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Integrating Scientific Expertise into Regulatory Decision-Making.

Risk Management Issues - Doing Things Safely with Words: Rules and Laws

JENS RASMUSSEN

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Rasmussen: *Integrating Scientific Expertise into Regulatory Decision-Making. Risk Management Issues - Doing Things Safely with Words: Rules and Laws*

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EUROPEAN UNIVERSITY INSTITUTE, FLORENCE

ROBERT SCHUMAN CENTRE

Integrating Scientific Expertise into Regulatory Decision-Making

Risk Management Issues – Doing Things Safely with Words: Rules and Laws

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Risk Management Issues -
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JENS RASMUSSEN* / **

1. INTRODUCTION

Accidents of the kind considered in this paper ultimately involve a physical process causing damage to people, equipment or the environment. The propagation of an accidental course of events depends on physical actions by people, either in provoking an accident or in diverting a normal course of events in a hazardous direction. Injuries, contamination of the environment, and loss of equipment are all dependent on physical processes capable of damaging physical (including biological) objects. Safety, then, involves the control of work processes so that accidental side effects causing harm to people, the environment, or investments are avoided.

Many levels of politicians, managers, safety officers and work planners are involved in the control of safety by means of words. They seek to motivate the actual performers, to educate them to guide them, or to constrain their behaviour by words, so as to increase the safety of their performance. They issue regulations, instructions, rules, etc. which are actually verbal means for the eventual control of physical processes.

Therefore, from the higher management levels, safe behaviour at work is largely controlled by words. How to do things safely with words? Rules are means for controlling the activities of other people or one's own activities at a later point in time. Rules are work environment characteristics selected, interpreted and compiled into a sequence of actions that will ultimately bring the state of affairs in some future situation into the intended target state.

We are thus concerned with control by rules. What kind of verbal control is included in 'rules'?

According to Webster, rules are defined as follows:

1. An established guide or regulation for action, conduct, method, arrangement, etc.

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In this sense of 'rules', we are concerned with the verbal control of the ultimate actor in the work system.

2. A complete set or code of regulations in a religious order; as, the Benedictine rule.

This definition is less relevant for our purposes, though safety campaigns are often presented with considerable emotional involvement.

3 A fixed principle that determines conduct; habit; custom; as, morning prayer was the rule of the household.

Here we move up a level in generality to definition of principles that can be interpreted as prescriptions for actions in a particular context.

4. A criterion or standard.

This definition, finally, is concerned with the objectives; what are the criteria of safety control?

The definitions presented by Webster actually refer to the different levels of the control hierarchy involved in social control of safety (see Figure 1).

At the top, society seeks to control safety through the legal system: safety has a high priority, but so has employment and trade balance. Legislation exemplifies priorities of conflicting goals and sets boundaries of acceptable human conditions. Research at this level is concentrated in the political and legal sciences. At this level rules are called laws, but the definition remains the same.

Law is, according to Webster:

1. all the rules of conduct established and enforced by the authority, legislation, or custom of a given community or other group.
2. any one of such rules.

The next level is that of industrial associations, trade unions and other interest groups. Here, the legislation is interpreted and implemented as rules to control activities in certain kinds of work places, for certain kinds of employees. This is the level of management and work sociologists. To be operational, the rules now have to be interpreted and implemented in the context of a particular company, taking into account the work processes and equipment applied. Again, many details relating to the local conditions and processes have to be added to make the rules operational and, again, a new discipline is involved, including work psychologists and safety researchers. Finally, we reach the level of the actual work activity; rules once again must be interpreted and implemented within the specific work process (see Figure 2).

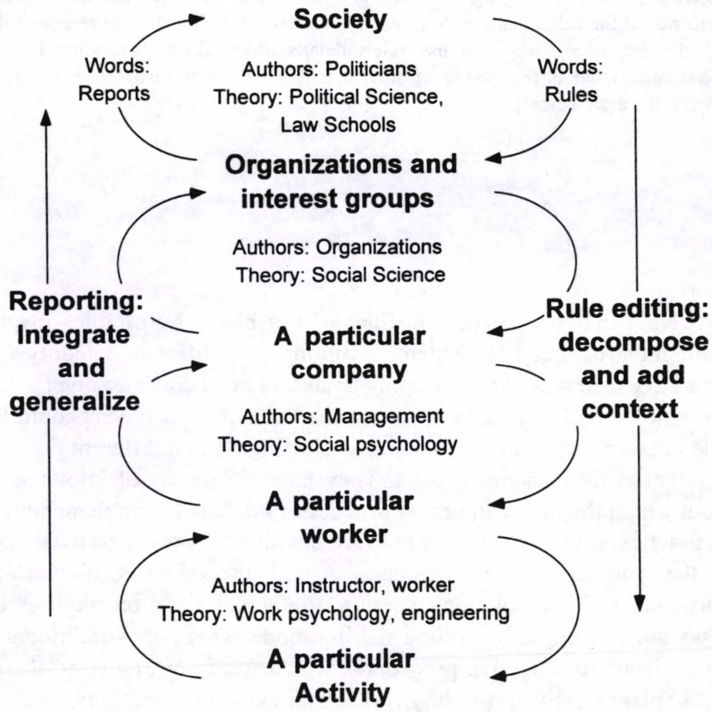

Figure 1. The different levels of the control hierarchy involved in the social control of safety by means of rules

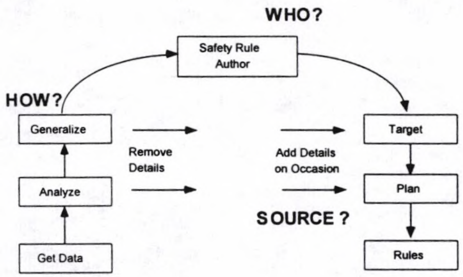

Figure 2. Rule-authoring involves the removal of details by generalization. What is the influence of the rule intention: to provide a reference for allocation of responsibility or to actually improve safety? To use rules, details must added, depending on the local conditions. What is the source of such details? Who adds them? A planner, a safety officer, the actor herself?

Note that we are here dealing with a hierarchy of rules displaying very different structures and content, involving very different categories of people - who have different and conflicting goals and must consider diverse time scales - but who are still trying to constrain the behaviour of other people in a context rule authors cannot know in detail, projecting on to a different point in time and a situation they cannot predict. They have no means of knowing the context from which the user will draw the necessary details for implementation.

In practice, therefore, rule authors are not able to foresee all local contingencies of the work context. For instance, a work procedure is often designed for a particular task in isolation, whereas, the actual situation requires that several tasks are carried out in a time-sharing mode. This poses additional constraints on the actually effective procedures which were not known to the designer or work planner. Even for highly constrained task situations, such as nuclear power operation, modification of procedures is repeatedly found[1], and operators'

[1] Fujita, (1991): What Shapes Operator Performance? paper presented at JAERI Human Factors Meeting, Tokyo, November, 1991; to be published as 'Data, Keyholes for the Hidden World of Operator Characteristics' *International Journal of Man-Machine Studies, forthcoming*. See also Vicente *et al.* (1995): A Fieldstudy of Operator Cognitive Monitoring at

violations appear to be quite rational, given the actual work load and timing constraints (cf. work-according-to-rules strikes by civil servants). An important consequence of this is that a basic conflict exists between error, seen as a deviation from the rational and *normally used, effective procedure* (typically not known by post-hoc accident analysts) and error, seen as *a deviation from normative procedure*. One implication in the present context is that following an accident it will be easy to find someone involved in the dynamic flow of events that has violated a formal rule by following established practice. Consequently, accidents are typically caused by 'human error' on the part of a train driver, pilot, or process operator. This invites a closer look at post hoc causal analysis.

2. Causal Explanations

Causes of accidents are identified by backtracking along the course of accidental events from the ultimate, unacceptable effect (see Figure 3).

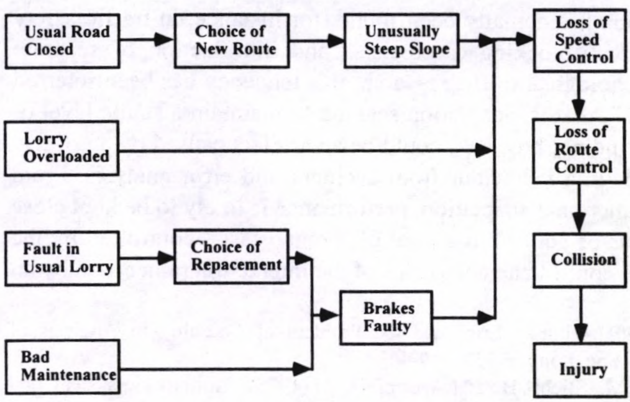

Figure 3. In accident analysis the course of events are backtracked to find causes. However, what should be included in the causal tree? Only the unusual events? And when to stop? How to improve safety? Removal of causes is likely to be compensated by adaptation to change.

Pickering Nuclear Generating Station. Tech. Report CEL 95-04. University of Toronto: Cognitive Engineering Laboratory.

