Rejection) = (100-m)%

One can then construct a membership function, as shown in Figure 4-8, from the match-ups performed by various experts on different configurations of control stand design. Additional information on the construction of a membership function with the help of the signal detection theory is given in Wickens (1984) and Zimmermann (1990).

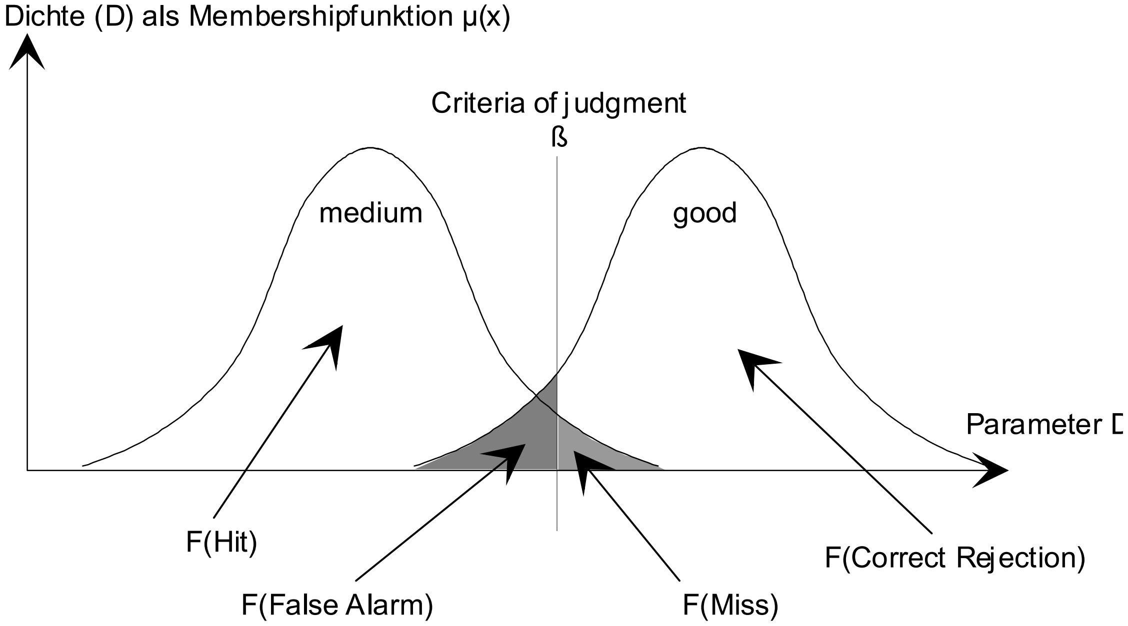

Figure 4-8 Construction of a Membership Function With the Help of the Signal Detection Theory

In the case of the signal detection theory, one also starts with the idea that the foundation consists of a certain distribution, the standard distribution. Although this form of distribution was also often observed for semantic interrelationships (Wickens, 1984), one cannot be sure that it applies to every interrelationship, in particular, for multiparametric statements. This procedure furthermore is rather problematical because the actual configuration must be in some way objectively measurable.

In scaling procedures, the form of distribution of the membership function is also determined. For this purpose, one needs data-intensive questioning of experts with methods of psychological test theory (see Zimmermann, 1990). In psychology, one speaks of a magnitude that is depicted on a dimension although that dimension is not directly measurable, in other words, one speaks in terms of a psychological construct. As regards the existence of a psychological construct, one assumes that (1) the magnitude is unidimensional and that it (2) can be completely described by the configurations given as distributions. These prerequisites are met only in the rarest cases; therefore, in psychological test theory, one assumes that constructs are multidimensional (for instance, the construct "control stand design" has multiple aspects, such as, for example, arrangement of individual elements or entire systems on Console A or Console B, feedback, alarm system, color system, etc.). This means that the attributes are subject to individual variability regarding the different aspects. An example: n% of all persons think that the property x for control stand design is good, (100-n)% think that it is bad; on the other hand, for example, (100-n)% think that the property z for control stand design is good and n% feel that it is poor. This means that the two design property x and property z cannot be depicted via a simple, constantly rising membership function. One would need two functions for property x and property z or one membership function with two peaks (one for property x and another one for property z).

At this point, as essential point of criticism leveled against the construction of the membership function, we find that the dimensions and scale intervals underlying a membership function $\mu_i(x)$ depend on the context and, in particular, on the context that constructive $\mu_i(x)$. This is also an essential point of criticism leveled against the Fuzzy-Set theory that is noted by Schefe (1987; p153). Accordingly, constructed dimensions and scale intervals as a rule differ from those of reality; in other words, their construct validity is deficient unless intensive investigations are conducted on the scaling of $\mu_i(x)$. Consequently, one must investigate to what extent the constructs are multifactorial or to what extent they can be described by a few dimensions or just a single dimension.

If this reduction to a few dimensions cannot be accomplished successfully, then this means that, strictly speaking, each membership function $\mu_i(x)$ would have to be distributed m-parametrically, in order correctly to illustrate frequencies for a combination of n attributes, where m again comprises the number of all possible combinations according to Equation 4-3, so as to be able to depict all effect interrelationships.

$$m = \sum_{i=2}^{k} \binom{n}{i} \qquad (4\text{-}3)$$

where

k *Number of all combinations of attributes desired during analysis*

n *Number of all attributes*

- **Discussion With Relation to Analysis Model**

Summarizing, we may say that, in the case of the Fuzzy-Set theory, one can of course determine statements on frequencies with the help of the membership function. The main problem of the Fuzzy-Set theory however resides in the fact that a membership function, once formed, must have sufficient construct validity so that, with its help, it will be possible to predict and a priori formed interrelationship also always in the form a posteriori. The membership function must be generally valid so that it can do this.

The illustration via membership functions is thus not always suitable when the connection between different concepts is not known or when any accommodations of concepts cannot be depicted via a small number of membership functions because the underlying construct is too heterogeneous. In this case - which exists in connection with the evaluation of practical operational experience - it is required that one not start with unit dimensional magnitudes on the level of the construct and that one does not express membership in the construct via a membership function but rather that one specifies, for individual interrelationships, a specific membership in the form of a weighted relationship. In this case, Fuzzy-sets blend into so-called probabilistic networks (see Zimmermann, 1990) which will be discussed below.

A.4.3 Probabilistic Networks

Probabilistic networks are used among other things for modeling knowledge of experts in medical diagnosis. They are depicted comprehensively in Pearl (1988); an overview of probabilistic methods is given, among others, by Spiegelhalter et al. (1993). The point of departure for considerations regarding probabilistic networks is the Bayes Theorem. If the Bayes Theorem is applied to different statements, then this results in a so-called Bayes- or also probabilistic network.

- **Bayes Theorem**

The Bayes Theorem for two mutually dependent events A and C looks like this (among others, according to Bortz, 1989):

$$P(A|\mathrm{C}) = \frac{\mathrm{P(A \cap C)}}{P(C)} \Leftrightarrow \mathrm{P(A \cap C)} = P(A|\mathrm{C}) * P(C) \qquad \textit{(4-4)}$$

where

C Condition for A

For the special case of complete independence of A and C, this theorem blends into the following equation for complete independence:

$$P(A|\mathrm{C}) = P(A) = \frac{\mathrm{P(A \cap C)}}{P(C)} \Leftrightarrow \mathrm{P(A \cap C)} = P(A) * P(C) \qquad \textit{(4-5)}$$

If one assumes that different conditions C_i prevail for Event A and is Event A depends on all events C_i, then - the condition that all C_i are completely independent of each other - the following relationship obtains:

$$\mathrm{P(A \cap C)} = \sum_{i=1}^{n} \left(P(A|\mathrm{C_i}) * P(C_i) \right) \qquad \textit{(4-6)}$$

where:

C_i Condition or context for A

n Number of conditions C_i for A

In this case, several C_i are decisive for the probability P(A C); therefore, the quantity of all C_i is also labeled as context for A (see Pearl, 1988). A context for the conditions C_i can be interpreted either in a temporal or logic way; therefore, probabilistic networks are credited with being able to depict not only conditions but also time change procedures. If equation 4-6 is used to illustrate several events A_j under several conditions C_{ij}, then one gets a Bayes or probabilistic network.

- **Bayes or Probabilistic Network**

The theory of graphs is the foundation for the construction of a probabilistic network. There one differentiates between (1) hierarchical and non-hierarchical graphs, (2) directed and undirected graphs, as well as (3) between acyclic and cyclic graphs (Lipschutz, 1976). When the edges have a meaning, they are labeled as mentioned graphs (Bonato, 1990). Figure 4-9 shows various network types. Probabilistic networks can process only directed acyclic graphs.

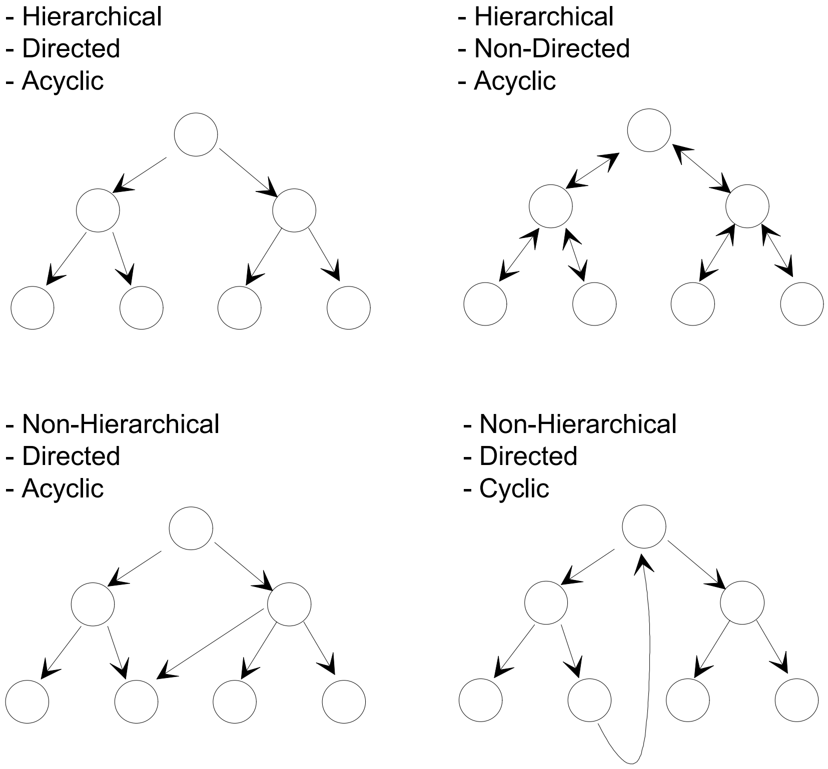

Figure 4-9 Different Types of Graphs

As for the further discussion of probabilistic networks, there is one question that is significant: what happens when different characteristics of the context depend on each other. A precise quantitative analysis of a graph calls for a rather accurate knowledge of all $A \mid C_i$ and all reciprocal interrelations $C_i \mid C_j$. If not all relations are known or when known relations are not considered for the purpose of calculating the probability of the statement A, then a probabilistic network can make a statement about the accuracy and application of A only via the following consideration: if an even A depends on several events C_i, then this can be illustrated in a network diagram, such as we have it for instance in Figure 4-10 (initially, only the solid lines are significant).

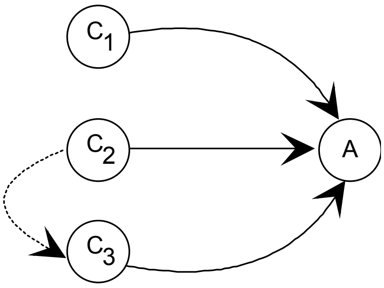

Figure 4-10 A Simple Probabilistic Network

If there is complete independence of all C_i, then the probability for event A can be calculated as follows $\vec{P}(C)$={0.3; 1.0; 0.1} and $\vec{P}(A|C)$={0.6; 0.5; 0.4} according to Equation 4-6:

$$\mathrm{P}(\mathrm{A} \cap \mathrm{C}) = \begin{bmatrix} 0,3 \\ 1,0 \\ 0,1 \end{bmatrix} * \begin{bmatrix} 0,6 \\ 0,5 \\ 0,4 \end{bmatrix} = 0,18 + 0,5 + 0,04 = 0,72$$

If some C_i are not completely independent of each other, then Equation 4-6 calculates a value that no longer represents a probability; strictly speaking, it is no longer valid. In the figure, for example, we assume a dependence between C_2 and C_3 by means of a broken line. That would give us the following probability for event A $\vec{P}(C)$={0.3; 1.0; 1.0}

$$\mathrm{P}(\mathrm{A} \cap \mathrm{C}) = \begin{bmatrix} 0,3 \\ 1,0 \\ 1,0 \end{bmatrix} * \begin{bmatrix} 0,6 \\ 0,5 \\ 0,4 \end{bmatrix} = 0,18 + 0,5 + 0,4 = 1,08$$

The result is greater than one and thus no longer corresponds to the probability theorem $P \in \{0,..,1\}$. To get around this problem of dependencies in context, we calculate, in probabilistic networks, with so-called mass functions instead of probabilities if not all dependencies are known (see Schocken & Hummel, 1993). By means of the mass function, we achieve a normalization of the observed values within the limits of {0,...,1}. The values of the above equation can for instance, be so limited that the following will apply:

$$Mass\ (A \cap C) = \sum_{i=1}^{n} m_i = 1 \Leftrightarrow \sum_{i=1}^{n} \left(k * P(C_i) * P(A|C_i)\right) = 1 \qquad (4\text{-}7)$$

where:

k *Normalization factor*

m_i *Specific mass of relation i*

n *Number of all conditions C_i for A*

The mass function thus no longer represents a probability according to Equation 4-6; instead, it is a measure that so considers reciprocal dependencies within the C_i context that a statement regarding Event A will be in the value range of {0,...,1}.

To tie the statement about the materialization of an event A, under conditions C_i, in with a meaning, the measure for the correctness and applicability of a statement is termed as being a believe function in probabilistic networks. The belief in an event A under conditions C_i results from Equation 4-7 as follows:

$$Bel\ (A \cap C) = \sum_{i=1}^{x \subseteq n} \left(k * P(C_i) * P(A|C_i)\right) = \sum_{i=1}^{x \subseteq n} m_i \qquad (4\text{-}8)$$

where:

k *Normalization factor*

m_i *Specific mass of relation i*

x *Number of conditions C_i for A, that are used for the statement*

n *Number of all conditions C_i for A*

Within the example in Figure 4-10, the probability of the occurrence of an event A under conditions $\vec{P}(C)$={0.3; 1.0; 1.0} is given as follows, by way of example:

$$\mathrm{Bel}(\mathrm{A} \cap \mathrm{C}) = \begin{bmatrix} 0,925 * 0,3 \\ 0,925 * 1,0 \\ 0,925 * 1,0 \end{bmatrix} * \begin{bmatrix} 0,6 \\ 0,5 \\ 0,4 \end{bmatrix} = 0,166 + 0,462 + 0,370 = 1,0$$

If the meaning of a sub-quantity of the context for event A is now to be considered, then we would get, for instance, with $\vec{P}(C)$={0.0; 1.0; 1.0}:

$$\mathrm{Bel}(\mathrm{A} \cap \mathrm{C}) = \begin{bmatrix} 0,925 * 0,0 \\ 0,925 * 1,0 \\ 0,925 * 1,0 \end{bmatrix} * \begin{bmatrix} 0,6 \\ 0,5 \\ 0,4 \end{bmatrix} = 0,0 + 0,462 + 0,370 = 0,833$$

The differential between the maximum possible belief and the belief in the current context in this example amount to 1-0.833=0.166 and is termed as uncommitted belief if its origin is unknown.