Causal explanations

Nature of causality shapes analysis:
Decomposition, how far?
- to the level of events familiar to the analyst;

Events to include?
- the unusual events; normal ones are taken for granted;

Stop rule to apply?
- depends on the objective of the analyst

What should be included in the causal tree and to which extent should the search be taken?[2] Causal analysis sets focus on the individuals directly involved in the dynamic flow of events (operators, train drivers, pilots) in an artificial way. Furthermore, the search to identify improvements is basically different from the legally-oriented search to find somebody to blame.

Causal trees obtained from an accident analysis are not models of functional mechanisms, but rather records of particular cases. As such, they do not reflect the adaptation of the people involved according to general criteria, such as effectiveness, work load and social pressure. Improvement of safety by removing causes is very likely compensated by people's adaptation.

Such compensation has actually been found, for instance, in traffic safety work in response to anti-blocking car brakes[3], and introduction of separate bicycle paths.[4] In psychological traffic research, this tendency has been referred to as 'risk homeostasis', that is, adaptation seeking to maintain a stable level of perceived risk.[5] This finding, however, could be an artefact caused by an overly narrow focus on modelling behaviour from accident and error analysis. From the point of view of functional adaptation, performance is likely to be kept close to the boundary to loss of control in a kind of 'homeostasis' controlled by the perception of dynamic control characteristics of the interaction rather than by an

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[2] Rasmussen, J. (1990a): Human Error and the Problem of Causality in Analysis of Accidents. Phil. Trans. R. Soc. Lond. B 327, 449-462.

[3] Aschenbrenner, K. M., Biehl, B. and Wurm, G. M.(1986): Antiblockiersystem und Verkerhssicherheit: Ein Vergleich der Unfallbelastung von Taxen Mit und Ohne Antiblockiersystem. (Teilbericht von die Bundesanstalt für Strassenwesen zum Forshungsproject 8323: Einfluss der Risikokompenzation aut die Wirkung von Sicherheitsaussnahmen),. Mannheim, F.R. Germany. Cited in Wilde: G.S. (1988): Risk Homeostasis Theory and Traffic Accidents: Propositions, Deductions, and Discussion in Recent Reactions. Ergonomics. 31, 441-468. See also Status (1994): What Antiblocks Can Do, What they Cannot Do. Status, Vol. 29, No. 2, January 1994, pp. 1-5. Arlington, VA: Insurance Institute for Highway Safety.

[4] Ekner, K.V. (1989): 'Preliminary Safety Related Experiences from Establishment of Bicycle Paths in Copenhagen, 1981-83'. Technical Report (in Danish) Copenhagen: Stadsingniørens Direktorat.

[5] Wilde, G.J.S., (1976): 'Social Interaction Patterns in Driver Behaviour: An Introductory Review', Human Factors, 18, 477-492.

abstract variable such as 'risk', that is, touching the boundary to loss of control is necessary, for instance, for a dynamic 'speed-accuracy' trade-off[6].

It follows that a new system-oriented approach is needed to understand the adaptive behaviour of socio-technical systems and its influence on system safety as well as to develop new methods to identify system parameters that are sensitive with respect to safety improvement. Such an approach must be based on in-depth studies of accident cases and the *normal functioning* of the systems. In other words, errors and accidents are not particular, separable phenomena, but must be studied as the effect of normal, adaptive behaviour drifting toward the boundaries of acceptable performance.[7] An important implication is that a research programme should not only include 'risk' research efforts within the various disciplines, but also basic behavioural research addressing the performance of individuals, organizations and society in a coherent way.

STOP RULES OF CAUSAL ANALYSIS

Accident analyst:

- an event of a familiar category is found;
- focus on people directly involved in the course of unusual events

Therapist, Designer:

- a cure is known; therefore, different results obtained by the organizational sociologist; work psychologist and safety officer

Lawyer:

- an individual 'in control' of actions who did not behave according to the norms is identified
- the person who could have prevented the accident with the least expense to society ('scientific liability theory').

In consequence, the required low probability of major accidents together with the fast pace of change of modern socio-technical systems call for a fundamental review of methods for the analysis of major accidents. Separate approaches will be needed in the legal system to identify the responsible persons and to develop ways to improve safety in the risk management system.

To come closer to the new requirements, it is thus necessary:

- to examine the present *changing conditions of risk management* and safety control;
- to define the socio-technical *safety control system* in more functional terms; and
- to describe in detail the object of control, that is, the *sources of hazard* within industrial installations.

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[6] Rasmussen, J. (1990b): Role of Error in Organizing Behaviour. Ergonomics, 1990, vol. 33, nos 10/11, 1185-1190.

[7] Rasmussen, J. (1994): Risk Management, Adaptation, and Design for Safety, in: Sahlin, N. E. and B. Brehmer (Eds.): Future Risks and Risk management. Dordrecht: Kluwer. 1994.

These aspects are the topics of the following sections.

3. Changing Requirements for Risk Management

CHANGING REQUIREMENTS TO RISK MANAGEMENT

- *Fast pace of technological change:*
  - Safety cannot be based on past experience
- *Large-scale systems:*
  - increased hazards
- *Highly integrated systems:*
  - effects or errors propagate widely
- *Dynamic and competitive environment:*
  - pressure toward cost-effectiveness
- *Changing business strategies*
  - focus on finance and investment
- *Increased public awareness*
  - 'right to know' legislation

Industrial organizations are presently facing a highly dynamic and competitive environment due to the fast pace of technological change. In addition, activities are increasingly integrated and, therefore, effects of inappropriate decisions and errors propagate rapidly and widely. At the same time, centralization is creating potentially dramatic effects on the environment and on society. This has focused public attention on the problems involved in the *low-risk operation of high-hazard systems*.

Analyses of recent major accidents invariably have pointed to the role of human error; indeed it is often stated that 80-90 per cent of industrial accidents may be traced to this factor. Consequently, considerable resources have been spent on human error research. Comprehensive programmes have been developed to define and quantify human errors, though without any significant success; reliable 'human error' data bases still do not exist. The concept of human error is, in fact, very elusive. At a closer look, the frequent allocation of accidental causes to human error appears to be a direct reflection of the nature of causal analysis, as already noted.

The investigations of recent major accidents all present a complex set of preconditions that shaped the stage of the accident. Several decision-makers in different organizational units, performing diverse management, planning and operational tasks at all levels of the organization contributed to the preparation of the path of accidental events.

A review of reports on all recent large-scale accidents[8], including Flixborough, Zeebrugge, Clapham Junction and Chernobyl shows that such accidents are not caused by a stochastic coincidence of violations of the designed defenses, but by systemic processes leading to operation outside the designed regime.[9]

When such systems are operated outside the design envelop, the problem becomes one of inadequate maintenance of designed defenses, not errors on the part of the individual people actually operating the systems. It would appear that we need to understand better the conflict between the forces shaping management performance in a dynamic and highly competitive environment and the requirements of low-risk operation of high-hazard systems.

LOW-RISK OPERATION OF HIGH-HAZARD SYSTEMS

Some observations:

• Human error is often reported to be the cause of 80-90% of accident cases, *but reports also show a complex coincidence of errors, violations and technical faults*

• Accidents are not caused by stochastic coincidence of events, *but by a systematic drift of organizational performance under competitive pressure resulting in operation outside design criteria, that is, inadequate management of designed defenses*

Solution is not to fight human error, but to support the maintenance of defenses

4. The Safety Control System

To identify the implications on risk management of the fast pace of change in a modern dynamic society, a review of the socio-technical system involved in safety control as presented in Figure 4 will be illustrative.

All large-scale accidents involve the loss of control of hazardous physical processes, such as the loss of control of large-scale equipment (ships, aeroplanes, trains), large amounts of energy (nuclear plants, chemical process plants), or hazardous material (nuclear or chemical plants, transport of hazardous substances). The cause of accidents, therefore, is often attributed to the people in direct contact with the hazardous processes, such as pilots, train drivers, plant operators. However, inappropriate decisions at any level of the social system, as shown in Figure 4, will influence safety.

[8] HMSO (1975): The Flixborough Disaster, Report of the Court. London: Her Majesty's Stationary Office; HMSO (1987): M V Herald of Free Enterprise. Report of Court, London: Her Majesty's Stationary Office; HMSO (1989): Investigation into the Clapham Junction Railway Accident.. London: Her Majesty's Stationary Office; see also Lewis, H. W. (1986): The Accident at Chernobyl Nuclear Power Plant and its Consequences. Environment, 28 (9), 25-27.

[9] Rasmussen, J. (1993): Market Economy, Management Culture and Accident Causation: New Research Issues? Proceedings Second International Conference on Safety Science. Budapest: Meeting Budapest Organizer Ltd.; Rasmussen, J. (1994), *op cit*, note 7.