- **Probabilistic Networks as Analysis Model**

On account of its flexibility in the illustration of the most varied relations and due to the possibility of a quantitative depiction of unknown interrelationships about the belief function, this approach seems to be sufficiently sturdy to analyze the collected practical operational experience as different individual events. To predict quantitative data about human reliability, one would thus for instance, get the network illustrated in Figure 4-11.

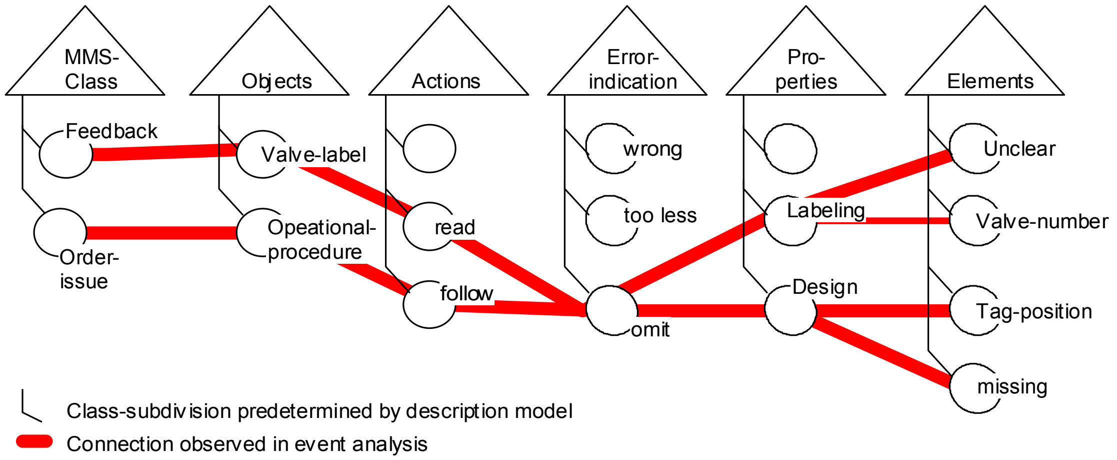

Figure 4-11 Set-up of a Probabilistic Network for the Analysis of Event Descriptions

They hypothetical network shown in the figure points up two possible errors of omission: (1) omitting the reading of a valve text due to unclear labeling of the valve number and (2) omitting following an instruction step within the operating handbook due to absence of unhooking positions. If 10 events with errors of relation were observed, then we would get the following frequency for the possibility of an error of omission, for instance:

$$h\ (omission)=10$$

An inquiry regarding the consolation of conditions or the context $\vec{C}_1$={Valve text, read off} would for instance yield the following:

$$h(omission|\vec{C}_1)=6$$

because, in these 10 events, a valve text was to be read off six times. Another inquiry for consolation condition $\vec{C}_2$={operating handbook; follow} would yield the following:

$$h(omission|\vec{C}_2)=7$$

because, in the 10 events, instructions were to be followed in the operating handbook 7 times. But if one were to add up frequencies for $\vec{C}_1$ and $\vec{C}_2$, one would get a result that would be definitely greater than the maximum possible value h(omit):

$$h(omission|\vec{C}_1)+ h(omission|\vec{C}_2)=13$$

The reason for this overestimation of the number of errors of the mission in this example is due to the fact that, in three events, both context were effective together and that the dependencies of both contexts were not depicted in the network. In this case, the possibility of interpreting the frequency of the occurrence of $\vec{C}_1$ and $\vec{C}_2$ would exist only by virtue of the belief function:

$$Bel(h(omission|\vec{C}_1))+Bel(\ h(omission|\vec{C}_2))=10$$

In this case, however, the individual amounts of $\vec{C}_1$ and $\vec{C}_2$ could no longer be interpreted as frequencies. Summarizing, we can thus state that probabilistic networks do not offer a possibility of providing a uniform and unambiguously interpretable measure both for general context and for specific context (for example, either in the form of frequencies or in the form of belief values).

- **Discussion With Relation to the Analysis Model**

The preceding consideration show that probabilistic networks will lead to meaningful qualitative and correct quantitative statements only if the network provides a well structured and directed search area. Ambiguous quantitative solutions occur when dependencies between the nodes of the network are not completely known. If characteristics depend on each other, this problem can be solved only according to Pearl (1988; p.44) if each dependence is known or if it can be made known by adding an auxiliary variable. The prerequisite here is that an auxiliary variable can be found in the first place (see also Whittaker, 1993). Effects from correlation statistics (for example, suppression effects between variables) must thus be completely cleared up before they can be described by a probabilistic network. The relations of the influencing variables here must be given explicitly (see, for instance, Bortz, 1989).

Summarizing, probabilistic networks always lead to erroneous statements if one cannot specify - with respect to all theoretically possible combinations - the probability with which one can observe those combinations. If such information cannot be provided (as in the case of hidden reciprocal interactions), then probabilistic networks are not suitable for analysis. In this case, compared to object oriented approaches, probabilistic networks only offer the advantage of being able to make relative statements about the relationship between two contexts (for example, Context 1 is more frequent than Context 2). This disadvantage in the effort correctly to interpret incomplete data - that are expressed in interactions between observed interrelationships - only with the help of the belief function, accordingly, is also something that the probabilistic networks are being reproached for (see Schocken & Hummel, 1993; p.424). This means that this approach is not suitable for calculating quantitative data with sufficient consistencies. In practical operational experience however we are precisely dealing with incomplete data because - in an event or a limited number of events - all possible interrelationships are not always observed and because there will always be incomplete data. Furthermore, based on practical operational experience, one can observe only frequencies of the common appearance of concepts and one cannot observe any probabilities.

This means that probabilistic networks are not suitable as method of analysis essentially for three reasons: (1) The possible interrelationships (combinations) that are present in the description model can be imaged only by means of a combinatory explosion of relations.

(2) One needs complete data on all relations. (3) The data must be specified as probabilities; absolute frequencies will not suffice. The problem fields, resulting from these disadvantages, are the usual areas of employment of neuronal and connectionism networks.

A.4.4 Neuronal and Connectionism Networks

The "Recent connectionism" ("Neuere Konnektionismus", Kempke, 1988) comprises a series of approaches to the quantitative and qualitative processing of information. The addition "recent" here goes back to the circumstance that this approach was used already around 1950 in the psychology of commission for the purpose of modeling human information processing and was revised again around 1980 in the engineer science field. There, the approach was initially considered as a suitable algorithm for the recognition and processing of visual or auditive patterns (image processing, speech identification).

In the psychology of cognition, this approach is also considered as an alternative to other information processing models (for example, process or models oriented by data processing) because (1) it is oriented by the structure of the frame consisting of simple nerve cells and because (2) it could be applied to simple problems of artificial intelligence, such as the word recognition model of McClelland and Rummelhart (1981) or the model for the modeling of typos according Rummelhart and Norman (1982). In judging the meaning of neuronal networks, Neumann (1992) even goes so far as to consider connectionism - on account of its characteristics - as a new paradigm of research in the psychology of cognition. Additional discussions on categorization in terms of the psychology of cognition can also be found in Strube (1990) or Stoffer (1989). Of course, so far, hardly any classical cognition psychology findings have been modeled in connectionism models, such as, for example, Miller (1956), Sanders (1975) or Attneave (1974). Approaches to cognition psychology modeling can be found among others in Shastri (1988), Fu (1993) or Emmanji et al. (1992).

Within the theory of neuronal networks, there is a vast number of differing approaches, among others, in Rummelhart and McClelland (1986), Kohonen (1988), Nauck et al. (1994). Kempke (1988) presents an overview of various setups. We will not go into detail here as regards this large number of possible approaches. The characterization and discussion undertaken here will suffice for a consideration as to the extent to which one can obtain - from this approach - a solution to the above mentioned problems of probabilistic models in the analysis of information from the description model.

Compared to the approaches done so far, connectionism imposes the least restrictions regarding the structure of the information processing mechanism. On account of this high adaptability, this approach seems suitable for solving problems that the models discussed so far encounter in case of a qualitative and quantitative analysis of the data in the description model. Of course, so far, connectionism models can be applied primarily to image processing or speech recognition and they are hardly ever viewed in conjunction with the processing of semantic or symbolic information. The components of a connectionism network are cells that are replicated after the neurobiological model as well as the architecture or topology of the network formed by the cell. Within this subdivision, one differentiates between the microlevel (the procedures on the cells) and the macrolevel (the performances of the entire system, for example, in the form of image or speech processing).

- **Microlevel**

The microlevel of a neuronal network runs heavily along the lines of the structure and the processing mode of a neuronal cell in the human brain. One distinguishes dendrites on the input side, axons on the output side, and the soma (the cell) for processing input information and transformation into an output information. Figure 4-12 summarizes these elements.

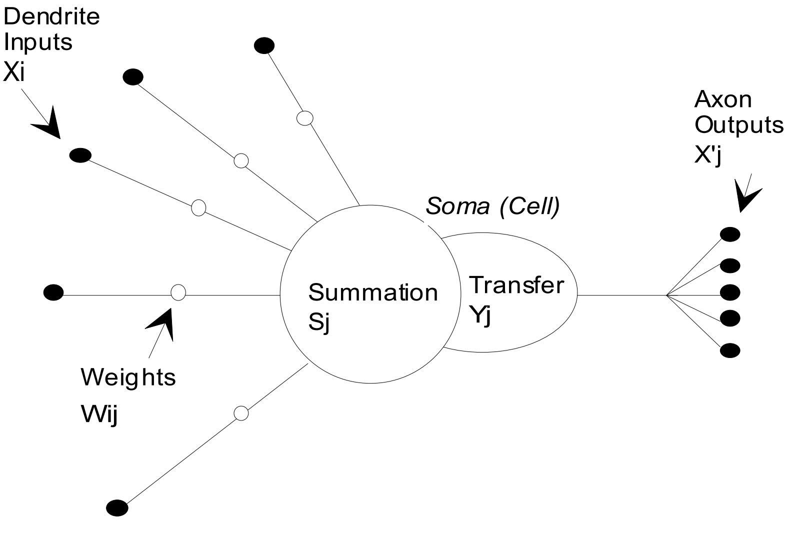

Figure 4-12 Structure of a Nerve Cell

As one can see in the illustration, information processing takes place in that a vector of activations X_j, from prepositioned cells, with a weighting vector W_j, is converted into an input activation of a cell j. This activation is then processed by means of a transfer function (S_j) in the cell to get an output vector Y_j.

The transfer function, also called activation function, limits the value range as a rule to the interval {0,..,1} and rises monotonously but necessarily steadily. It represents the number of input information items that the cell just happens to be getting via the dendrites at a point in time t. The information of the output vector, constituted by the transfer function, then again is used as input information for subordinate cells. Information processing here takes place in the simplest case according to the following equations:

$$S_j = \sum_{i=1}^{n} \left(w_{ij} * x_{ij} \right) \tag{4-9}$$

and

$$Y_j = f(S_j) \in \left\{ \frac{S_j}{1+S_j}; \frac{e^{S_j}}{1+e^{S_j}}; \ldots \right\} \tag{4-10}$$

where:

i	*Number of incoming connections*
Y_j	*Output activations*
X_i	*Input activations*
w_{jj}	*Strength of nodes ij*

As in the biological model, a uniform activation function applies to all cells in most practical uses. Hybrid networks form an exception; they use differing activation functions related to differing layers. Basically the same condition applies to transfer functions as was discussed earlier in connection with the membership functions of the Fuzzy-sets: They must be constructed in a way that a cell will assume a meaningful function in the entire network. Even in the case of neuronal networks, these functions however are constructed on the basis of holistic considerations and are validated in that the network produces the best results with a certain transfer function.

- **Macrolevel**

The macrolevel is subdivided into areas processing levels (so-called layers or strata). The necessary processing layers are the input layer and the output layer. To process complex information, additional hidden layers are worked in-between the input layer and the output layer in some network architectures. Figure 4-13 shows a rough structure of a connectionism model.

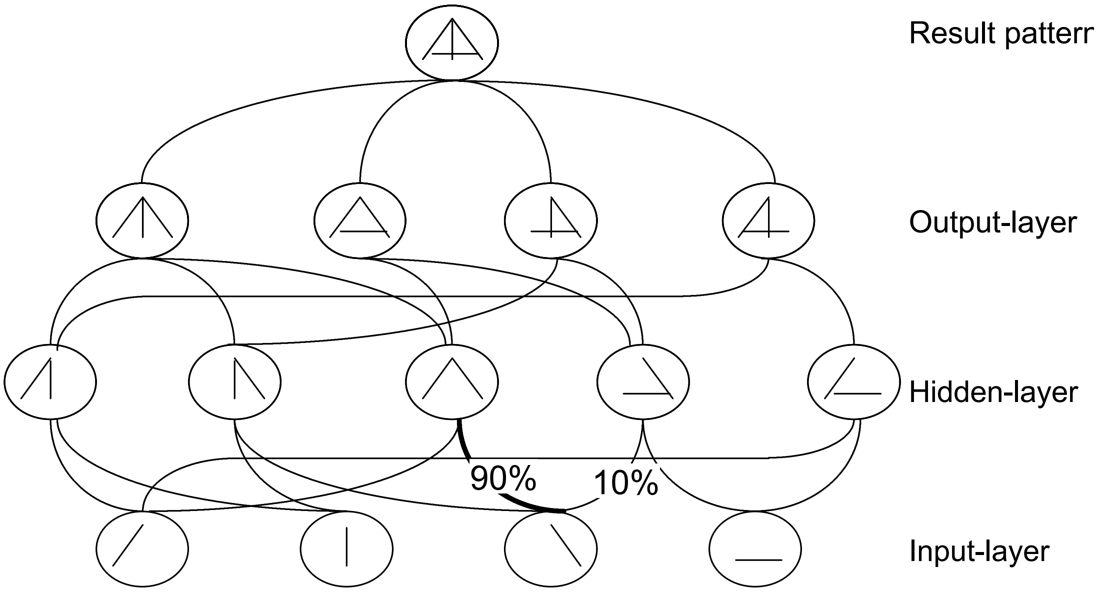

Figure 4-13 Rough Structure of a Simple Connectionism Model

The network consists of nodes and connections between various nodes. The arrangement of the nodes makes it possible to assemble complex patterns (hidden layers on the middle layers) from simple patterns (input layer on the lowest level) which in the end are assembled to form a final pattern (output layer on upper level). Each level (or class) here represents a certain degree of abstraction that depends on the information that can be found on these levels. Both nodes and connections have weightings and the possibility of accepting activations. With the help of this attribute, one can reinforce certain paths in the network. In that way, for example, one can make a statement in case of incomplete patterns as clearly indicated by the more solid path in the figure: On the lowest level, only the symbol "\" is available as information. On account of the stronger bond with the symbol "/\", this superordinate pattern is considered as more likely than the neighboring symbol ">".