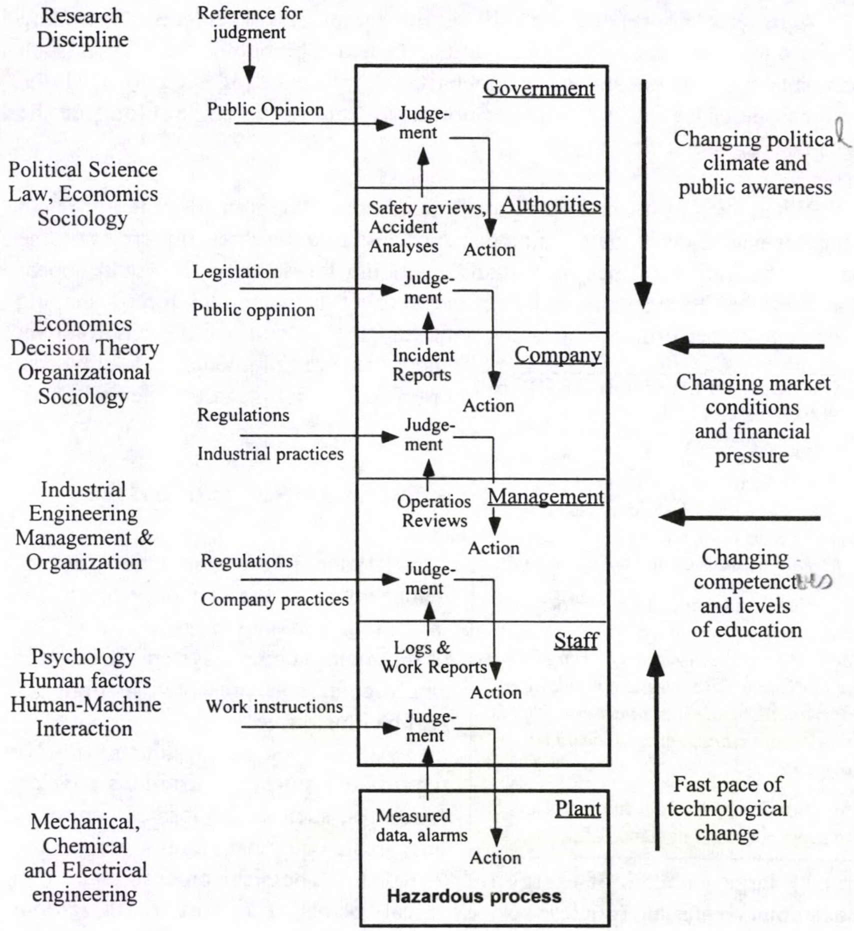

Figure 4. Many nested levels of decision making involved in the control of hazardous production processes. Low risk operation of such high hazard processes depends on proper coordination of decision making at all levels. Study of the overall interaction among these decision processes under the influence of the dynamic environmental pressures is necessary to identify research problems which should be considered within the different academic disciplines.

At present, the effectiveness of decision makers at all levels is strained by various trends: regulation of safety by society through legislation and instruction is slow and less effective under the current dynamic conditions; proper risk awareness among company management is stressed by an aggressive, competitive environment; and established work practices are challenged by the fast pace of change of technology. In this way, the social system that serves to control not only the productive processes of industry and transport, but also the risks involved, is presently subject to several transformations. At the same time, organizations are changing from the traditional, hierarchic command-and-control structure toward more flexible, distributed management structures. In some cases, the introduction of flexible, self-organizing management structures has been used explicitly to improve risk management (see Figure 5).[10]

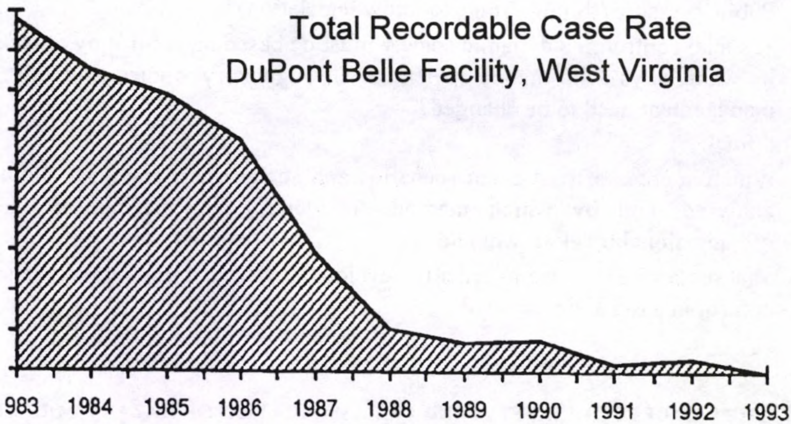

Figure 5. The reportable case frequency through the change from a traditional command-and-control organization toward a employer-involving, self-organizing structure (source: Knowles, 1993).

This raises the question of the interaction between normal business management and risk management. We will return to this question following a

[10] A success story with respect to such changes of business and risk management has been presented at the recent OECD workshop in Paris, July 1995, describing the DuPont developments at the Belle, West Virginia facility. A detailed description is found in: Knowles, R. N. (1993): Life on the Bubble: Leading near the Edge of Chaos. 3rd Annual Chaos Network Conference, Minnesota, September, 1993.

brief discussion of the object of safety control, that is, a hazardous productive process.

The changing conditions of risk management raise a number of research questions:

- What kind of changes in the social environment are currently posing pressure on the functions of work organizations? Increased competition? Fast pace of technological change? Changing professional background of decision-makers? Public opinion?
- What are the time constants of the different sources of pressure and their influence on organizational behaviour?
- What is the nature of the interaction between the time constants of the pace of change of such pressures and the response time of regulatory bodies?
- If social policy-making and regulatory rule-making cannot catch up with the environmental pace of change, what should replace social control of safety by rules of conduct? Control by objectives? Request for 'ethical accounting'?[11] Public pressure (through right-to-know legislation)?
- If social control in a dynamic society must be based on control by objectives, in what ways will the competencies of regulatory bodies and company management need to be changed?

And finally:

- Which sources of past-event scenarios and social science studies should be analysed, and by which method, to identify the mechanisms behind organizational break-down; and
- what research is needed in order to develop legislative improvements in safety control in a dynamic society?

5. The Concept of 'Safety' and a Classification of Hazard Sources

A glance at most programmes of conferences and courses on industrial safety shows discussions organized around topics, such as organizational aspects of safety, human error, management issues, social factors and safety culture. Topics are normally categorized according to classical academic disciplines, often even when such discussions take place in interdisciplinary assemblies. Furthermore, the concept of *safety* is normally accepted without much debate about the source of the actual hazards which indeed raise the need to study safety. This can lead to the observation during discussions that any statement by the speakers may be meaningfully contradicted if one chooses a

[11] See e.g., Bogetoft P. and Pruzan, P. (1991): *Planning with Multiple Criteria*. Amsterdam: North Holland.

suitable assumption about the speaker's implicit context and preconditions. In other words, agreement and disagreement with a speaker can be equally well-justified in most cases depending on the choice of context.

In consequence, such discussions would often be much more fruitful if the concept of safety and the relevant sources of hazard were more explicitly defined and categorized. The purpose of the following reflections is to point attention to some basic issues which need clarification for a meaningful, scientific discussion to take place. However, once these basic issues have been clarified and the constituents of 'industrial safety control' have been identified, each of these components of 'safety' requires an interdisciplinary study, not a separate discussion within the classical disciplines.

It is often argued, that a new discipline of *safety science* should be established and, indeed, the first two triennial 'World Congresses on Safety Science' have already been held. However, the question remains as to whether 'safety' can be separated and defined satisfactorily as a concept for scientific investigation within a particular discipline or whether safety is a reflection of the interaction of the normal behaviour of individuals and organizations with the boundaries of acceptable performance as defined by the work environment.[12] It has been argued elsewhere[13], that 'errors' do not form a stable category of human behaviour, but are the reflections of normal (and normally very effective) psychological mechanisms and of the interaction with the boundary conditions of performance in a particular environment. 'Error', therefore, is not a field of study which can be approached by separate analysis. In the same way, 'safety' is not a separable property of the behaviour of a socio-technical system. Safety is a value aspect reflecting the degree of interaction with boundary conditions of the normal behaviour of such a system. An observation from several general discussions of safety - social aspects of safety, safety culture, etc. - reflects this problem. Very often, the term 'safety' can be replaced with other value statements such as, for instance, 'beauty', without the discussion becoming less meaningful. The key problem is that value features are not operational with respect to understanding a mechanism or controlling a process. Value features can only define priority properties useful for choosing among alternatives identified by other means, that is, from a *functional* understanding of a system's performance.

Research aimed at enhancing understanding of the functional or operational preconditions of safety must, therefore, be concerned with an understanding of the *normal* performance of a system and its natural variability together with the interaction resulting from such variability with the boundary conditions of acceptable performance. The behaviour of a complex socio-technical system cannot be understood unless the relevant phenomena are

[12] Rasmussen, J. (1990a), *op. cit.*, note 2.

[13] Rasmussen, J. (1990b), op cit., note 6.

subjected to coordinated studies involving diverse technical and human sciences. Safety, therefore, is not the topic of a particular science but a conceptual marketplace calling for cooperation among researchers working within the core of several classical disciplines. This is especially the case as paradigms are presently changing simultaneously due to the wide acceptance of the cognitive point of view across disciplines. We return to this convergence later in an appendix to this paper.

Safety is often, and implicitly, defined by the absence of a *negative* attribute such as accidents. When attempts are made toward a definition identifying the presence of a *positive* attribute, typically very general concepts related to quality aspects emerge, such as the presence of concern and care, good housekeeping and standard practices, 'safety culture', etc. Such definitions are difficult to make operational, except in motivational safety campaigns.

Focused efforts to control safety must eventually influence the physical processes which can lead to accidents. All accidents are the ultimate effects of some physical processes resulting in damage to property or injury to persons. Therefore, the choice of measures for safety control, to be effective, depends on a proper identification of the accident-creating process which is to be harnessed by the control effort. There are, however, basically different strategies for control of the operational performance of a system having basically different properties and preconditions. A brief discussion of these strategies will be useful.

6. Sources of Hazards

In a well balanced society, an inverse relationship appears to be found between magnitude and frequency of accidents. That is, the efforts spent by society to a large degree depend on the integrated losses during a given period across accidents within the categories of accidents. This relationship immediately leads to different modes of hazard control. Even if accidents actually appear as a continuous spectrum in the resulting -45^0 log-log plot, some characteristic categories related to the applied hazard control can be defined.

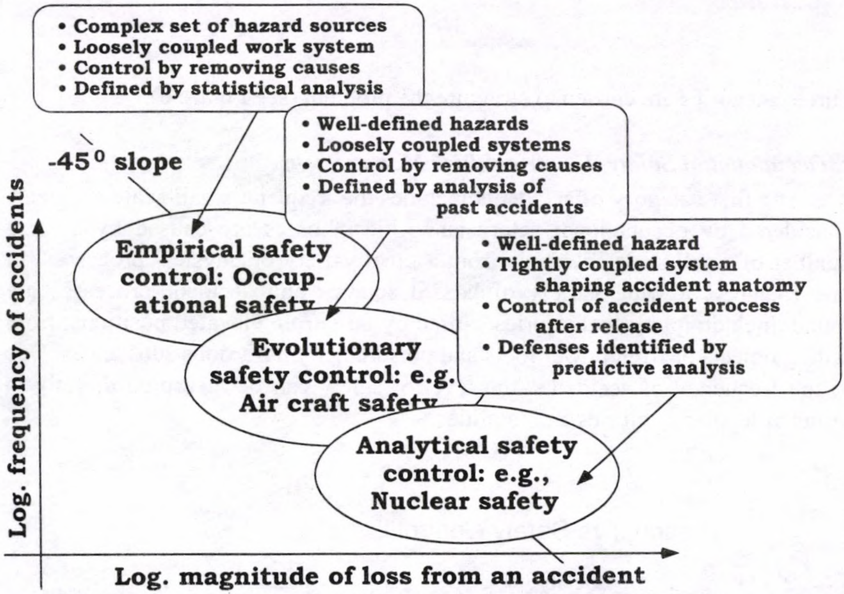

Figure 6. The figure illustrates the basic features of different hazards and the related hazard sources which have led to different risk management strategies.

Three categories are chosen to structure the problem (see Figure 6).

1. Occupational Safety, Empirical Risk Management

The first category of accidents includes the frequent, small-scale accidents considered by occupational safety authorities. Losses are caused by a large number of small-scale accidents from a great variety of physical processes. In this category, a wide variety of hazard sources and accident processes are found, including physical injuries caused by falls from elevated positions, from falling objects or from power tools and poisoning by hazardous substances. Due to the frequency of accidents, the level of safety can be measured directly in terms of lost-time injuries and fatalities.

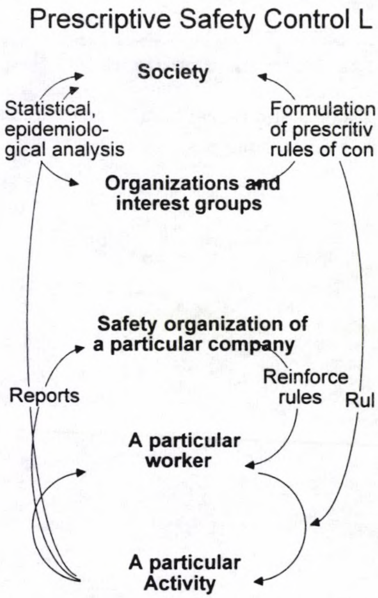

Figure 7. Prescriptive Safety Control Loops. Simplistic illustration of the traditional control of safety by prescriptive rules of safe conduct.

The category typically includes cases where the victim is the actor herself during work activities in homes, construction sites, and so on. Control of occupational safety involving frequent, but small-scale accidents is normally based on an *epidemiological analysis* of accident reports. Such analyses do not normally examine the accident process because the reports on which analyses are based are standard case reports required by work safety authorities. This generally implies that hazard management cannot be directed toward specific accident processes except for large sets of uniform accidents such as loss of control by drivers during high-speed highway driving. In this case, protection is aimed at controlled release of kinetic energy (brakes, crash-barriers, collision-proof car bodies, airbags, safety-belts, etc.).

In other words, the aim of safety precautions will be to prevent future repetitions of a reasonably large subset of cases from the past by *removing the statistically most significant causes and conditions.* Causality in this sense is defined by set membership and the logical necessity of set relations. That is, causes are defined by the defining attributes of a *category* of accidents, not by the functional relations among events in the physical accident *process*.

Safety rules for this category are derived by statistical analysis across companies and cases, and are typically phrased as rules of conduct relating to the behaviour of the actor (frequently also the victim), the work planner and the company management. Recent examples are rules of conduct of companies and actors with respect to the use of scaffolds for construction work, asbestos for isolation, organic solvents for painting and cleaning and driving rules. Rules are based on generalizations from statistics and are therefore authored by regulatory bodies and organizations at a high level of society. Safety control involves monitoring and penalizing violations of the rules of conduct as well as evaluation of the effects on accident statistics. Since rules are based on statistics, not on functional prediction, the safety organizations will typically be separate from the productive line organization (see Figure 7).

2. Medium-size Accidents, Evolutionary Risk Management

The second category includes major accidents, that is, cases in which multiple persons are affected or major losses are incurred (aircraft accidents, major hotel fires, capsizing of ro-ro ferries). Losses are related to single events and the frequency of accidents in this category also enables direct measurement of the actual level of safety. However, the accidents are of a magnitude that calls for detailed analysis of the accident process in each case. In this category, therefore, safer systems evolve from design improvements in response to *analysis of the latest individual major accident*. Typically, accidents are related to rather well-defined major hazards and accident processes. The risk management mode to be applied depends on the nature of the system and the related accident process. In some cases, the relevant processes have a uniform anatomy and control of the effects of the process can therefore take place after its release (fire hazards can be controlled after ignition by means of smoke detectors, alarms, sprinklers, sectioning of buildings, etc.). The strategy is thus largely independent of the particular cause of release. In other cases, the accident processes after release are much more varied and effective control must be directed toward avoidance of release; that is, it will be based on fighting the possible causes of release (for instance, capsizing of ro-ro-ferries, explosions in petrochemical installations). Due to the size and well-defined source of hazards, multiple defenses against releasing causes have normally evolved from analyses of past accidents. However, due to more loosely coupled systems, they will be based on administrative rules defining safe conduct.

3. Rare, Large-scale Accidents, Analytical Risk Management

The third category comprises very rare accidents in very large, integrated installations, such as nuclear power plants, major chemical process plants. Consequently, the hazard source and the accident process are well defined and known. Large-scale accidents can only be caused by the release of substantial amounts of energy or hazardous substances. The actual level of safety in this category cannot be measured empirically, but must be determined by *probabilistic risk analysis*. As the consequences of this type of accident are extremely severe, the acceptable mean time between accidents is very long compared to the life time of the individual installation. In this case, risk management cannot be based on direct measurement of the level of safety in terms of evidence from accidents, but must be based on prediction of the risk involved in operation. This is possible when the hazard is well-defined (loss of control of major energy accumulations), when it is possible to detect release of the hazard (detection of loss of control by measurement, for example of pressures and temperatures indicating approaching run-away), and when the accident process is well-confined (release of energy channelled and controlled by multiple defenses). That is, a reliable, predictive risk analysis is possible when a tightly-coupled technical core of the system creates a well-defined anatomy of accidents.

For this purpose, probabilistic risk analysis (PRA) has been developed. System design is then based on an estimation of the probability of a full-scale accident, considering the likelihood of simultaneous violations of all the designed defenses. Given the level of acceptable risk and the reliability (including maintenance) of the individual defenses (which can be known from statistical evidence), the necessary number of causally independent defenses can be estimated. The assumption is that the probability of violation of the defenses individually can and will be verified empirically during operation, even if the probability of a stochastic coincidence must be extremely low. Thus, the frequency of the individual constituents of an accident can be directly observed and the quality of the related activities can be empirically controlled. In this way, the reference for monitoring the performance of staff during work operations is *derived from the system design assumptions*. Risk control for this category thus depends on an operational management based on monitoring the state of the defenses with reference to the design assumptions, not to empirical evidence from past accidents.

Rules for control of safety in high-hazard installations are not directed toward control of the average performance during a large number of different work processes and of hazards by removing causes and conditions that are correlated with past accidents. Rules must be specific for the particular productive process and design of the related equipment and must serve to control the state of the defenses developed for the particular hazard. For this category, rules of conduct are generated top-down in the social control hierarchy for each type of high hazard installation.