Various subdivisions are performed regarding the functionality of a neuronal network. According to Strube (1990), for example, one can differentiate - with regard to the goal of utilization - between symbolic (quantitative) and semantic (qualitative) processing. A subdivision into associative and connectionism networks is important for the further discussion of neuronal networks in this study.

In associated networks, the nodes of the hidden layers are so connected to the nodes of the input layer and the output layer that there is no possibility of establishing a causal connection between input and output. Neither the connections nor the nodes in the hidden layers contain specific semantic information. Instead, all knowledge, that is needed for the conversion of the input information into the output information, is distributed over the activation of the nodes and is deposited on the weightings of the connections. Image processing networks are a good example of this type of representation. In connectionism networks, the information can be interpreted in each level and at each node as semantic information. Each node in the network carries a very specific semantic information. The simplest form of a connectionism network is an undirected hierarchical graph or a semantic network (Bonato, 1990). Interconnections in connectionism networks are obtained on the basis of weightings of the individual meaning carriers (nodes). Therefore, in connectionism networks, there is a certain relationship to probabilistic networks if a probabilistic network is not considered as a connectionism network capable of learning.

Although associated in connectionism networks, on the macrolevel, can be capable of identical performances, they differ greatly regarding the distribution of activations and weightings. The original information is so greatly distributed by the hidden layers in associative networks that, in the output layer, there is nothing left to refer to their original meaning, in other words, one cannot establish any semantic relationships between input and output.

- **Attributes of Neuronal Networks**

The attributes of neuronal networks can be circumscribed with the terms of ability to learn, determination of similarity, and self organization. They are not possible in this form in conventional databanks with fixed acquisition structure and fixed analysis structure.

The central hypothesis of learning in neuronal networks is this: relations between nodes are reinforced with common activation (called Hebb's synapses modification rule; Hebb, 1949). In neuronal networks, the ability to learn is mostly confined to the alteration of activations of nodes or of connection intensities. The modification is here performed during a learning phase in that one or several patterns to be learned are iteratively presented at the input layer and that these patterns must, in the output layer, lead to a desired output pattern. The goal during the learning phase is to minimize errors between the actual output and the required output. The error is calculated here either with relation to the entire network (thermodynamic model), with relation to the output layer, or with relation to the individual connections (back propagation models). After the learning phase, the network, ideally, is capable of identifying different output patterns on the basis of the input information.

In neuronal networks, learning happens mostly "with evaluator." There is no algorithm that would control the meaningful build-up of connection intensities or the meaningful supplementation of new neurons into the entire cell complex. Kohonen (1988) does of course touch the possibility of using statistically significant interrelationships between the input patterns for this purpose. These so-called self organizing networks, that offer a possibility of learning "without evaluator," however so far have resulted in hardly any efficient uses on account of the circumstance that statistical interrelationships are very difficult to interpret semantically. The main difficulty consists in the fact that statistical interrelationships still do not tell us anything as to the quality of these interrelationships (for instance, a connection between two variables may have come about by confusion or suppression effects of an unknown third variable).

- **Discussion With Reference to Analysis Model**

The neuronal and connectionism networks have the ability to solve the problems touched on so far in the analysis of data of the prescription model. This seems possible for the reason that they have a series of attributes that are required for the analysis model. We can see the following regarding these attributes:

Connectionism and associative networks: Regarding the differentiation between connectionism and associative networks, it became clear that, in associative networks, it is impossible to make a judgment of the semantic meaning of the nodes or relations between the input layer and the output layer. For this reason, they are unsuitable for an analysis of practical operational experience. Connectionism networks on the other hand seem suitable for analyzing practical operational experience.

Learning ability: In connectionism models, often occurring concepts (nodes) or connections between various nodes are reinforced by their joint appearance. Other connections, that are not used, on the other hand, weaken their connection in relation to the strengthened ones. As a result, the network can learn. Often observed concepts or connections of concepts represent the experience of the network. Unobserved concepts on the other hand become weaker and are isolated from the remaining network with growing experience.

Self organization: Self organization has the following meaning regarding the description and analysis of events: First of all, new events can be described with already existing concepts so that the connection intensities between the used concepts are modified automatically and so that learning is possible without evaluator. Besides, there is a possibility of introducing new concepts and to establish a meaningful connection between these new concepts and already existing ones because the new concepts - via joint utilization with already known concepts - are semantically determined in an event and are thus determined there in relation to a certain class (man-machine system component or description stage) and are thus tied into the object hierarchy.

Determination of similarity: As described earlier, similarities in connectionism networks are always represented by correspondence in the activity distributions of the patterns. This possibility of determining similarities of various events is required in order to be able to come up with differently detailed inquiries, such as they are demanded for a human reliability analysis. By means of this attribute, one can also work out the data on case correspondences and thus dimensions for the transferability of the information items contained in various events.

Polymorphism: Connectionism and associative networks can depict polymorphous relationships in that relationships are depicted between any combinations of concepts within a hidden layer.

- **Approach for the Analysis Model**

When a connectionism network is to be constructed for the analysis of event descriptions, one gets, on the whole, the following variants of a network topology in order to generate frequency data for complex statements: (1) Topology related to the statements that one wishes to gain with the help of the network. (2) Topology related to the objects that are used for event description. (3) Topology related to the events that are to be analyzed.

But the topology is to be used in determining both frequencies, with which a statement occurred in the events observed hitherto, as well as relationships to concepts which are connected with this statement. To achieve this, we will in the following discuss all three network topologies with the help of the conversion of the statement A="AND valve AND open AND omit".

- **Variant 1: Statement Related Topology**

The most obvious variants is the statement related topology. In it, each statement, that has a higher value than a combination of two nodes, is illustrated by a new nodes. Each node on the statement level in this case has relations to all concepts that are of significance in the statement. Figure 4-14 shows a simple implementation of the above statement in the statement related topology.

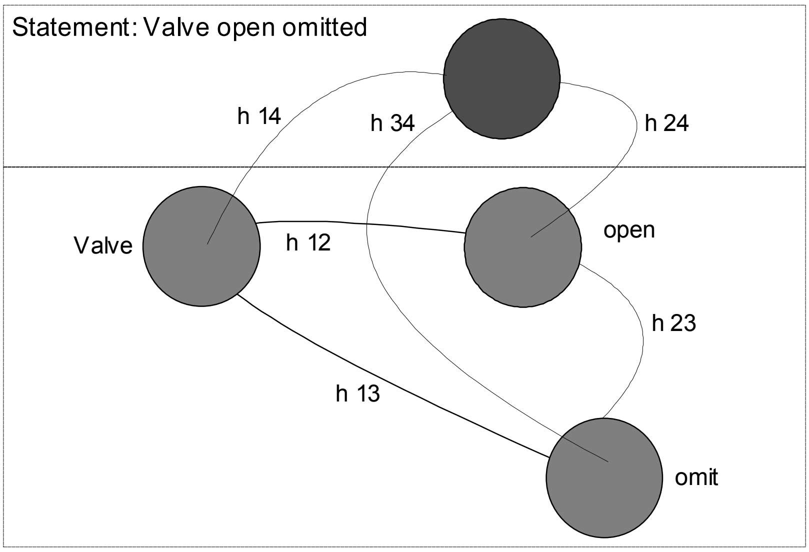

Figure 4-14 Statement Related Topology of the Connectionism Network

There are two possible solutions within this topology when it comes to determining the frequency of the statement "AND valve AND open AND omit:

All events are searched for the statement and we count out those in which the combination occurred. This solution leads to the same problems as were encountered in the previously discussed methods. The number of statements for which all events must be searched will lead to a combinatory explosion. (2) The frequency of statement A is determined via the weights of the relations. In Figure 4-14, they are h14, h24 and h34. The designed indication would then result for example, in the following manner:

$$h(AND\ valve\ AND\ open\ AND\ omit) =$$

$$h_{14}*(Valve) + h_{24} * h(open) + h_{34} * h(omit)$$

The frequencies $h_{.4}$ however emerge neither directly from the number of concepts, nor from the number of observed events. This variant thus is not suitable for event analysis because the necessary data for building up the network are missing or because the analysis effort, which specifically used to be minimized, will also lead to a combinatory explosion.

- **Variant 2: Objected Related Topology**

Connectionism networks can process both activating (excitatory) and inhibiting (inhibitor) activations. In Variant 2, this circumstance is exploited in order to realize every higher value statement by means of a certain quantity of inhibiting impulses upon a maximum bivalent connection (Figure 4-15). In physiology, the behavior of this variant is known by the name of "Lateral Inhibition."

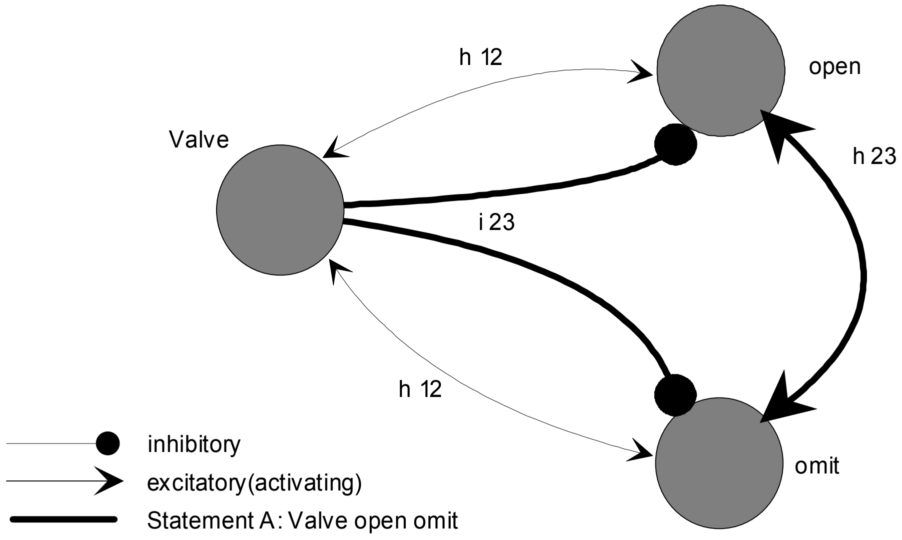

Figure 4-15 Object Related Topology With Inhibitory Connections

In this variant, Statement A would come about in that one selects a bivalent connection h_{ij} from the n-valent statement and that one thereupon lets all other nodes, except for nodes i and j, exert inhibiting action on nodes i and j. The question as to how strong such an inhibition should be can be answered in the following manner: the frequency of a bivalent statement must be reduced by this amount so that a correct frequency indication will become possible for the higher value statement. This means that the statement "AND Valve AND open AND omit" can also be expressed by the following calculation:

$$h(\text{AND valve AND open AND omit}) =$$

$$h(\text{AND open AND omit}) - i_{23}$$

This kind of calculation is possible in a connectionism network only if one can determine, for each node, the level of the inhibiting relation which is required for the production of higher valent statements. The latter does not emerge directly from the individual events. This means that this variant also needs data that are not directly observable from events. The higher the valence of the statements, the more difficulty will it be to determine the intensity of the inhibiting connections; therefore, this variant likewise does not seem practical.

- **Variant 3: Event Related Topology**

Each relation in Variant 3 is realized by an event. A decisive difference with respect to past variants is represented by the fact that, in this variant, bivalent statements likewise are not illustrated as direct connections between two nodes but instead that the latter (such as higher valent statements) must take a "detour" via the event nodes, such as, for example, h_{12} in Figure 4-16.

An event node in this variant has direct connections only to all of those nodes that were used in the event description. By way of example, two events were observed in the figure. In Event 1, it was observed that a valve was opened, and in Event 2 it was observed that the opening of a valve was omitted.

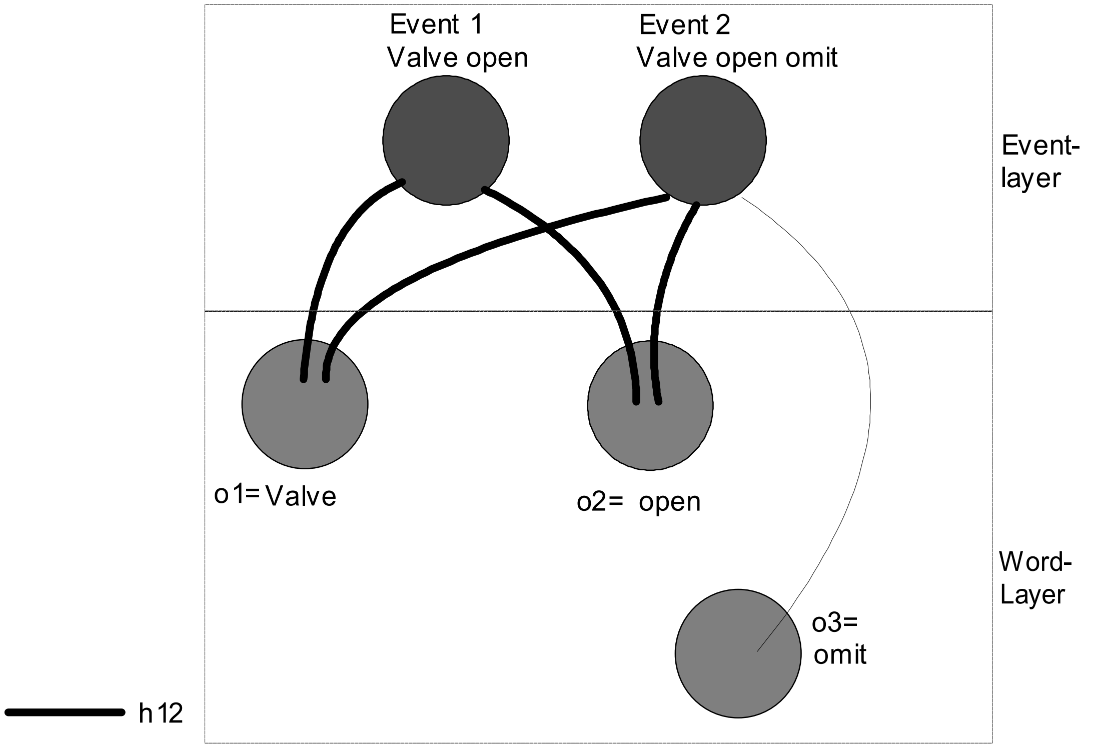

Figure 4-16 Event Related Topology of a Connectionism Network

We thus get the following for the frequency with which the task "open valve" was to be performed,

$$h(AND\ valve\ AND\ open)=h_{12}=2,$$

because this task was observed in two events. We get the following for the number of omissions that occurred during the execution of the task "open valve":

$$h(AND)\ valve\ and\ open\ AND\ omit)=1,$$

because that was observed only in one event.