Through regulatory bodies, government sets priorities and targets for installations based on a predictive hazard analysis. The predictive risk analysis specifies the preconditions for safe operation and regulatory bodies formulate rules of conduct for the operation of systems. These are implemented for the particular plant by the plant suppliers and the operating organization and, in turn, the work planners issue formal work orders, including rules for safe conduct.

In this case, risk management is functionally based, requiring substance matter expertise. It should, therefore, be integrated in the productive organization (see Figure 8). This is actually the background of the success of the DuPont experiment presented in Figure 5. The typical characteristics of empirical and analytical risk management are shown in Figure 9.

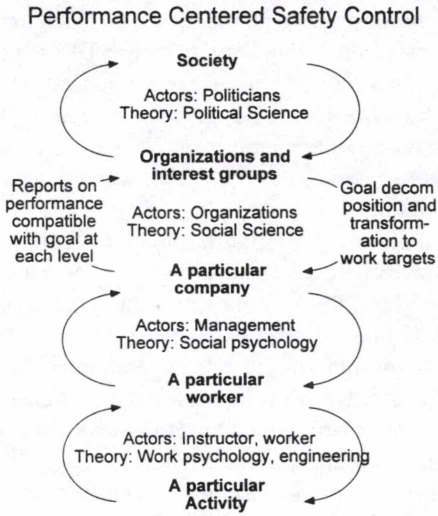

Figure 8. The different levels of the control hierarchy involved in the general control of industrial activities.

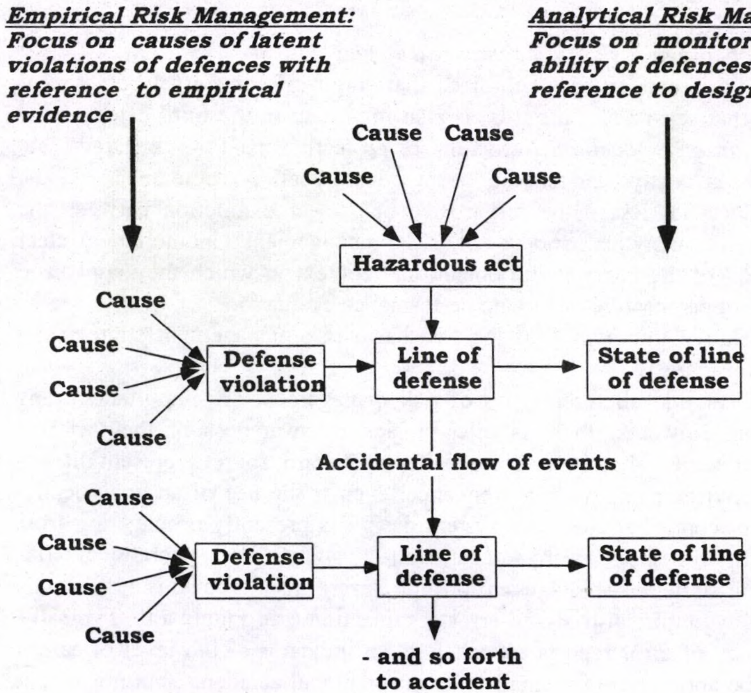

Figure 9. Risk management in high-hazard systems is focused on monitoring the availability of defenses with reference to design specifications, not on an empirical control of the causes of past accidents as is the case for general work safety.

Interaction between Risk Management Strategies

It should, however, be emphasized that empirical control (by removal of the causes that can release hazards) is also important in the third category for the *protection of production.* Activation of protective measures in large-scale installations is costly, and should be avoided by all possible means. This, however, does not lessen the importance of a clear distinction between the empirical and analytical modes of risk management, including a clear identification of the hazards and operational context in which they apply and their different perspective on human performance evaluation.

The relative importance of the two basic risk management strategies is indicated in Figure 10.

It is clear that all three types of risk management are important in any organization. However, there is often a lack of awareness of the fact that different strategies are required for different hazard sources present in one particular environment. As a consequence, even if the use of an analytically-based safety control strategy for system design is presently propagating from high-hazard systems toward occupational safety, the operational risk management strategy applied, even for high hazard installations, is still heavily influenced by empirical trial-and-error organization (see Figure 11). Typically, the frequency of error reports are taken as an indicator of the level of safety. This may be appropriate for small-scale occupational accidents, but not for the risk of large scale accidents. As we will see, precursors of accidents in a system designed by a defense-in-depth strategy will not be minor accidents, but inadequate maintenance of defenses.

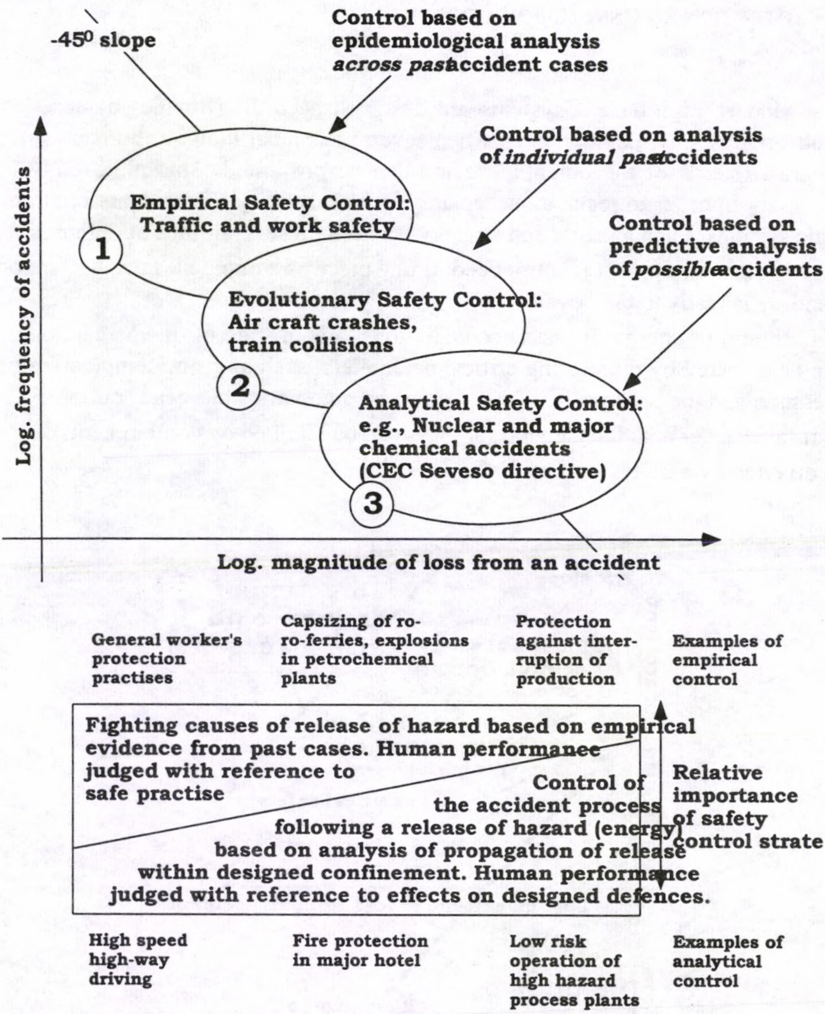

Figure 10. The figure illustrates the basic features of different hazards which have led to different risk management strategies. The top figure locates different hazard categories in the frequency-magnitude spectrum. The lower parts illustrates the relative importance of typical risk management strategies across the spectrum together with some illustrative examples.

7. PROTECTION AGAINST MAJOR ACCIDENTS

Modern high-hazard systems are designed according to the 'defense-in-depth' philosophy; namely, even when several technical faults or human errors occur, a release of the potential hazard can be prevented. This philosophy is necessary in order to reach an acceptably low probability of accidents in large-scale systems. Such a protection strategy is based on several lines of defenses:

1) redundant equipment is introduced; if one piece of equipment fails, a spare or stand-by is ready to take over;

2) if control of energy or mass accumulations fails in spite of this precaution, it can be detected by monitoring critical parameters, such as rising temperature or pressure, and the process can be shut down by automatic emergency actions;

3) if this barrier also fails, energy or mass can be retained by containment, or

4) diverted by barriers, and so forth.

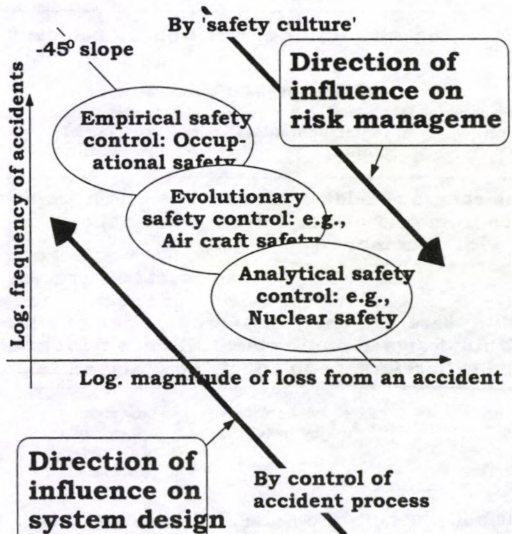

Figure 11. Evidence from past major accidents tends to demonstrate that while system design is increasingly influenced by the analytical risk management strategies developed for high-hazard systems management strategies, even of high-hazard systems, are influenced mainly by the empirical management strategies developed for low-hazard systems.

Only a coincidence of errors and faults violating all lines of defenses will release a full-scale accident. Therefore, hazard control is directed toward keeping the barriers intact. In this way, the safety strategy is planned by analysis of the normal work process and the hazards involved, not by an empirical control of the causes of past accidents.

However, the defense-in-depth philosophy also has a negative side. When a system is made functionally insensitive to individual errors and faults, it is more difficult to detect errors during work and latent effects of errors are more likely to be neglected in maintenance work.[14]

Migration toward Accidents

There seems to be a natural migration toward the boundaries of acceptable performance in any active work organization[15]. Human behaviour in any system is shaped by objectives and constraints, which must be respected by the actors for work performance to be successful. Such objectives and constraints define the boundary conditions of a work space within which the human actors can navigate freely. The choice among several possible work strategies for navigation within the envelope specified by these boundaries depends on subjective criteria related to process features, such as time spent, work load, pleasure, excitement of exploring new territory, and so forth.

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[14] Rasmussen, J. (1991): Safety Control: Some Basic Distinctions and Research Issues in High Hazard Low Risk Operation. Contribution to the May '91 Bad Homburg workshop on Risk Management, in: Brehmer, B. and Reason, J. T. (Eds.): Control of Safety. Hove, UK: Lawrence Earlbaum (forthcoming).

[15] Rasmussen, J. (1990), *op cit.*, note 2.

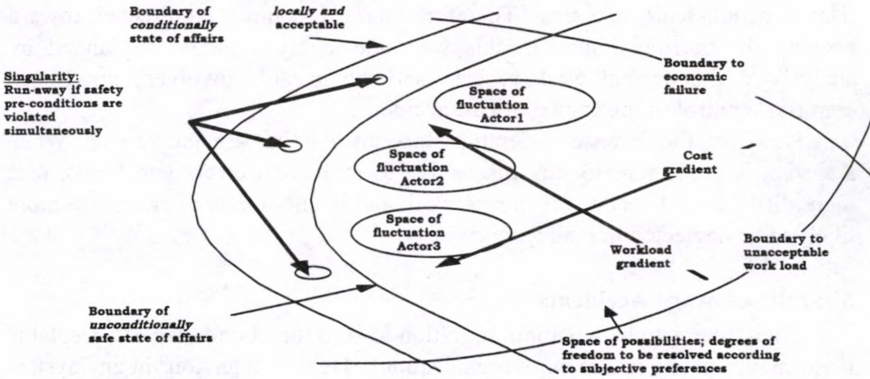


Figure 12. An analogy between migration toward boundaries to loss of control of human activities under pressure to optimize effectiveness and the Brownian movements of particles in a field subject to strong gradients. In addition, in a complex organization, several actors are migrating more or less independently within the space of acceptable performance. In systems designed according to the defense-in-depth principle, major accidents are caused by simultaneous violation of singular points within the boundaries defining acceptable performance, as seen locally.

Activity, therefore, will show great variability due to local, situational features which, in turn, leads to frequent modifications of (and shifts among) strategies. In this sense, activity, characterized by local, situation induced variations within the work space, calls to mind the 'Brownian movements' of gas molecules. Such variability will give the actors themselves ample opportunity to identify an 'effort gradient', while management is likely to build up a 'cost gradient'. The result will very likely be a systematic migration toward the boundary of acceptable performance. Therefore, a precondition for safe and reliable performance depends on *these boundaries being visible and reversible* to the staff.

In a system designed according to the defense-in-depth policy, safety preconditions related to different parts of a protective system, including passive stand-by functions and functional redundancy, can be locally and individually violated - as a result of an error or an intentional act (for example, related to testing and maintenance) without operational effects. If, however, several defenses are violated simultaneously by different actors, the margin to accident decreases drastically; that is, the boundary of acceptable performance for the individual actor is conditionally dependent on the state of other defenses. Unfortunately, the different lines of defense are often controlled by different parts of an organization. Local optimization in response to economic pressure and other kinds of changes (in products, staffing, etc.) very likely will lead to the introduction of resident, latent violations of safety preconditions which, in turn, imply a degradation of the higher level safety policy. In consequence, large-scale accidents are singularities involving a global system structure, overseen only by decision-makers at a level where knowledge about technical matters is not evolving or maintained through practice.

The effects of adaptation under competitive pressure may in fact be the fallacy of the defense-in-depth design strategy: systems designed so as not to be functionally sensitive to individual operations and maintenance failures will have a tendency to systematically migrate toward accidents.

The conclusion to be drawn from such considerations is that low-risk operation of high hazard systems cannot be based on an empirical trial-and-error strategy, as is the case for general work safety, because the level of safety with regard to the high-hazard processes cannot be measured directly. It can only be estimated by a predictive risk analysis which considers the operational state of the designed defenses.

In addition, risk management should not be focused on prescriptive rules of conduct to control human error. Errors and violations are symptoms of an adaptive migration toward the boundaries. Therefore, risk management should be based on an adequate monitoring of the state of the designed lines of defense against particular accident processes.

8. Hazard Control in Adaptive Systems

It follows that low-risk operation of high-hazard systems based on the defense-in-depth philosophy and operating in a competitive, dynamic environment depends on a number of conditions regarding the structure of the management system:

- 1) *Information*: the conditional boundaries of acceptable performance should be visible to the individual staff members as well as to decision-makers at the management level.
- 2) *Competency*: the decision-makers at the management level should be competent with respect to the functional properties of the technical core and the basic safety design philosophy.
- 3) *Awareness*: the decision-makers should be aware of the safety implications of their business and work-planning decisions.
- 4) *Commitment*: management should be willing to allocate adequate resources to the maintenance of defenses.

The violation of any of these conditions gives rise to the danger that performance will migrate in an uncontrolled way toward an accident. In the subsequent sections, we take a closer look at these requirements.

1. Adequate Performance Information

The first precondition for safe operation, of course, is that the individual decision-makers have information about the state of affairs concerning the preconditions for safe operation, that is, the actual state of the defenses.

In practice, this implies that the theoretical performance boundaries must be made visible and should preferably actively respond to violations, thereby indicating inappropriate adaptation. This may require the introduction of a new information environment for monitoring and work-planning at the management level that can make visible to all decision-makers the otherwise invisible requirements of the safety design strategy. One possibility would be the introduction of a direct indication of the margin to loss of control based on an on-line, simplified 'default' risk analysis.[16]

Furthermore, visible margins to safety boundaries can increase operations efficiency by removing the need for excessive margins to invisible boundaries. The reason, why this system has not been put in operational use is that its use would violate the present prescriptive operational regulations.

Organizational Issues

Management Capability;
- *Better informed management in high-hazard systems?*
- *More visible boundaries of safe operation?*

Management Competency
- *High-hazard systems require technically competent CEOs?*

Management Consciousness;
- *experts only ask questions to find resolutions among action alternatives: Management does not take risks, but runs risks in non-risk related decisions?*

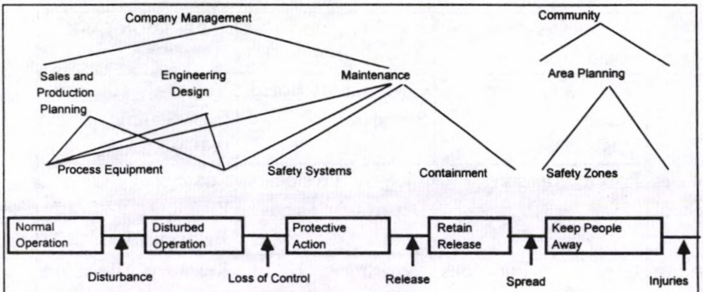
Management Incentives;
- *Time horizons?*
- *Is level of safety economically acceptable?*

This kind of performance monitoring should be active through all the changes of operations and modifications in equipment that management may plan in response to pressure from its competitive environment during the entire operational life of a plant.

As already mentioned earlier, safety cannot be based on a separate safety organization, but must be integrated with the normal business management as an explicit and active performance criterion. A key issue is how information is communicated, interpreted, and implemented in a dynamic organization, as shown in Figure 8. How are performance criteria (including safety) propagated through the organization? What are the

[16] Fussell, J. B. (1987): Prisim - A Computer Program that Enhances Operational Safety. Presented at the Post-Smirt Workshop on Accident Sequence Modeling: Human Actions, System Response, and Intelligent Decision Support. Munich, August 1987.

implications of the present change from prescriptive toward performance-based regulation? This issue seems to coincide with an increased interest in the management science discipline to study more complex performance criteria than the traditional financial criterion.[17] There are strong arguments for a new approach to planning on the basis of multiple criteria, including concepts such as 'ethical' accounting. In addition, management science seems to be moving away from a focus on normative, rational models toward more descriptive models of actual performance, which may prove to be very important in the present context.



Stochastic coincidence of safety barrier breaches*: Accepted risk;*

Systematic coincidence from coupling through management decisions and staff activities*: Violation of safety policy;*

Different management functions are considering different safety preconditions.