More information required for Variant 3 can be obtained directly from the events (the concept that was used for event description and the relation to the event in which it was used); therefore, this variant is available as network topology for the analysis model.

Appendix 5: Extract of Chapter 20 of the THERP Handbook

In this appendix, we present the tables from Swain and Guttmann (1983) with which the data from practical operational experience were compared. To the reader who does not have this literature available, the Appendix is intended to give the information required so as to be able to replicate the comparison that was performed.

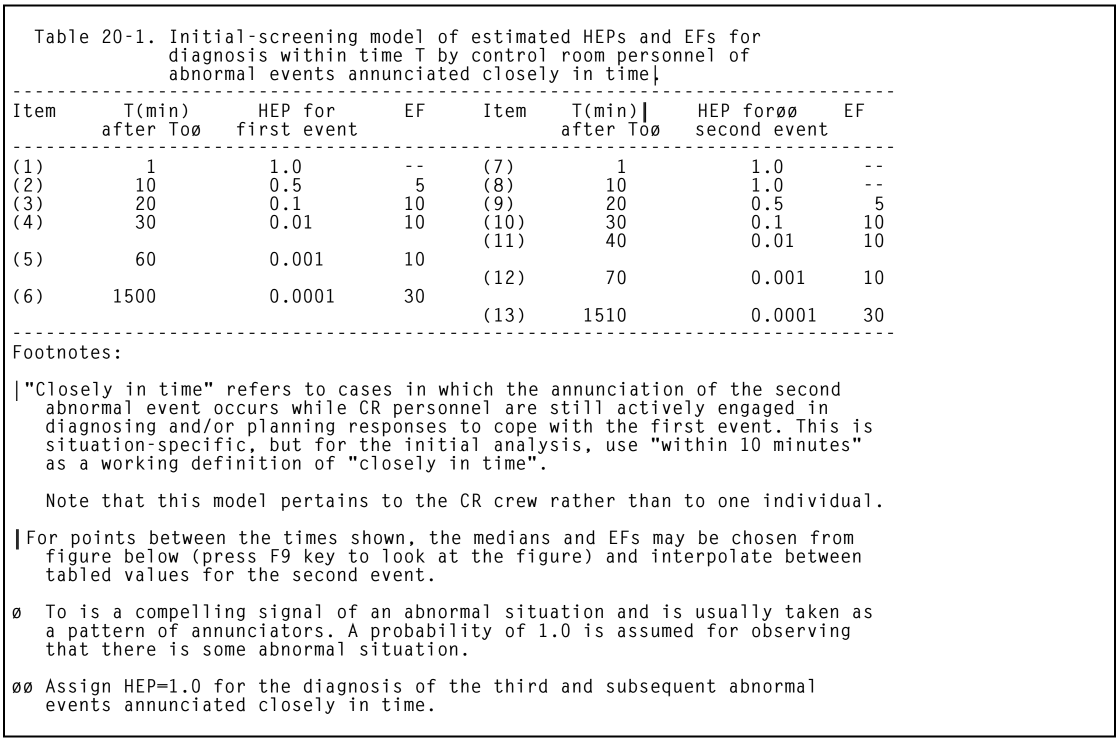

Table 20-1. Initial-screening model of estimated HEPs and EFs for diagnosis within time T by control room personnel of abnormal events annunciated closely in time|

Item	T(min) after Toø	HEP for first event	EF	Item	T(min)‖ after Toø	HEP forøø second event	EF
(1)	1	1.0	--	(7)	1	1.0	--
(2)	10	0.5	5	(8)	10	1.0	--
(3)	20	0.1	10	(9)	20	0.5	5
(4)	30	0.01	10	(10)	30	0.1	10
				(11)	40	0.01	10
(5)	60	0.001	10				
				(12)	70	0.001	10
(6)	1500	0.0001	30				
				(13)	1510	0.0001	30

Footnotes:

|"Closely in time" refers to cases in which the annunciation of the second abnormal event occurs while CR personnel are still actively engaged in diagnosing and/or planning responses to cope with the first event. This is situation-specific, but for the initial analysis, use "within 10 minutes" as a working definition of "closely in time".

Note that this model pertains to the CR crew rather than to one individual.

‖For points between the times shown, the medians and EFs may be chosen from figure below (press F9 key to look at the figure) and interpolate between tabled values for the second event.

ø To is a compelling signal of an abnormal situation and is usually taken as a pattern of annunciators. A probability of 1.0 is assumed for observing that there is some abnormal situation.

øø Assign HEP=1.0 for the diagnosis of the third and subsequent abnormal events annunciated closely in time.

Table 20-2. Initial-screening model of estimated HEPs and EFs for rule-based actions by control room personnel after diagnosis of an abnormal event|

Item	Potential Errors	HEP	EF
	Failure to perform rule-based actions correctly when written procedures are available and used:		
(1)	Errors per critical step without recovery factors	.05	10
(2)	Errors per critical step with recovery factors	.025	10
	Failure to perform rule-based actions correctly when written procedures are not available or not used:		
(3)	Errors per critical step with or without recovery factors	1.0	--
(4)	Failure to perform an immediate emergency action for the reactor vessel/containment critical parameters, when (a) it can be judged to have been commited to memory, (b) it can be classified as skill-based actions, and there is a backup written procedure	.01	5

Footnotes:

| Note that this model pertains to the CR crew rather than to one individual.

Table 20-3. Nominal model of estimated HEPs and EFs for diagnosis within time T by control room personnel of abnormal events annunciated closely in time(*).

Item	T(min) after To(#)	HEP for first event	EF	Item	T(min)(**) after To(#)	HEP for(##) second event	EF	Item	T(min)(**) after To(#)	HEP for(##) third event	EF
(1)	1	1.0	--	(7)	1	1.0	--	(14)	1	1.0	--
(2)	10	0.1	10	(8)	10	1.0	--	(15)	10	1.0	--
(3)	20	0.01	10	(9)	20	0.1	10	(16)	20	1.0	--
(4)	30	0.001	10	(10)	30	0.01	10	(17)	30	0.1	10
				(11)	40	0.001	10	(18)	40	0.01	10
								(19)	50	0.001	10
(5)	60	0.0001	30								
				(12)	70	0.0001	30				
								(20)	80	0.0001	30
(6)	1500	0.00001	30								
				(13)	1510	0.00001	30				
								(21)	1520	0.00001	30

Footnotes:

(*)"Closely in time" refers to cases in which the annunciation of the second abnormal event occurs while CR personnel are still actively engaged in diagnosing and/or planning responses to cope with the first event. This is situation-specific, but for the initial analysis, use "within 10 minutes" as a working definition of "closely in time".

Note that this model pertains to the CR crew rather than to one individual.

The nominal model for diagnosis includes the following activities: "perceive","discriminate","interpret", "diagnosis", and the first level of "decision-making. The modeling includes those aspects of behaviour included in the Annunciator Response Model; therefore, when the nominal model for diagnosis is used, the annunciator model should not be used for the initial diagnosis. The annunciator model may be used for estimating recovery factors for an incorrect diagnosis.

(**)For points between the times shown, the medians and EFs may be chosen from figure below (press F9 key to look at the figure) and interpolate between tabled values for subsequent events.

(#)To is a compelling signal of an abnormal situation and is usually taken as a pattern of annunciators. A probability of 1.0 is assumed for observing that there is some abnormal situation.

(##)Guidelines for adjusting nominal HEPs are as follows:
- (1) Use upper bound if:
  - (a) the event is not covered in training (or)
  - (b) the event is covered but not practiced except in initial training of operators for becoming licensed (or)
  - (c) the talk-through and interviews show that not all operators know the pattern of stimuli associated with the event.
- (2) Use lower bound if:
  - (a) the event is a well-recognized classic (and)
  - (b) the talk-througs and interviews indicate that all the operators have a good verbal recognition of the relevant stimulus patterns and know what to do or which written procedures to follow.
- (3) Use nominal HEP if:
  - (a) the only practice of the event is in simulator requalification exercises and all operators have had this experience (or)
  - (b) none of the rules for the use of upper or lower bound apply.

Table 20-4. Number of reactor operators and advisors available to cope with an abnormal event and their related levels of dependence : assumptions for PRA |

Item	Time after recognition of an abnormal event‖	Operators or advisors handling unit affectedø	Dependence levels with othersøø
(1)	0 to 1 minute	on-duty RO	
(2)	at 1 minute	on-duty RO	
		SRO (assigned SRO or supervisor,an SRO)	high with RO
(3)	at 5 minutes	on-duty RO	
		assigned SRO	high with RO
		shift supervisor	low to moderate with other operators
		1 or more AOs§	
(4)	at 15 minutes	on-duty RO	
		assigned SRO	high with RO
		shift supervisor	low to moderate with other operators
		shift technical advisor	low to moderate with others for diagnosis & major events; high to complete for detailed operations
		1 or more AOs	

Footnotes:

| These assumptions are nominal and can be modified for plant- and situation-specific conditions.

‖ For PRA, "recognition" is usually defined as the response to a compelling signal, such as the alarming of one or more annunciators.

ø No credit is given for additional operators or advisors.

øø This column indicates the dependence between each additional person and those already on station. The levels of dependence are assumed to remain constant with time and may be modified in a plant-specific analysis.

§ Availability of other AOs after 5 minutes and related levels of dependence should be estimated on a plant- and situation-specific basis.

Table 20-5. Estimated HEP per item (or perceptual unit§) in preparation of written material|

Item	Potential Errors	HEP	EF
(1)	Omitting a step or important instruction from a formal or ad hoc procedure‖ or a tag from a set of tags.	.003	5
(2)	Omitting a step or important instruction from written notes taken in response to oral instructionsø.	Negligible	
(3)	Writing an item incorrectly in a formal or ad hoc procedure or on a tag.	.003	5
(4)	Writing an item incorrectly in written notes made in response to oral instructionsø.	Negligible	

Footnotes:

| Except for simple reading and writing errors, errors of providing incomplete or misleading technical information are not addressed in the Handbook.

The estimates are exclusive of recovery factors, which may greately reduce the nominal HEPs.

‖ Formal written procedures are those intended for long-time use; ad hoc written procedures are one-of-a-kind, informally prepared procedures for some special purpose.

ø A maximum of five items is assumed. If more than five items are to be written down, use .001 (EF=5) for each item in the list.

§ A perceptual unit is either (1) an individual item such as a display, control, valve, etc., or (2) some functional group of items that are completely dependent and that are the equivalent of a single item with regard to EOMs. It is the operator's perception of what is functionally related that defines this unit.

Table 20-6. Estimated HEPs related to failure of administrative control.

Item	Task	HEP	EF
(1)	Carry out a plant policy or scheduled tasks such as periodic tests or maintenance performed weekly, monthly, or at longer intervals.	.01	5
(2)	Initiate a scheduled shiftly checking or inspection function.	.001	3
	Use written operations procedures under:		
(3)	normal operating conditions	.01	3
(4)	abnormal operating conditions	.005	10
(5)	Use a valve change or restoration list.	.01	3
(6)	Use written test or calibration procedures.	.05	5
(7)	Use written maintenance procedures.	.3	5
(8)	Use a checklist properly.|	.5	5

Footnotes:

| Read a single item, perform the task, check off the item on the list. For any item in which a display reading or other entry must be written, assume correct use of the checklist for that item.

Table 20-7. Estimated probabilities of errors of omission per item of instruction when use of written procedures is specified.|

Item|	Omission of item:	HEP	EF
	When procedures with checkoff provisions are correctly usedø:		
(1)	Short list, <= 10 items	.001	3
(2)	Long list, > 10 items	.003	3
	When procedures without checkoff provisions are used, or when checkoff provisions are incorrectly usedøø:		
(3)	Short list, <= 10 items	.003	3
(4)	Long list, > 10 items	.01	3
(5)	When written procedures are available and should be used but are not usedøø	.05 §	5

Footnotes:

| The estimates for each item (or perceptual unit) presume zero dependence among the items (or units) and must be modified by using the dependence model when a nonzero level of dependence is assumed.

| The term "item" for this column is the usual designator for tabled entries and does not refer to an item of instruction in a procedure.

ø Correct use of checkoff provisions is assumed for items in which written entries such as numerical values are required of the user.

øø Table 20-6 ("Administrative Control") lists the estimated probabilities of incorrect use of checkoff provisions and of nonuse of available written procedures.

§ If the task is judged to be "second nature", use the lower uncertainty bound for .05, i.e., use .01 (EF=5).

Table 20-8. Estimated probabilities of errors in recalling oral instruction items not written down.(*)

HEPs as a function of number of items to be remembered(**)

Item(#)	Number of Oral Instruction Items (Perceptual Units)	Pr[F] to recall item "N", order of recall not important (a) HEP	EF	Pr[F] to recall all items, order of recall not important (b) HEP	EF	Pr[F] to recall all items, order of recall is important (c) HEP	EF
	Oral instructions are detailed:						
(1)	1(##)	.001	3	.001	3	.001	3
(2)	2	.003	3	.004	3	.006	3
(3)	3	.01	3	.02	5	.03	5
(4)	4	.03	5	.04	5	.1	5
(5)	5	.1	5	.2	5	.4	5
	Oral instructions are general:						
(6)	1(##)	.001	3	.001	3	.001	3
(7)	2	.006	3	.007	3	.01	3
(8)	3	.02	5	.03	5	.06	5
(9)	4	.06	5	.09	5	.2	5
(10)	5	.2	5	.3	5	.7	5

Footnotes:

(*)It is assumed that if more than five oral instruction items or perceptual units are to be remembered, the recipient will write them down. If oral instructions are written down, use Table 20-5 for errors in preparation of written procedures and Table 20-7 for errors in their use.

(**)The first column of HEPs (a) is for individual oral instruction items, e.g., the second entry, .003 (item 2a), is the Pr[F] to recall the second of two items, given that one item was recalled, and order is not important. The HEPs in the other columns for two or more oral instruction items are joint HEPs, e.g., the .004 in the second column of HEPs is the Pr[F] to recall both of two items to be remembered, when order is not important. The .006 in the third column of HEPs is the Pr[F] to recall both of two items to be remembered in the order of performance specified.