Will better information and visible limits of safe operations help?

[17] Bogetoft P. and Pruzan, P. (1991), *op cit*., note 11.

2. Management Competency

An industrial organization can be represented at several levels of a means-ends hierarchy describing the internal functional structure, which relates the operation of the technical core to the higher-level institutional goals and objectives.[18]

Basically different decision tasks and competence requirements are found at the various levels. Normally, therefore, the activities of the various levels are allocated to different persons with different professional backgrounds. This is the case both for management structures based on a formal hierarchy or on a more informal cooperation.

	MEANS-ENDS RELATIONS	**ACTORS**	**DECISION TASK**
	Goals and Purposes, Constraints	Chairman of Board; President	Value Analysis; Goal-Setting; Policy-Making
Business & Law school graduates	Priority Measures	Vice Presidents; Department Heads	Strategical Planning; Priority Judgements
Engineers & bureaucrats	General Functions and Activities	Department Heads; Office and Group Leaders	Resource Allocation and Function Coordination
Skilled & unskilled workers	Physical Processes and Work and Equipment	Skilled Staff	Execute Work Procedures; Control Equipment Operation
	Appearance, Locationand Configuration of Material Objects	Skilled and Unskilled Staff	Find Work Items, Move Things, Plan Navigation and Transport

Figure 14. Even if analytical reasoning is activated during decision making, the professional background is likely to be less than adequate at the level of an organization at which an overview of the global safety preconditions related to a defense-in-depth design policy.

[18] Rasmussen, J. (1991), *op cit.*, note 14.

One basic problem in the operation of a high-hazard system appears to be that the professional competence with respect to the technical core and the safety design philosophy applied is likely to be less than adequate at the level of an organization where managers oversee the global safety preconditions related to the defense-in-depth design policy. This is partly the case because technical knowledge is not maintained during normal management activities at higher levels of the organization and partly because high-level managers are often law and business school graduates with a general financial background, not technically competent people promoted from the technical staff.[19]

Thus, from the point of view of low-risk operation of high-hazard systems in a dynamic and highly competitive environment, the technical competence of management comes into focus. Similar questions have recently been raised about the management structure of American industry, also from a purely business-related perspective. Lack of product and manufacturing knowledge at the executive management level has been mentioned as a problem in dynamic, 'customer driven' operations.[20]

Management Competency

Specialized companies are increasingly turned into purely financial operations:

- *Ships are operated by banks and investors, not professional shipping people?*
- *High-level executives in the chemical industry are law or business school graduates?*
- *With short-term career patterns?*

High-hazard systems require technically competent CEOs?

3. Management Awareness

When examining management capability, the central issue is not only whether managers are *capable* of adequate safety planning when asked to sit down and explicitly plan a safety policy for the company. It is also whether they are *aware* of all relevant safety preconditions when they are not explicitly considering safety, but are making operational decisions in the turmoil of competitive pressure, economic setback and workforce problems. This raises the question of the nature of decision-making by experts under actual work conditions.

[19] A case in point is the recent ferry fire - Scandinavian Star - and the oil spill at the Shetland Islands, after which a representative of the Danish marine safety authorities expressed his fear during a TV interview that marine safety would decline because ships were now operated by banks and investors rather than by professional shipping companies.

[20] Dertouzos, M. L. et al (1988): Made in America: Regaining the Productive Edge. Cambridge: MIT Press.

Management Consciousness

Nature of 'naturalistic decision-making':

• *Alternatives for action are intuitively determined by context*

• *Only the information necessary to choose among perceived alternatives is consulted*

• *Managers run risks, they do not take risks*

• *During non-risk related decisions*

Necessary to prompt risk consideration in non-risk-related decisions by including a background risk analysis in the general planning tools?

In familiar situations, analytical reasoning and planning based on the actual objectives and constraints are replaced by a simple choice among familiar action alternatives - that is, on practice and know-how.[21] When, in such situations, operational decisions are taken, they will not be based on an analysis of the attributes defining the actual conditions for acting, including basic safety preconditions, but only on the information which, in the given context, is necessary to choose among the perceived alternatives for action. Very likely, the most influential management decisions, from a safety point of view, are not seen to be safety-related at the time of the decision. In Waagenaar's terms: managers do not consciously 'take' risks, they implicitly 'run' risks.[22] As seen from the front end, it is difficult to view the total picture during daily operational decision-making.

Recent developments in decision theories offer new approaches to the analysis of decision-making that are very relevant to risk management studies.[23]

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[21] Rasmussen, J. (1993): Deciding and Doing: Decision Making in Natural Context. In: Klein, G., Orasano, J., Calderwood, R. and Zsambok, C. E. (Eds.), (1993): Decision Making in Action: Models and Methods. Norwood, NJ: Ablex Publishing.

[22] Waagenaar, W. (1989): Risk evaluation and the causes of Accidents. Invited Contribution to the CEC Workshop on Errors in Operation of Transport Systems; MRC-Applied Psychology Unit, Cambridge May 1989. To appear in: *Ergonomics*.

[23] For a review of the nature of 'natural' decision making versus the rational, normative decision theories, see Klein, G. and Calderwood, C. (1993): Decision Making in Action: Models and Methods. Norwood, NJ: Ablex Publishing. For a discussion of the mode of decision making actually applied in successful industrial management, see Morone, G. (1993): Winning in High-Tech Markets. Boston, MA: Harvard Business School Press.

4. Management Commitment

Management Incentives?

Given a competent and informed management, are the incentives in place?

A problem of time horizons:

• *Financial responsibility toward shareholders: Annual?*

• *Personal career: A few years?*

• *Financial strategy: A decade?*

• *Acceptable time-between-major-accidents: A century?*

New ways to ensure management commitment are necessary:
New form of legal pressure?
Formal ethical accounting?

However, even when managers are competent and actually aware of the hazards, a crucial question appears to be whether managers are *willing* to make the effort required for effective risk management.[24] In many cases, as judged after the fact, liabilities and losses could have been anticipated, accidents were foreseeable and obviously preventable. In theory, one would expect that the fear of potential liability would serve as a substantial incentive for companies to voluntarily undertake management initiatives to prevent risk. However, despite ample evidence of a liability explosion in the USA, companies continue to experience numerous accidents, indicating that the liability incentive in reality is incomplete or obstructed in several respects. Why do companies fail to act voluntarily to prevent risk and its economic impacts? Could an economic necessity during periods of high competitive pressure be the major reason? This raises the important problem of management incentives. Is the present level of safety actually financially acceptable?

Analysis of recent major accidents leaves the impression that we are facing a basic problem of time scales in technological development, political election periods, personal careers of managers, planning horizons for companies and public services and, finally, acceptable mean-time-to-accidents in individual companies.

Is it realistic to expect managers - juggling a personal career planning horizon of a few years, a legal responsibility toward shareholders to be economically sound in the short run, and possibly facing economic crisis - to balance financial decisions rationally against a risk of major accident over a horizon of a century?

One proposal recently put forward to control management incentives is the establishment of formal systems for 'ethical accounting', including not only financial accounts but formal reviews of a company's influence on all aspects of the surrounding society, such as environmental pollution, risk, employment,

24 Baram, M. (1988): Liability as an Incentive for Improving Corporate Management of Chemical Risks. World Bank Workshop on Safety Control and Risk Management, Karlstad, Sweden, '88

local development, school system and service facilities, and a basis for cultural activities.[25]

It would appear that the control of management incentives by society is a pressing issue, and several changes are presently becoming visible.

One such development is the increasing focus on product liability. The common law liability concepts have evolved over the centuries without an explicit theoretical basis. In the United States this situation has been changing in response to the fast pace of technological change and a movement toward a rational criterion of liability has formed. The stopping rule for causal search suggested by this 'liability science' is to find the 'cheapest cost avoider', that is, from a social point of view to minimize the cost of accidents.[26] Ironically, this approach has brought with it the present boom of liability cases in American courts involving scientific expert witnesses.[27]

Another change has been reinforced by a recent US court practice to control management incentives with respect to environmental and safety regulation. During recent years, there has been a clear trend towards extending the criminal law to cover 'wishful blindness' on part of corporate executive officers (hereafter: CEOs). Previously, criminal law had only been in effect for acts of deliberate illegal intentions, whereas civil law dealt with careless acts, and so on. This has changed due to the traditional mismatch between the size of penalties for violations of environmental laws and the cost of environmental protection measures. Difficulties of reinforcing environmental protection laws have led court practice to apply criminal law to cases where CEOs delegated the environmental protection measures to lower level staff without effectively monitoring that the measures were in place and active. Not knowing the risk involved in operation nor understanding the implications of management decisions on environmental protection and safety do not remove managers' accountability. The simple fact that CEOs have the power to be 'in control' is sufficient for them to be imprisoned for a violation of environmental laws due to decisions taken by any company staff member.[28]

Finally, the use of pressure from public opinion and grass-root groups through the 'right-to-know' law complex appears to have been very effective.

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[25] See e.g., Bogetoft P. and Pruzan, P. (1991), op cit., note 11

[26] Calabresi, G. (1970): The Cost of Accidents: A Legal and Economic Analysis. New Haven: Yale University Press.

[27] Huber, P. (1991): Galileo's Revenge: Junk Science in the Court Room. New York: Basic Books.

[28] Addison, III, F. W. and E. E. Mack, (1991): Creating an Environmental Ethics in Corporate America: The Big Stick of Jail Time. *South Western Law Journal*, 1991, Vol. 44, pp. 14271448

9. Conclusion

Safety of high-hazard systems depends on several factors. While these issues are presently the subject of separate research within different disciplines, they should be taken into account together. High-hazard systems are designed or have evolved according to 'the defense-in-depth' philosophy. Accordingly, risk management must be focused on the maintenance of the defenses, not on removing causes of past events. During a period of fast pace of change, risk management cannot be empirically based, but must be planned with reference to an explicit identification of the designed defenses. For this to occur, management must be competent with respect to accident processes and defenses relevant to the system; they must be given the opportunity to judge the safety consequences of operational decisions and their awareness of such concerns must be properly prompted. To meet this latter requirement, an information environment for business planning, including an operational version of a risk analysis, must be made available to compensate for the characteristics of 'natural' decision-making. And last but not least, to make management committed to safety during financial crises, a proper incentive system must be established. Indeed, a first priority may well be to better understand the dynamics of management decision-making during crises in order to activate a proper multi-criteria decision-making process.

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Appendix: Current Trends in Paradigms of Human Sciences

There have recently been some important trends in the development of societal conditions that significantly influence the risk management problem and stress the need for interdisciplinary, system-oriented research. Fortunately, however, some developments within the governing academic research disciplines can also be identified that greatly facilitate such interdisciplinary approaches.

Analyses of recent major accidents have invariably concluded that 'human error' is the predominant cause, and recommendations have often focused on the means to remove human error by better instruction, training, supervision or equipment. However, experience from such attempts have often been less than effective because humans are boundary seeking and therefore often compensate the changes, they adapt to changes in a way that improves effectiveness rather that safety.

The concept of human error, then, seems to be less effective as a basis for risk management. It is indeed interesting to note that a similar perception is acknowledged in several human sciences; that is, the concept of 'human error', of 'decision bias', etc., is found only in a certain phase of the description of human behaviour within several professional fields. Typically, descriptions of human behaviour start with identification of rational behaviour by normative models. Actual behaviour is then described in terms of some kind of deviation, that is, error, with reference to the normative behaviour. At present, there is a clear tendency towards directly describing actual behaviour in terms of behaviour-shaping constraints of the environment and the adaptive mechanisms of human actors within that environment.

Some brief examples are given here:

Decision research. Some clear stages may be seen in the evolution of research paradigms within decision theory. The classic *decision theory* was of a normative nature, based on the expected utility theory developed by economists and mathematicians (Von Neumann and Morgenstern). The emphasis was not on what decision-makers *actually do*, but what they *should do*. Later, mathematical modelling of subjective probability and utility was promoted (Keeney and Raiffa) to aid decision-makers in achieving logical consistency. To account for the behaviour of practical decision-making, this theory was followed by the *psychological decision theory* (Tversky and Kahneman) followed, using concepts of biases and heuristics. This theory seek to *explain* human behaviour in terms of deviation from rational behaviour or, in other words, by an error concept. So far, 'decisions' have been perceived as discrete events: an actor realizes a problem and a situation analysis is then performed to diagnose the situation and define the problem. This is followed by an evaluation of the present goals and a plan of action. Recently, however, human interaction with the environment has been increasingly considered to be a continuous control task. *Separate 'decisions' are therefore difficult to identify.* Thus, further development of decision theories has taken place toward direct description of actual behaviour through analysis of behaviour/performance in complex work environments, with little emphasis on the identification of errors or biases with reference to normative models. One line of development is the research on *naturalistic decision-making* (Klein); another is the study of *dynamic decision-making* (Brehmer).

The concept of dynamic decision-making has very important implications for the understanding of expert behaviour in the work context and of accident causation; that is, of the kind of natural behaviour that may lead to system failure. In Waagenaar's terms, managers 'run' risks, they do not 'take' risks.

Organizational theory. In management and organizational research, normative, rational models take different shapes. The *Scientific Management* model (Taylor) is focused primarily on manufacturing and similar production activities, and employs economic efficiency as the ultimate criterion; it seeks to maximize efficiency by rational work procedures, preplanned by system design and reinforced by training, instruction and punishment of staff in case of deviations (errors). Later, the focus of study moved to analysis of particular organizations in terms of biases and deviation from rational behaviour. To cope with complexity, organizations must develop processes for searching and learning, as well as for deciding. In this phase, decisions are *satisficing* rather than maximizing and are based on 'bounded rationality' (Simon); decision-makers are not rational, but 'muddle through' the work requirements (Cyert, and March). Still, reference is to the normative behaviour from which deviations are found. Recently, several researchers have focused on the actual learning behaviour of organizations; that is, on the mechanisms that shape actual behaviour in order to explain not only errors but, in particular why highly reliable organizations are found, given the high variability in human performance. Such studies have been based on ethnological and anthropological approaches to analyse the evolution of organizational behaviour (Rochlin). Organizational researchers have recently concentrated attention on the problem of decision-making in highly integrated and dynamic socio-technical systems (Mitroff), particularly the problem that several different perspectives must be taken into account: the *technical* (science and technology), the *organizational* (social entities, formal and informal), and the *personal* (individuation). In fact, learning behaviour of organizations (Senge) has become an important research topic. This evolution is clearly parallel to the evolution found in decision research paradigms.

Implications for Research and for Control of Human Behaviour. As is illustrated in Figure 15, parallel convergent changes are shaped by the increased interest in cognitive, intentional concepts, shown in the centre of the diagram, replacing the past focus on the mechanistic, normative approaches at its periphery. This is clearly a most promising precondition for the proposed interdisciplinary approach to the problem of failure of socio-technical systems. It is important to consider that the changing conception used for representation of human behaviour has important implications for the development of means to control the behaviour of individuals and organizations - that is, for risk management. In this respect, approaches to the design of work systems based on principles derived from ecological psychology are important candidates[29].

[29] Rasmussen, J. and K. J. Vicente (1990): : Ecological Interfaces: A Technological Imperative in High tech systems? International Journal of Human Computer Interaction 2(2)93-111 (1990).

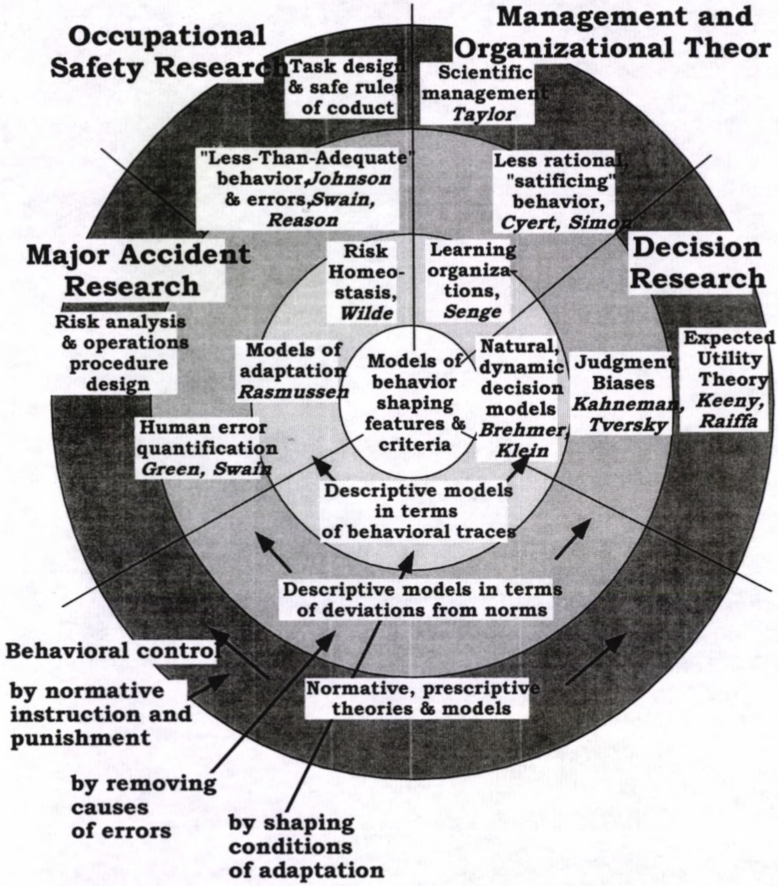

Figure 15. Modelling in terms of sequences of acts and errors seems to be an intermediate phase in behavioural research. In several behavioural sciences, a common trend is found in modelling behaviour: efforts are shifting from normative models of rational behaviour, through efforts to model the observed less rational behaviour by means of models of the deviation from the rational, toward a focus on representing directly the actually observed behaviour, and. ultimately, to efforts to model behaviour-generating mechanisms. This convergence is promoted by the general adoption of a cognitive point of view and of control theoretic concepts.

This change draws attention to the need for new ways of controlling behaviour and offers a new potential for interdisciplinary research, provided that cooperating groups are chosen carefully with respect to their research paradigms.

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