(#)The term "item" for this column is the usual designator for tabled entries and does not refer to an oral instruction item.

(##)The Pr[F] in rows 1 and 6 are the same as the Pr[F] to initiate the task.

Table 20-9. Estimated probabilities of errors in selecting unannunciated displays or annunciated displays no longer annunciating for quantitative or qualitative readings.

Item	Selection of Wrong Display:	HEP†	EF
(1)	when it is dissimilar to adjacent displays‡	Negligible	
(2)	from similar-appearing displays when they are on a panel with clearly drawn mimic lines that include displays	.0005	10
(3)	from similar-appearing displays when they are part of well-delineated functional groups on a panel	.001	3
(4)	from an array of similar-appearing displays identified by labels only	.003	3

Footnotes:

† The listed HEPs are independent of recovery factors. In some cases, the content of the quantitative or qualitative indication from an incorrect display may provide immediate feedback of the selection error, and total error can be assessed as negligible.

‡ This assumes the operator knows the characteristics of the display for which he is searching.

Table 20-10. Estimated HEPs for errors of commission in reading and recording quantitative information from unannunciated displays.

Item	Display or Task	HEP|	EF
(1)	Analog meter	.003	3
(2)	Digital readout (<=4 digits)	.001	3
(3)	Chart recorder	.006	3
(4)	Printing recorder with large number of parameters	.05	5
(5)	Graphs	.01	3
(6)	Values from indicator lamps that are used as quantitative displays	.001	3
(7)	Recognize that an instrument being read is jammed, if there are no indicators to alert the user	.1	5
	Recording task: Number of digits or letters|to be recorded:		
(8)	<= 3	Negligible	
(9)	> 3	.001 (per symbol)	3
(10)	Simple arithmetic calculations with or without calculators	.01	3
(11)	Detect out-of-range arithmetic calculations	.05	5

Footnotes:

| Multiply HEPs by 10 for reading quantitative values under a high level of stress if the design violates a strong populational stereotype; e.g., a horizontal analog meter in which values increase from right to left.

| In this case, "letters" refer to those that convey no meaning. Groups of letters such as MOV do convey meaning, and the recording HEP is considered to be negligible.

Table 20-11. Estimated HEPs for errors of commission in check-reading displays.|

Item	Display or Task	HEP	EF
(1)	Digital indicators (these must be read, there is no true check-reading function for digital displays)	.001	3
	Analog meters:		
(2)	with easily seen limit marks	.001	3
(3)	with difficult-to-see limit marks, such as scribe lines	.002	3
(4)	without limit marks	.003	3
	Analog-type chart recorders:		
(5)	with limit marks	.002	3
(6)	without limit marks	.006	3
(7)	Confirming a status change on a status lamp	Negligible|ø	
(8)	Misinterpreting the indication on the indicator lamps	Negligible|ø	

Footnotes:

| "Check-reading means reference to a display merely to see if the indication is within allowable limits; no quantitative reading is taken. The check-reading may be done from memory or a written checklist may be used. The HEPs apply to displays that are checked individually for some specific purpose, such as a scheduled requirement, or in response to some developing situation involving that display.

| If operator must hold a switch in a spring-loaded position until a status lamp lights, use HEP=.003 (EF=3), from Table 20-12 (Errors of commision in operating manual controls), item 10.

ø For levels of stress higher than optimal, use HEP=.001 (EF=3).

Table 20-12. Estimated probabilities of errors of commission in operating manual controls.[|]

Item	Potential Errors	HEP	EF
(1)	Inadvertent activation of a control	Situation-specific	
(1A)	Select wrong control when it is dissimilar to adjacent controls	Negligible	
	Select wrong control on a panel from an array of similar-appearing controls[‖]:		
(2)	identified by labels only	.003	3
(3)	arranged in well-delineated functional groups	.001	3
(4)	which are part of well-defined mimic layout	.0005	10
	Turn rotary control in wrong direction (for two-position switches, see item 8):		
(5)	when there is no violation of populational stereotypes	.0005	10
(6)	when design violates a strong populational stereotype and operating conditions are normal	.05	5
(7)	when design violates a strong populational stereotype and operation is under high stress	.5	5
(8)	Turn a two-position switch in wrong direction or leave it in wrong setting	[ø]	
(9)	Set a rotary control to an incorrect setting (for two-position switches, see item 8)	.001	10[øø]
(10)	Failure to complete change of state of a component if switch must be held until change is completed	.003	3
	Select wrong circuit breaker in a group of circuit breakers[‖]:		
(11)	densely grouped and identified by labels only	.005	3
(12)	when PSFs are more favourable	.003	3
(13)	Improperly mate a connector (this includes failure to seat connectors completely and failure to test locking features of connectors for engagement)	.003	3

Footnotes:

[|] The HEPs are for errors of commission only and do not include any errors of decision as to which controls to activate.

[‖] If controls or circuit breakers are to be restored and are tagged, adjust the tabled HEPs according to Table 20-15 (Tagging levels).

[ø] Divide HEPs for rotary controls (items 5-7) by 5 (use the same EFs).

[øø] This error is a function of clarity with which indicator position can be determined: designs of control knobs and their position indications vary greately. For plant specific analyses, an EF of 3 may be used.

Table 20-13. Estimated HEPs for selection errors for locally operated valves.

Item	Potential Errors	HEP	EF
	Making an error of selection in changing or restoring a locally operated valve when the valve to be manipulated is:		
(1)	Clearly and unambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags|	.001	3
(2)	Clearly and unambiguously labeled, part of a group of two or more valves that are similar in one of the following: size and shape, state, or presence of tags|	.003	3
(3)	Unclearly or ambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags|	.005	3
(4)	Unclearly or ambiguously labeled, part of a group of two or more valves that are similar in one of the following: size and shape, state, or presence of tags|	.008	3
(5)	Unclearly or ambiguously labeled, part of a group of two or more valves that are similar in all of the following: size and shape, state, and presence of tags|	.01	3

Footnotes:

| Unless otherwise specified, Level 2 tagging is presumed. If other levels of tagging are assessed, adjust the tabled HEPs according to Table 20-15 (Tagging levels).

Table 20-14. Estimated HEPs in detecting stuck locally operated valves.

Item	Potential Errors	HEP	EF
	Given that a locally operated valve sticks as it is being changed or restored|, the operator fails to notice the sticking valve, when it has:		
(1)	A position indicator| only	.001	3
(2)	A position indicator| and a rising stem	.002	3
(3)	A rising stem but no position indicator|	.005	3
(4)	Neither rising stem nor position indicator|	.01	3

Footnotes:

| Equipment reliability specialists have estimated that the probability of a valve's sticking in this manner is approximately .001 per manipulation, with an error factor of 10.

| A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

Table 20-15. The four levels of tagging or locking systems.

Level	Description	Modifications to Nominal HEPs|
1	A specific number of tags is issued for each job. Each tag is numbered or otherwise uniquely identified. A record is kept of each tag, and a record of each tag issued is entered in a suspense sheet that indicates the expected time of return of the tag; this suspense sheet is checked each shift by the shift supervisor. An operator is assigned the job of tagging controller as a primary duty. For restoration, the numbers on the removed tags are checked against the item numbers in the records, as a recovery factor for errors of omission or selection. OR The number of keys is carefully restricted and under direct control of the shift supervisor. A signout board is used for the keys. Keys in use are tagged out, and each incoming shift supervisor takes an inventory of the keys.	Use lower UCBs
2	Tags are not accounted for individually - the operator may take an unspecified number and use them as required. In such a case, the number of tags in his possession does not provide any cues as to the number of items remaining to be tagged. For restoration, the record keeping does not provide a thorough checking for errors of omission or selection. If an operator is assigned as tagging controller, it is a collateral duty, or the position is rotated among operators too frequently for them to maintain adequate control tags and records and to retain skill in detecting errors of omission or selection. OR The shift supervisor retains control of the keys and records their issuance but does not use visual aids such as signout boards or tags.	Use nominal HEPs
3	Tags are used, but record keeping is inadequate to provide the shift supervisor with positive knowledge of every item of equipment that should be tagged or restored. No tagging controller is assigned. OR Keys are generally available to users without logging requirements.	Use upper UCBs
4	No tagging system exists. OR No locks and keys are used.	Perform separate analysis

Footnotes:

| The nominal HEPs are those in the Handbook that relate to tasks involving the application and removal of tags and, unless otherwise specified, are based on Level 2 tagging.

Table 20-16. Modifications of estimated HEPs for effects of stress and experience levels.

Item	Stress Level	Modifiers for Nominal HEPS|	
		(a)Skilled|	(b)Novice|
(1)	Very low (Very low task load):	x2	x2
	Optimum (Optimum task load):		
(2)	Step-by-stepø	x1	x1
(3)	Dynamicø	x1	x2
	Moderately high (Heavy task load):		
(4)	Step-by-stepø	x2	x4
(5)	Dynamicø	x5	x10
	Extremely high (Threat stress)		
(6)	Step-by-stepø	x5	x10
(7)	Dynamicø Diagnosisøø	.25 (EF=5) These are the actual HEPs to use with dynamic tasks or diagnosis - they are NOT modifiers.	.50 (EF=5)

Footnotes:

| The nominal HEPs are those in the data tables. Error factors are listed in

Table 20-17. Equations for conditional probabilities of success and failure on Task "N", given success or failure on previous Task "N-1", for different levels of dependence.

Level of Dependence	Success Equation	Equation No.	Failure Equation	Equation No.
ZD	P[S(N)/S(N-1)] = n	(10-9)	P[F(N)/F(N-1)] = N	(10-14)
LD	P[S(N)/S(N-1)] = (1+19n)/20	(10-10)	P[F(N)/F(N-1)] = (1+19N)/20	(10-15)
MD	P[S(N)/S(N-1)] = (1+6n)/7	(10-11)	P[F(N)/F(N-1)] = (1+6N)/7	(10-16)
HD	P[S(N)/S(N-1)] = (1+n)/2	(10-12)	P[F(N)/F(N-1)] = (1+N)/2	(10-17)
CD	P[S(N)/S(N-1)] = 1.0	(10-13)	P[F(N)/F(N-1)] = 1.0	(10-18)

Table 20-18. Conditional probabilities of success or failure for Task "N" for the five levels of dependence, given FAILURE on preceding Task "N-1".

	Task "N" Conditional Probabilities(*)									
	ZD(**)		LD		MD		HD		CD	
	S	F	S	F	S	F	S	F	S	F
Item	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
(1)	.75	.25	.71	.29	.64	.36	.37	.63	0	1.0
(2)	.9	.1	.85	.15	.77	.23	.45	.55	0	1.0
(3)	.95	.05	.9	.1	.81	.19	.47	.53	0	1.0
(4)	.99	.01(#)	.94	.06	.85	.15	.49	.51	0	1.0
(5)	.995	.005	.95	.05	.85	.15	.50	.50	0	1.0
(6)	.999	.001	.95	.05	.86	.14	.50	.50	0	1.0
(7)	.9995	.0005	.95	.05	.86	.14	.50	.50	0	1.0
(8)	.9999	.0001	.95	.05	.86	.14	.50	.50	0	1.0
(9)	.99999	.00001	.95	.05	.86	.14	.50	.50	0	1.0

Footnotes:

(*) All conditional probabilities are rounded. Equations 10-14 through 10-18 (Table 20-17 - Dependence Equations) were used to calculate the values in the F columns. The values in the S columns were obtained by substraction.

(**)The conditional probabilities given ZD are the basic probabilities for Task "N".

(#) For PRA purposes, it is adequate to use CHEPs of .05 (for LD), .15 (for MD), and .5 (for HD) when BHEP <= .01.

Table 20-19. Conditional probabilities of success or failure for Task "N" for the five levels of dependence, given SUCCESS on preceding Task "N-1".

	Task "N" Conditional Probabilities(*)									
	ZD(**)		LD		MD		HD		CD	
	S	F	S	F	S	F	S	F	S	F
Item	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
(1)	.75	.25	.76	.24	.79	.21	.87	.13	1.0	0
(2)	.9	.1	.9	.1	.91	.09	.95	.05	1.0	0
(3)	.95	.05	.95	.05	.94	.06	.97	.03	1.0	0
(4)	.99	.01	.99	.01	.991	.009	.995	.005	1.0	0
(5)	.995	.005	.995	.005	.996	.004	.997	.003	1.0	0
(6)	.999	.001	.999	.001	.999	.001	.9995	.0005	1.0	0
(7)	.9995	.0005	.9995	.0005	.9996	.0004	.9997	.0003	1.0	0
(8)	.9999	.0001	.9999	.0001	.99991	.00009	.99995	.00005	1.0	0
(9)	.99999	.00001	.99999	.00001	.999991	.000009	.999995	.000005	1.0	0

Footnotes:

(*) All conditional probabilities are rounded. Equations 10-9 through 10-13 (Table 20-17 - Dependence Equations) were used to calculate the values in the S columns. The values in the F columns were obtained by substraction.

(**)The conditional probabilities given ZD are the basic probabilities for Task "N".

Table 20-20. General guidelines for estimating uncertainty bounds for estimated HEPs.|

Item	Task and HEP Guidelines|	EFø
	Task consists of performance step-by-step procedureøø conducted under routine circumstances (e.g., a test,maintenance, or calibration task); stress level is optimal:	
(1)	Estimated HEP < .001	10
(2)	Estimated HEP .001 to .01	3
(3)	Estimated HEP > .01	5
	Task consists of performance of step-by step procedureøø but carried out in nonroutine circumstances such as those involving a potential turbine/reactor trip; stress level is moderately high:	
(4)	Estimated HEP < .001	10
(5)	Estimated HEP <= .001	5
	Task consists of relatively dynamicøø interplay between operator and system indications, under routine conditions, e.g., increasing or reducing power; stress level is optimal:	
(6)	Estimated HEP < .001	10
(7)	Estimated HEP <= .001	5
(8)	Task consists of relatively dynamicøø interplay between operator and system indications but carried out in nonroutine circumstances; stress level is moderately high	10
(9)	Any task performed under extremely high stress conditions, e.g., large LOCA; conditions in which status of ESFs is not perfectly clear; or conditions in which the initial operator responses have proved to be inadequate and now severe time pressure is felt	5§

Footnotes:

| The estimates in this table apply to experienced personnel.

|For UCBs for HEPs based on the dependence model, see Table 20-21 (Conditional HEPs & UCBs).

ø The highest upper bound is 1.0.

øø See Table 20-16 (Stress - Experience) for definitions of step-by step and dynamic procedures.

§ An EF of 5 is assigned for the extremely high stress conditions because the upper UCB is truncated at 1.0, and it is desirable to have a more conservative (i.e., higher) lower UCB for such tasks.

Table 20-20 (Estimate UCBs).

|A skilled person is one with 6 months or more experience in the tasks being assessed. A novice person is one with less than 6 months experience. Both levels have the required licensing or certificates.

ø Step-by step tasks are routine,procedurally guided tasks, such as carrying out written calibration procedures. Dynamic tasks require a higher degree of man-machine interaction, such as decision-making, keeping track of several functions, controlling several functions, or any combination of these. These requirements are the basis of the distinction between step-by-step tasks and dynamic tasks, which are often involved in responding to an abnormal event.

øø Diagnosis may be carried out under varying degrees of stress, ranging from optimum to extremely high (threat stress). For threat stress, the HEP of .25 is used to estimate performance of an individual. Ordinarily, more than one person will be involved. Tables 20-1 (Diagnosis - screening model) and 20-3 (Diagnosis - nominal model) list joint HEPs based on the number of control room personnel presumed to be involved in the diagnosis of an abnormal event for various times after annunciation of the event, and their presumed dependence levels, as presented in the staffing model in Table 20-4

Table 20-21.Approximate CHEPs and their UCBs for dependence levels(*) given FAILURE on the preceding task.

Item	Levels of Dependence	BHEPs, Nominal CHEPs and (Lower to Upper UCBs)(#)					
		(a)	(b)	(c)	(d)	(e)	(f)
(1)	ZD**	<.01 (EF=3,5,10)	.05 (EF=5)	.1 (EF=5)	.15 (EF=5)	.2 (EF=5)	.25 (EF=5)
(2)	LD	.05 (.015,.15)	.1 (.04,.25)	.15 (.05,.5)	.19 (.05,.75)	.24 (.06,1.0)	.29 (.08,1.0)
(3)	MD	.15 (.04,.5)	.19 (.07,.53)	.23 (.1,.55)	.27 (.1,.75)	.31 (.1,1.0)	.36 (.13,1.0)
(4)	HD	.5 (.25,1.0)	.53 (.28,1.0)	.55 (.3,1.0)	.58 (.34,1.0)	.6 (.36,1.0)	.63 (.4,1.0)
(5)	CD	1.0 (.5,1.0)	1.0 (.53,1.0)	1.0 (.55,1.0)	1.0 (.58,1.0)	1.0 (.6,1.0)	1.0 (.63,1.0)

Footnotes:

(*) Values are rounded. All values are based on skill personnel (i.e., those with > 6 months experience on the task being analyzed).

(**)ZD = BHEP. EFs for BHEPs should be based on Table 20-20 (Estimate Uncertainty Bounds).

(#) Linear interpolation between stated CHEPs (and UCBs) fo values of BHEPs between those listed is adequate for most PRA studies.

Table 20-22. Estimated probabilities that a checker will fail to detect errors made by others|

Item	Checking operation	HEP	EF
(1)	Checking routine tasks, checker using written materials (includes over-the-shoulder inspections, verifying position of locally operated valves, switches, circuit breakers, connectors, etc., and checking written lists, tags, or procedures for accuracy)	.1	5
(2)	Same as above, but without written materials	.2	5
(3)	Special short-term, one-of-a-kind checking with alerting factors	.05	5
(4)	Checking that involves active participation, such as special measurements	.01	5
	Given that the position of a locally operated valve is checked (item 1 above), noticing that it is not completely opened or closed:		
(5)	Position indicator|only	.1	5
(6)	Rising stem with or without position indicator|	.5	5
(7)	Neither a position indicator|nor rising stem	.9	5
(8)	Checking by reader/checker of the task performer in a two-men team, OR checking by a second checker, routine task (no credit for more than 2 checkers)	.5	5
(9)	Checking the status of equipment if that status affects one's safety when performing his tasks	.001	5
(10)	An operator checks change or restoration tasks performed by a maintainer	Above HEPs ö 2	5

Footnotes:

| This table applies to cases during normal operating conditions in which a person is directed to check the work performed by others either as the work is being performed or after its completion.

| A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

Table 20-23. The Annunciator Response Model: estimated HEPs(*) for multiple annunciators alarming closely in time(**).

Item	Number of ANNs	Pr[Fi] for each annunciator (ANN) or completely dependent set of ANNs) successively addressed by the operator 1	2	3	4	5	6	7	8	9	10	$\overline{\text{Pr[Fi]}}$#
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
(1)	1	.0001										.0001
(2)	2	.0001	.001									.0006
(3)	3	.0001	.001	.002								.001
(4)	4	.0001	.001	.002	.004							.002
(5)	5	.0001	.001	.002	.004	.008						.003
(6)	6	.0001	.001	.002	.004	.008	.016					.005
(7)	7	.0001	.001	.002	.004	.008	.016	.032				.009
(8)	8	.0001	.001	.002	.004	.008	.016	.032	.064			.02
(9)	9	.0001	.001	.002	.004	.008	.016	.032	.064	.13		.03
(10)	10	.0001	.001	.002	.004	.008	.016	.032	.064	.13	.25	.05
(11)	11-15											.10
(12)	16-20	Pr[Fi] for each additional ANN beyond 10 = .25										.15
(13)	21-40											.20
(14)	>40											.25

Footnotes:

(*) The HEPs are for the failure to initiate some kind of intended corrective action as required. The action carried out may be correct or incorrect and is analyzed using other tables. The HEPs include the effects of stress and should not be increased in consideration of stress effects.
EF of 10 is assigned to each HEP. Based on compute simulation, use of EF of 10 for $\overline{\text{Pr[Fi]}}$ yields approximately correct upper bounds for the 95th percentile. The corresponding lower bounds are too high; they are roughly equivalent to 20th percentile rather than the usual 5th percentile bounds. Thus, use an EF of 10 for the mean Pr[Fi] values provide a conservative estimate since lower bounds are biased high.

(**)"Closely in time" refers to cases in which two or more annunciators alarm within several seconds or within a time period such that the operator perceives them as a group of signals to which he must selectively respond.

(#) $\overline{\text{Pr[Fi]}}$ is the expected Pr[F] to initiate action in response to a randomly selected ANN (or completely dependent set of ANNs) in a group of ANNs competing for the operator's attention. It is the arithmetic mean of the Pr[Fi]s in a row, with upper limit of .25. The column (k) assumes that all of the ANNs (or completely dependent sets of ANNs) are equal in terms of the probability of being noticed.

Table 20-24. Estimated HEPs for annunciated legend lights|

Item	Task	HEP	EF
(1)	Respond| to one or more annunciated legend lights	See Annunciator Response Model	
(2)	Resume attention to a legend light within 1 minute after an interruption (sound and blinking cancelled before interruption)	.001	3
(3)	Respond to a legend light if more than 1 minute elapses after an interruption (sound and blinking cancelled before interruption)	.95	5
(4)	Respond to a steady-on legend light during initial audit	.90	5
(5)	Respond to a steady-on legend light during other hourly scans	.95	5

Footnotes:

| No written materials are used.

| "Respond" means to initiate some action in response to the indicator whether or not the action is correct. It does not include the initial acts of cancelling the sound and the blinking; these are assumed to always occur.

Table 20-25. Estimated probabilities of failure to detect one (of one) unannunciated deviant display|at each scan, when scanned hourly|.

Item	Display Type	(Initial Audit) 1	Hourly Scansø 2	3	4	5	6	7	8
Item		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
	Analog meters:								
(1)	with limit marks	.05	.31	.50	.64	.74	.81	.86	.90
(2)	without limit marks	.15	.47	.67	.80	.87	.92	.95	.97
	Analog-type chart recorders:								
(3)	with limit marks	.10	.40	.61	.74	.83	.89	.92	.95
(4)	without limit marks	.30	.58	.75	.85	.91	.94	.97	.98
(5)	Annunciator light no longer annunciating	.90	.95	.95	.95	.95	.95	.95	.95
(6)	Legend lightøø other than annunciator light	.98	.98	.98	.98	.98	.98	.98	.98
(7)	Indicator lampøø	.99	.99	.99	.99	.99	.99	.99	.99

Footnotes:

* "One display" refers to a single display or a group of completely dependent displays, i.e., a perceptual unit.

** For error factors, refer to Table 20-20 (Estimate Uncertainty bounds).

Written materials not used.

These displays are rarely scanned more than once per shift, if at all. HEPs for each are listed for completeness only.

Table 20-26. Estimated probabilities of failing to detect at least one|of one to five unannunciated deviant displays as a function of the BHEP for detection of a single deviant display during periodic scanning.

	Number of Deviant Indications 1	2	3	4	5
	BHEP	Pr[F] to detect at least one deviant display|			
Item	(a)	(b)	(c)	(d)	(e)
(1)	.99	.985	.98	.975	.97
(2)	.95	.93	.90	.88	.86
(3)	.90	.85	.81	.77	.73
(4)	.80	.72	.65	.58	.52
(5)	.70	.59	.51	.43	.37
(6)	.60	.48	.39	.31	.25
(7)	.50	.37	.28	.21	.16
(8)	.40	.28	.20	.14	.10
(9)	.30	.19	.13	.08	.05
(10)	.20	.12	.07	.04	.03
(11)	.10	.05	.03	.02	.01
(12)	.05	.03	.01	.007	.004
(13)	.01	.005	.003	.001	.001

Footnotes:

* To estimate the HEP for failure to detect other concurrent unannunciated deviant displays when one has been detected, use the HEP for the initial audit for those displays that are not functionally related to the display detected (from Table 20-25 - Scanning - One Deviant Display) and use the Annunciator Response Model for those displays that are functionally related to the display detected (from Table 20-23 - Annunciator Response Model). The HEPs apply when no written materials are used.

** For EFs, refer to Table 20-20 (Estimate Uncertainty Bound).

Table 20-27. Estimated probabilities that the basic walk around inspection|
will fail to detect a particular deviant indication of equipment
outside the control room within 30 days|

Item	Number of days between walk-arounds per Inspectorø	Cumulative Pr[F] within 30 days given one inspection per shiftøø
(1)	1 (daily walk-around for each inspector)	.52
(2)	2	.25
(3)	3	.05
(4)	4	.003
(5)	5	.0002
(6)	6	.0001
(7)	7 (weekly walk-around for each inspector)	.0001

Footnotes:

| One of the assumptions for basic walk-around inspections is that no written procedure is used; if a written procedure is used for a walk-around, use the tables related to errors of omission and commission for performance of rule-based tasks.

| Three shifts per day are assumed.

ø It is assumed that all inspectors have the same number of days between walk-arounds.

øø For EFs, use the procedure for UCBs propagation or use EF=10 as an approximation.

Appendix 6: Criteria for the Selection of Human Factor Cases, Inquiry Results on the THERP Tables

In this appendix, we will first of all present the criteria for the selection of human factor cases and then the inquiry results for the comparison of the calculated HEP values with the THERP tables.

- **Criteria for Selection of Human Factor Cases**

In looking for human factor cases, we searched for corresponding word passages in the event descriptions that point to a human factor event, a human factor relevant event, or a technical event. An event was classified accordingly when the word passage occurs. Here, we first of all classified the technical events, then the human factor relevant events, and finally, the human factor events.

The word passages are given in Table 6-1. Different codings were used in the table. A prefixed "+" means that we searched for this word, considering that capital letters and the lower case letters (for example, in the case of key words). An incomplete word, such as, for example, "irrtu" searches for different words starting with the same letters, such as "Irrtum" [mistake], or the like.

- **Inquiry Results on the THERP Tables**

In the following tables, we will first of all illustrate the inquiries for the absolute frequencies n_i (Table 6-2), then the inquiries for the reference magnitudes m_i (Table 6-3), and for the time level of the data (Table 6-4). When reference magnitudes are given for entire tables and when reference magnitudes are given for individual items in the tables, the reference magnitudes for individual items have precedence over the general reference magnitudes for entire tables. The inquiries are followed by the classes used in the inquiries, Table 6-5. They can be recognized by the prefixed "-". In conclusion, we present the comparison of the calculated HEP values to those of the THERP method in Table 6-6.

Note: In cases where the HEP values of different items of the THERP catalog were added up, it was necessary first of all to convert the HEP values into mean values, then to add them up, and again to convert them into the HEP value, because the HEP values are distributed in a logarithmic standard distribution. Only the mean values (EW) are allowed to be added, not the HEP values. Computation was done according to the rules given by Reer (1988).

Table 6-1

Category	***Criteria***
Human Factor Event (HF Event)	+TEST BROKEN OFF +OPERATING ERROR +wrongly recognized +wrongly assembled +WRONG MEASURE +MISHANDLING +MISSING/WRONG DISPLAY +DEFECTIVE ACTION +CLEARANCE ERROR +COMMUNICATIONS ERRORS +MEASURE CONTRARY TO OPERATING HANDBOOK +MEASURE CONTRARY TO IN-HOUSE REGULATIONS +PERSONNEL TRAINING +OMIT SWITCHOVER TO MANUAL OPERATION +OMITTED MEASURE +CONFUSION +Attention +operating error +instruct +started from +Mishandling +Wrong adjustment +Error recognition +Production error +Mistake +Assembly error +Not recognized +Not recognizable +Not assembled +Badly executed +Train +Trouble search +Overlooked +Over look +Unintentional +Omit +determination of cause +Provided [with]

Table 6-1 (cont.)

Category	*Criteria*
Human Factor Relevant Event (HR Event)	+CHANGE IN OPERATING INSTRUCTION +CHANGE IN TEST PLANS +INSTRUCTION +WORK INSTRUCTION +OPERATING HANDBOOK +SUBLIMITATION ADMINISTRATIVE INSTRUCTIONS +WRONG SETTING +CORRECTION IN OPERATING HANDBOOK +INCOMPLETE OPERATING INSTRUCTION +MESSAGE +MESSAGE CONCEPT TAMED +NHB [Accident Management Procedures, in German: NHB=Notfallhandbuch] +TESTING PLAN +INAPPROPRIATE EXECUTION +INCOMPLETE PROCEDURE +INAPPLICABLE SPECIFICATION +WHP [Repeated Test, in German: Wiederholungspruefung] +WKP [Periodic Test, in German: Wiederkehrende Pruefung] Instruction operate Operating handbook Display screen setting Wrong setting planned Handbook Maintenance Repair Instrument Communication Message Monitor Personnel Procedure Test Feedback Appropriate Provide [With] Confuse Manually Manually regulation choice Control stand Repeat test Recurring test
Technical Events	(All remaining events)

Table 6-2

Title	n_i	n_i *max*	n_i *min*	*Inquiries Concerning Formation of Absolute Frequencies*
THERP 20-01 (1) THERP 20-03 (01)	15	20	0	and MMS Type A or MMS Type Ba or MMS type B or MMS Type degrading and Situation-Tsw1 or Situation - Tsw12
THERP 20-01 (2) THERP 20-03 (2)	9	12	0	and MMS Type A or MMS Type Ba or MMS Type B or MMS Type C degrading and Situation-Tsw12 or Situation-Tsw23
THERP 20-01 (3) THERP 20-03 (3)	6	8	0	and MMS Type A or MMS Type Ba or MMS Type B or MMS Type C degrading and Situation-Tsw123 or Situation-Tsw23 or Situation-Tsw3 or Situation-Tsw34
THERP 20-01 (4) THERP 20-23 (4)	3	3	0	and MMS Type A or MMS Type Ba or MMS Type B or MMS Type C degrading and Situation-Tsw34 or Situation-Tsw45
THERP 20-01 (5) THERP 20-03 (5)	4	4	0	and MMS Type A or MMS Type Ba or MMS Type B or MMS Type C degrading and Situation-Tsw45 or Situation-Tsw5
THERP 20-01 (6) THERP 20-03 (6)	1	1	0	and MMS Type A or MMS Type Ba or MMS Type B or MMS Type C degrading and Situation-Tsw6
THERP 20-02 (1.2)	43	54	0	and task [error] or person [error] or activity [error] and order issue instruction
THERP 20-02 (3)	119	191	0	and task [error] or person [error] and activity [error] and not order issue instruction
THERP 20-02 (4)	4	20	0	and situation-T11 or Situation-T12 and task [error] or person [error] or activity [error] and order issue instruction
THERP 20-05 (1)	13	54	0	and omit task and activity not wrong and order issue instruction
THERP 20-05 (3)	3	6	0	and order dispatch [error] or order dispatch [attribute] and order dispatch instruction or order dispatch connection plans or order dispatch instructions
THERP 20-06 (1)	34	49	0	and Situation Periodic Test and task [error] or person [error] or activity [error] and or feedback [error] or order dispatch [error] or order issue [error]
THERP 20-06 (2)	19	49	0	and Situation Periodic Test and supervise task or check task or inspect task and task [error] or person [error] or activity [error] and or feedback [error] or order dispatch [error] or order issue [error]
THERP 20-06 (3)	45	54	0	and MMS Type A or MMS Type B or MMS Type AO or MMS Type B or MMS Type T and task [error] or person [error] or activity [error] and or feedback [error] or order dispatch [error] or order issue [error] and order issue
THERP 20-06 (4)	2	34	0	and MMS Type C and task [error] or person [error] or activity [error] and or feedback [error] or order dispatch [error] or order issue [error] and order issue Procedure

Table 6-2 (cont.)

Title	n_j	n_j *max*	n_j *min*	*Inquiries Concerning Formation of Absolute Frequencies*
THERP 20-06 (5)	8	38	0	and task valve or activity valve and task [error] or person [error] or activity [error] or feedback [error] or order dispatch [error] or order issue [error] and order issue instructions
THERP 20-06 (6)	25	54	0	and supervised task or check task or inspect task or discontinue task or adjust task or diminish task or reduce task or normalize task and task [error] or person [error] or activity [error] or feedback [error] or order dispatch [error] or order issue [error] and order issue instructions
THERP 20-06 (7)	32	54	0	and situation Periodic Test or situation revision inspection or person maintenance personnel or person operation personnel or person producer personnel or person assembly personnel or person outside personnel and task [error] or person [error] or activity [error] or feedback [error] or order dispatch [error] or order issue [error] and order issue instructions
THERP 20-06 (8)	39	39	-	and follow order issue instruction [error]
THERP 20-07 (1+2+3+4+5)	13	52	0	and omit task and activity not wrong and order issue instructions
THERP 20-08 (1)	4	4	-	and order dispatch personnel [error]
THERP 20-08 (6)	4	4	-	and order dispatch personnel [error]
THERP 20-09 (2)	11	13	0	and activity [error] and feedback display or feedback display/qualitative or feedback display/quantitative and feedback [error] and feedback marking or feedback display accuracy or feedback reliability or feedback display range
THERP 20-09 (3)	4	6	0	and activity [error] and feedback display or feedback display/qualitative or feedback display/quantitative and feedback [error] and feedback instruction
THERP 20-09 (4)	4	5	0	and activity [error] and feedback display or feedback display/qualitative or feedback display/quantitative and feedback [error] and feedback labeling
THERP 20-10 (1,3,5)	5	14	0	and activity [error] and feedback [error] and feedback reading/quantitative and feedback meter/analog
THERP 20-10 (2)	0	12	1	and activity [error] and feedback [error] and feedback reading/quantitative and feedback meter/digital
THERP 20-10 (4)	4	14	0	and activity [error] and feedback [error] and feedback reading/quantitative and feedback meter/print

Table 6-2 (cont.)

Title	n_i	n_i *max*	n_i *min*	*Inquiries Concerning Formation of Absolute Frequencies*
THERP 20-10 (6)	12	49	0	and activity [error] and feedback [error] and not feedback reading/quantitative and feedback display/quantitative
THERP 20-10 (7)	40	49	0	and activity [error] and feedback [error] and feedback display/qualitative or feedback display/quantitative
THERP 20-11 (1)	7	12	1	and feedback [error] and feedback reading/qualitative and feedback meter/digital
THERP 20-11 (2,5)	17	48	0	feedback [error] and feedback meter/analog or feedback meter/graph and not feedback [attitude]
THERP 20-11 (3,4,6)	16	24	0	and feedback [error] and feedback meter/analog or feedback meter/graph and feedback [attitude]
THERP 20-12 (2)	6	12	0	and activity wrong and activity control or activity control/switch or activity control/system and activity operability
THERP 20-12 (3+4)	1	6	0	and activity wrong and activity control or activity control/switch or activity control/system and feedback instruction
THERP 20-12 (5+6)	37	66	0	and activity control or activity control/system and activity wrong or activity faulty
THERP 20-12 (7)	7	50	0	and situation T11 or situation T12 or task task-preparation or task Time Pressure or task precision or task complexity and not task simplicity and activity control or activity control/system and activity wrong or activity faulty
THERP 20-12 (8->5+6)	39	47	0	and activity control/switch and activity wrong or activity faulty
THERP 20-12 (8->7)	10	47	0	and situation T11 or situation T12 or task task-preparation or task Time Pressure or task precision or task complexity and not task simplicity and activity control or activity control/system and activity wrong or activity faulty
THERP 20-12 (9)	17	36	0	and activity control or activity control/system and activity quantitative error
THERP 20-12 (.10)	8	21	0	and activity control or activity control/system and activity time error
THERP 20-12 (.11)	6	17	0	and activity control/switch and activity wrong and activity operability or feedback instruction
THERP 20-12 (.12)	26	47	0	and feedback control/switch and activity wrong and not activity operability and not feedback instruction
THERP 20-12 (.13)	9	29	-	and activity control/switch and activity faulty
THERP 20-13 (1+2)	13	38	0	and task valve or activity valve and activity wrong or omit task and environment on site
THERP 20-13 (3+4+5)	3	6	0	and task valve or activity valve and activity wrong or omit task and feedback marking and environment on site

Table 6-2 (cont.)

Title	n_j	n_j *max*	n_j *min*	*Inquiries Concerning Formation of Absolute Frequencies*
THERP 20-14 (1+2+3+4)	6	38	0	and task valve or activity valve and omit task and environment on site
THERP 20-16 (1)	7	7	-	and task simplicity or activity monotony
THERP 20-16 (4)	21	26	0	and man-machine system static and task task-preparation or task precision or task complexity
THERP 20-16 (5)	3	26	0	and man-machine system dynamic and task task-preparation or task precision or task complexity
THERP 20-16 (6)	10	27	0	and man-machine system static and situation T1 or task Time Pressure
THERP 20-16 (7)	10	27	0	and man-machine system dynamic and situation T1 or task Time Pressure
THERP 20-22 (1)	16	54	0	and check task or supervise task or inspect task or monitor task or observe task or feedback display/checker or order dispatch personnel and task [error] and order issue instructions
THERP 20-22 (2)	34	90	0	and check task or supervise task or inspect task or monitor task or observe task or feedback display/checker or order dispatch personnel and task [error]
THERP 20-22 (3)	8	45	0	and check task or supervise task or inspect task or monitor task or observe task or feedback display/checker or order dispatch personnel and task [error] and feedback message or feedback alarm
THERP 20-22 (4)	7	13	0	and measure task or search for task and task [error]
THERP 20-22 (5)	3	38	0	and check task or supervise task or inspect task or monitor task or observe task or feedback display/checker or order dispatch personnel and task [error] and task valve or activity valve and environment on site
THERP 20-23 (1a-j)	2	2	-	and feedback message not possible or omit feedback message or feedback alarm not possible or omit alarm feedback
THERP 20-24 (2)	1	17	0	and situation T11 or situation T12 and task [error] or person [error] or activity [error] and feedback message system or feedback signal or feedback instrumentation or feedback signaling
THERP 20-24 (3,4,5)	12	17	0	and task [error] or person [error] or activity [error] and feedback message system or feedback signal or feedback instrumentation or feedback signaling

Table 6-3[18]

Title	m_i	*Queries for Building relative Frequencies*
Swain 20-01 n, 20-03 n	32	and Situation -Tsw1 or Situation -Tsw12 or Situation -Tsw123 or Situation -Tsw23 or Situation -Tsw3 or Situation -Tsw34 or Situation -Tsw45 or Situation -Tsw5 or Situation -Tsw56 or Situation -Tsw6 or Situation -Tsw7
Swain 20-02 (4) n	19	and Situation -T11 or Situation -T12
Swain 20-05 n, 20-06 n	158	and Order issue Presence
Swain 20-06 (5,6,7) n	111	and Situation Periodic Test or Situation Revision or Situation Maintenance or Situation Test or Person Maintenance Personnel or Person Construction Personnel or Person Installation Personnel
Swain 20-06 (8) n	58	and Order dispatch [Object] or Order issue [Object]
Swain 20-07 n	52	and Order issue Procedure
Swain 20-09 n, 20-10 n, 20-11 n	143	and Feedback lacks
Swain 20-12 (7) n, 20-12 (8->7) n	24	and Situation -T11 or Situation -T12 or Task Task-Preparation or Task Time-Pressure or Task-Precision or Task Complexity and not Task Simplicity and Activity -Control or Activity -Control/System or Activity -Control/Switch
Swain 20-12 n	146	and Activity (Object)
Swain 20-13 (1+2) n	132	and Environment in the plant
Swain 20-13 (3+4+5) n	13	and Task Valve or Activity Valve and Activity wrong or Task omit and Environment in the plant
Swain 20-14 (1+2+3+4) n	23	and Task Valve or Activity Valve and Environment in the plant
Swain 20-16 (4,6) n	157	and MMS Sequential and Task (error) or Person (error) or Activity (error)
Swain 20-16 (5,7) n	24	and MMS Dynamic and Task (error) or Person (error) or Activity (error)
Swain 20-18 I n	75	and MMS Type Ba or MMS Type C
Swain 20-22 (5) n	10	and Task proof or Task check or Task inspect or Task supervise or Task observe or Feedback -Display/Checker or Order-dispatch Personnel and Task Valve or Activity Valve and Environment in the plant
Swain 20-22 n	81	and Task proof or Task check or Task inspect or Task supervise or Task observe or Feedback -Display/Checker or Order-dispatch Personnel
Swain 20-23 n	45	and Feedback Message or Feedback Alarm
Swain 20-24 n	17	and Feedback Message system or Feedback Signal or Feedback Instrumentation or Feedback Signalization

Table 6-4

Title	n_{MMS}	*Inquiries for Time Reliability Distribution [TRC]*
TRC Type T1	16	and MMS type A or MMS type Ba or MMS type B or MMS type C degrading and situation T11 or situation T12
TRC Type T2	5	and MMS type A or MMS type Ba or MMS type B or MMS type C degrading and situation T21 or situation T22
TRC Type T3	4	and MMS type A or MMS type Ba or MMS type B or MMS type C degrading and situation T3
TRC Type T4	3	and MMS type A or MMS type Ba or MMS type B or MMS type C degrading and situation T4
TRC Type T5	1	and MMS type A or MMS type Ba or MMS type B or MMS type C degrading and situation T5

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[18] Note that this table is deviating from the one in the German publication since it was an obsolete one there.

Table 6-5

Class	*Concept*	*Class*	*Concept*
-Armature	Fitting	-T11	1.7 second
-Armature	Flap	-T11	2 seconds
-Armature	Pump	-T11	23 seconds
-Armature	Slide	-T11	about 100 seconds
-Armature	Valve	-T11	immediately
		-T12	3 minutes
-Control	Fitting	-T12	4 minutes
-Control	Choke	-T12	5 minutes
-Control	Lever	-T12	6 minutes
-Control	Flap	-T12	8 minutes
-Control	Motor	-T21	10-15 minutes later
-Control	Pump	-T21	12 minutes
-Control	Slide	-T21	18 minutes
-Control	Valve	-T22	30 minutes
-Control	Pilot control magnet valve		
		-T22	32 minutes
-Control/Switch	24/48-vault direct current system	-T22	39 minutes
-Control/Switch	Battery	-T3	1.5 hour
-Control/Switch	Subassembly	-T3	2 hours
-Control/Switch	Digital multimeter	-T3	2.5 hours
-Control/Switch	Rectifier	-T3	3 hours
-Control/Switch	Cable	-T4	24 hours
-Control/Switch	Terminal	-T4	4 day
-Control/Switch	Measurement instrument	-T4	7 days later
-Control/Switch	Multimeter	-T5	Period of 14 days
-Control/Switch	Pin		
-Control/Switch	Computer	-Tsw1	1.7 second
-Control/Switch	Relay	-Tsw1	2 seconds
-Control/Switch	Switching system	-Tsw1	23 seconds
-Control/Switch	Switching system drawer	-Tsw1	about 100 seconds
-Control/Switch	Switch		
-Control/Switch	Switch card	-Tsw1	immediately
-Control/Switch	Rail	-Tsw12	3 minutes
-Control/Switch	Fuse	-Tsw12	4 minutes
-Control/Switch	Memory	-Tsw12	5 minutes
-Control/Switch	Plug	-Tsw123	6 minutes
-Control/Switch	Control	-Tsw123	8 minutes
-Control/Switch	Key	-Tsw23	10-15 minutes later
-Control/Switch	Automated switchover	-Tsw23	12 minutes
		-Tsw3	18 minutes
-Control/System	Time subassembly	-Tsw34	30 minutes
-Control/System	Accessory device	-Tsw34	32 minutes
-Control/System	BE gripper	-Tsw45	39 minutes
-Control/System	KAM	-Tsw5	1.5 hour
-Control/System	Cooler	-Tsw5	2 hours
-Control/System	Test instrument	-Tsw5	2.5 hours
-Display/Checker	Turbine	-Tsw56	3 hours
-Display/Checker	Binoculars	-Tsw6	24 hours
	Television camera	-Tsw7	4 days
		-Tsw7	7 days later
		-Tsw7	Period of 14 days

Table 6-5 (cont.)

Class	***Concept***		***Class***	***Concept***
-Display/qualitative	Alarm		-Reading/qualitative	Weight
-Display/qualitative	Connection		-Reading/qualitative	Failed
-Display/qualitative	Image		-Reading/qualitative	Triggered
-Display/qualitative	Socket		-Reading/qualitative	Note
-Display/qualitative	Television camera		-Reading/qualitative	Observe
-Display/qualitative	Form		-Reading/qualitative	Recognize
-Display/qualitative	Boundary value		-Reading/qualitative	Check
-Display/qualitative	Message system		-Reading/qualitative	Read
-Display/qualitative	Message plaque		-Reading/qualitative	See
-Display/qualitative	Signal		-Reading/qualitative	Perceive
-Display/qualitative	Signaling			
-Display/qualitative	Valve		-Reading/quantitative	Read off
			-Reading/quantitative	Displayed
-Display/quantitative	Display		-Reading/quantitative	Analyze
-Display/quantitative	Display range		-Reading/quantitative	Opened
-Display/quantitative	Pressure		-Reading/quantitative	Closed
-Display/quantitative	Filling level		-Reading/quantitative	Stopped
-Display/quantitative	Instrumentation		-Reading/quantitative	Track
-Display/quantitative	Multimeter		-Reading/quantitative	Receded
-Display/quantitative	Megawatt display			
-Display/quantitative	Computer		-Quantitative error	too strong
-Display/quantitative	Recorder		-Quantitative error	too weak
-Display/quantitative	Position		-Quantitative error	too inaccurate
-Display/quantitative	Closed position		-Quantitative error	too much
			-Quantitative error	too far
-Meter/analog	Display		-Quantitative error	too little
-Meter/analog	Display range			
-Meter/analog	Binoculars		-Time error	too early
-Meter/analog	Television camera		-Time error	too long
-Meter/analog	Filling level		-Time error	too fast
-Meter/analog	Multimeter		-Time error	too late
-Meter/analog	Megawatt display			
-Meter/analog	Recorder			
-Meter/analog	Position			
-Meter/Digital	Form			
-Meter/Digital	Computer			
-Meter/Digital	Plaque			
-Meter/Digital	Key			
-Meter/Digital	Close Position			
-Meter/Graph	Image			
-Meter/Print	Message			
-Meter/Signal	Signal			
-Meter/Signal	Signaling			

Table 6-6

Item	Cahr	THERP	THERP-max	THERP-min	Cahr. max	Cahr min	CAHR. n'i	ki=m/mi	mi for ki	Reason for ki	Hits, Total	Hits, THERP
T20-01 (1)	3.98E-01	1.00E+00	1.00E+00	1.00E+00	5.79E-01	2.18E-01	77.34375	5.15625	32	only 32 cases with time indications	0	0
T20-01 (2)	5.28E-02	5.00E-01	1.00E+00	1.00E-01	4.21E-01	2.18E-01	46.40625	5.15625	32	"	1	0
T20-01 (3)	1.59E-02	1.00E-01	1.00E+00	1.00E-02	3.45E-01	2.18E-01	30.9375	5.15625	32	"	1	1
T20-01 (4)	4.67E-03	1.00E-02	1.00E-01	1.00E-03	2.61E-01	2.18E-01	15.46875	5.15625	32	"	1	1
T20-01 (5)	7.03E-03	1.00E-03	1.00E-02	1.00E-04	2.77E-01	2.18E-01	20.625	5.15625	32	"	1	1
T20-01 (6)	2.05E-03	1.00E-04	3.00E-03	3.33E-06	2.31E-01	2.18E-01	5.15625	5.15625	32	"	1	1
T20-02 (1)	4.07E-02	5.00E-02	5.00E-01	5.00E-03	9.28E-02	1.36E-03	43	1	165	all cases because actions are rule-based (documented by standard log distribution)	1	1
T20-02 (2)	4.07E-02	2.50E-02	2.50E-01	2.50E-03	9.28E-02	1.36E-03	43	1	165	"	1	1
T20-02 (3)	9.49E-01	1.00E+00	1.00e+00	9.43E-01	1.00E+00	1.36E-03	119	1	165	"	1	1
T20-02 (4)	2.14E-02	1.00E-02	5.00E-02	2.00E-03	6.98E-01	3.19E-01	34.736842	8.68421	19	only 19 of the 32 time indications relevant here	1	1
T20-03 (1)	3.98E-01	1.00E+00	1.00E+00	1.00E+00	5.79E-01	2.18E-01	77.34375	5.15625	32	only 32 cases with time indications	0	0
T20-03 (2)	5.28E-02	1.00E-01	1.00E+00	1.00E-02	4.21E-01	2.18E-01	46.40625	5.15625	32	"	1	1
T20-03 (3)	1.59E-02	1.00E-02	1.00E-01	1.00E-03	3.45E-01	2.18E-01	30.9375	5.15625	32	"	1	1
T20-03 (4)	4.67E-03	1.00E-03	1.00E-02	1.00E-04	2.61E-01	2.18E-01	15.46875	5.15625	32	"	1	1
T20-03 (5)	7.03E-03	1.00E-04	3.00E-03	3.33E-06	2.77E-01	2.18E-01	20.625	5.15625	32	"	1	0
T20-03 (6)	2.05E-03	1.00E-05	3.00E-04	3.33E-07	2.31E-01	2.18E-01	5.15625	5.15625	32	"	1	0
T20-05 (1)	4.01E-03	3.00E-03	1.50E-02	6.00E-04	1.03E-01	1.84E-03	13.575949	1.0443	158	all cases for which no instructions are missing	1	1
T20-05 (3)	1.74E-03	3.00E-03	1.50E-02	6.00E-04	2.90E-03	1.80E-03	3.1329114	1.0443	158	"	1	1
T20-06 (1)	2.28E-02	1.00E-02	5.00E-02	2.00E-03	8.32E-02	1.80E-03	35.506329	1.0443	158	"	1	1
T20-06 (2)	6.61E-03	1.00E-03	3.00E-03	3.33E-04	8.32E-02	1.80E-03	19.841772	1.0443	158	"	1	0
T20-06 (3)	4.74E-02	1.00E-02	3.00E-02	3.33E-03	8.02E-02	1.36E-03	45	1	165	Assumtion that there are some procedures to follow in any case	0	0
T20-06 (4)	1.59E-03	5.00E-03	5.00E-02	5.00E-04	2.02E-02	1.36E-03	2	1	165	"	1	1
T20-06 (5)	3.51E-03	3.00E-02	3.00E-02	3.33E-03	1.98E-01	1.17E-02	11.891892	1.48649	111	only operation activities	1	1
T20-06 (6)	2.59E-02	2.50E-01	2.50E-01	1.00E-02	4.70E-01	1.17E-02	37.162162	1.48649	111	"	1	1
T20-06 (7)	5.76E-02	1.00E+00	1.00E+00	6.00E-02	4.70E-01	1.17E-02	47.567568	1.48649	111	"	1	0
T20-06 (8)	9.07E-01	1.00E+00	1.00E+00	1.00E-01	6.90E-01	8.95E-02	110.94828	2.84483	58	only if administrative check	1	1
T20-07 (1+2+3+4+5)	3.56E-02	9.01E-02	3.87E-01	2.09E-02	8.89E-01	1.13E-01	41.25	3.17308	52	only when instructions are used	1	1

Table 6-6 (cont.)

Item	Cahr	THERP	THERP-max	THERP-min	Cahr. max	Cahr min	CAHR. n'i	ki=m/mi	mi for ki	Reason for ki	Hits, Total	Hits, THERP
T20-08 (1)	1.87E-03	1.00E-03	3.00E-03	3.33E-04	1.87E-03	1.36E-03	4	1	165	General assumption that, in each case, a communication took place in some form	1	1
T20-08 (6)	1.87E-03	1.00E-03	3.00E-03	3.33E-04	1.87E-03	1.36E-03	4	1	165	"	1	1
T20-09 (2)	3.74E-03	5.00E-04	5.00E-03	5.00E-05	9.19E-03	3.27E-03	12.692308	1.15385	143	each event includes some kind of feedback unless reported explicitly as missing	1	1
T20-09 (3)	1.96E-03	1.00E-03	3.00E-03	3.33E-04	5.27E-03	3.27E-03	4.6153846	1.15385	143	"	1	1
T20-09 (4)	1.96E-03	3.00E-03	9.00E-03	1.00E-03	4.87E-03	3.27E-03	4.6153846	1.15385	143	"	1	1
T20-10 (1)	2.15E-03	3.00E-03	9.00E-03	1.00E-03	9.95E-03	3.27E-03	5.7692308	1.15385	143	"	1	1
T20-10 (2)	1.36E-03	1.00E-03	3.00E-03	3.33E-04	8.49E-03	3.48E-03	0	1.15385	143	"	1	1
T20-10 (3)	2.15E-03	6.00E-03	1.80E-02	2.00E-03	9.95E-03	3.27E-03	5.7692308	1.15385	143	"	0	1
T20-10 (4)	1.96E-03	5.00E-02	2.50E-01	1.00E-02	9.95E-03	3.27E-03	4.6153846	1.15385	143	"	1	0
T20-10 (5)	2.15E-03	1.00E-02	3.00E-02	3.33E-03	9.95E-03	3.27E-03	5.7692308	1.15385	143	"	1	0
T20-10 (6)	4.10E-03	1.00E-03	3.00E-03	3.33E-04	1.42E-01	3.27E-03	13.846154	1.15385	143	"	1	0
T20-10 (7)	5.18E-02	1.00E-01	5.00E-01	2.00E-02	1.42E-01	3.27E-03	46.153846	1.15385	143	"	1	1
T20-11 (1)	6.492.59	1.00E-03	3.00E-03	3.33E-04	8.49E-03	3.47E-03	8.0769231	1.15385	143	"	1	1
T20-11 (2)	6.49E-03	1.00E-03	3.00E-03	3.33E-04	1.32E-01	3.27E-03	19.615385	1.15385	143	"	1	0
T20-11 (3)	5.92E-03	2.00E-03	6.00E-03	6.67E-04	2.19E-02	3.27E-03	18.461538	1.15385	143	"	1	1
T20-11 (4)	5.92E-03	3.00E-03	9.00E-03	1.00E-03	2.19E-02	3.27E-03	18.461538	1.15385	143	"	1	1
T20-11 (5)	6.49E-03	2.00E-03	6.00E-03	6.67E-04	1.32E-01	3.27E-03	19.615385	1.15385	143	"	1	0
T20-11 (6)	5.92E-03	6.00E-03	1.80E-02	2.00E-03	2.19E-02	3.27E-03	18.461538	1.15385	143	"	1	1
T20-12 (2)	2.33E-03	3.00E-03	9.00E-03	1.00E-03	7.54E-03	2.90E-03	6.7808219	1.13014	146	only if activation took place	1	1
T20-12 (3+4)	1.49E-03	2.35E-03	1.18E-02	4.66E-04	4.68E-03	2.90E-03	1.130137	1.13014	146	"	1	1
T20-12 (5+6)	3.72E-02	6.89E-02	3.48E-01	1.37E-02	3.64E-01	2.90E-03	41.815068	1.13014	146	"	1	1
T20-12 (7)	6.01E-02	5.00E-01	1.00E+00	1.00E-01	9.54E-01	2.77E-01	48.125	6.875	24	only if activation took place under high stress	1	0
T20-12 (8->5+6)	4.42E-02	1.38E-02	6.96E-02	2.73E-03	1.11E-01	2.92E-03	44.075342	1.13014	146	only if activation took place	1	1
T20-12 (8->7)	2.50E-01	1.00E-01	5.00E-01	2.00E-02	9.43E-01	2.77E-01	68.75	6.875	24	only if activation took place under high stress	1	1

Table 6-6 (cont.)

Item	Cahr	THERP	THERP-max	THERP-min	Cahr. max	Cahr min	CAHR. n'i	ki=m/mi	mi for ki	Reason for ki	Hits, Total	Hits, THERP
T20-12 (9)	6.29E-03	1.00E-03	1.00E-02	1.00E-04	4.93E-02	2.95E-03	19.212329	1.13014	146	only if activation took place	1	1
T20-12 (10)	280E-03	3.00E-03	9.00E-03	1.00E-03	1.54E-02	2.92E-03	9.0410959	1.13014	146	"	1	1
T20-12 (11)	2.33E-03	5.00E-03	1.50E-02	1.67E-03	1.12E-02	2.90E-03	6.7808219	1.13014	146	"	1	1
T20-12(12)	1.41E-02	3.00E-03	9.00E-03	1.00E-03	1.11E-01	3.74E-03	29.383562	1.13014	146	"	1	0
T20-12(13)	3.06E-03	3.00E-03	9.00E-03	1.00E-03	2.87E-02	2.90E-03	10.171233	1.13014	146	"	1	1
T20-13(1+2)	4.97E-03	4.20E-02	1.26E-02	1.40E-03	9.62E-02	5.07E-03	16.25	1.25	132	only activities on site	1	1
T20-13(3+4+5)	2.78E-02	2.58E-02	7.75E-02	8.61E-03	4.90E-01	3.73E-01	38.076923	12.6923	13	only the portion of errors that can be traced back to unclear lettering	1	1
T20-14(1+2+3+4)	4.08E-02	2.00E-02	5.99E-02	6.66E-03	8.93E-01	2.85E-01	43.043478	7.17391	23	only errors on valves on site	1	1
T20-22(1)	1.81E-02	1.00E-01	5.00E-01	2.00E-02	7.46E-01	3.77E-02	32.592593	2.03704	81	only when examining activities	1	0
T20-22(2)	2.57E-01	2.00E-01	1.00E+00	4.00E-02	9.81E-01	3.77E-02	69.259259	2.03704	81	"	1	1
T20-22(3)	4.99E-03	5.00E-02	2.50E-01	1.00E-02	5.89E-01	3.77E-02	16.296296	2.03704	81	"	1	0
T20-22(4)	4.24E-03	1.00E-02	5.00E-02	2.00E-03	9.98E-02	3.78E-02	14.259259	2.03704	81	"	1	1
T20-22(5)	6.66E-02	1.00E-01	5.00E-01	2.00E-02	9.33E-01	4.01E-01	49.5	16.5	10	only when examining activity on site	1	1
T20-23(1a-j)	2.44E-03	5.00E-03	5.00E-02	5.00E-04	1.62E-01	1.42E-01	7.3333333	3.66667	45	only when feedback alarm or message	1	1
T20-24(2)	1.36E-03	1.00E-03	3.00E-03	3.33E-04	6.64E-01	3.36E-01	0	9.70588	17	only when feedback signal	1	1
T20-24(3)	9.38E-01	9.50E-01	1.00E+00	1.90E-01	6.64E-01	3.36E-01	116.47059	9.70588	17	"	1	1
T20-24(4)	9.38E-01	9.00E-01	1.00E+00	1.80E-01	6.64E-01	3.36E-01	116.47059	9.70588	17	"	1	1

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