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Reflecting on Jens Rasmussen's legacy. A strong program for a hard problem

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ABSTRACT

Jens Rasmussen has been a very influential thinker for the last quarter of the 20th century in the safety science field and especially in major hazard prevention. He shaped many of the basic assumptions regarding safety and accidents which are still held today. One can see that many of his ideas underlie more recent advances in this field. Indeed, in the first decade of the 21st century, many have been inspired by his propositions and have pursued their own research agendas by using, extending or criticising his ideas. The author of numerous articles, chapters of books and books, Rasmussen had an inspiring scientific research record spreading over 30 years, expanding across the boundaries of many scientific disciplines. This article introduces selected elements of Rasmussen's legacy, including the SRK model, his theoretical approach of errors, the issue of investigating accidents, his model of migration and the sociotechnical view. It will be demonstrated that Jens Rasmussen provided key concepts for understanding safety and accidents, many of which are still relevant today. In particular, this article introduces how some principles such as degree of freedom, self organisation and adaptation, defence in depth fallacy but also the notion of error as '*unsuccessful experiment with unacceptable consequences*' still offer powerful insights into the challenge of predicting and preventing major accidents. It is also argued that they combine into a specific interpretation of the 'normal accident' debate, anticipating current trends based on complexity lenses. Overall, Jens Rasmussen defines the contours of what is called 'a strong program for a hard problem'.

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1. Introduction

1.1. Two articles on Jens Rasmussen's legacy

Jens Rasmussen, a pioneer in the field of safety science (with a focus on major accident research), continues to be of importance because of the lasting influence of his models and the ambition of his research program. The purpose of this study (that has been divided in two articles, there is a second proposed paper, to be submitted and published in the future), is to explore Jens Rasmussen's contribution to the field of safety science. This paper offers an overview of his key contributions over 30 years of cross disciplinary publications. Methodologically, approximately 30 papers have been reviewed in order to extract his key attributions to the field of safety. This overview shows the evolution of his intellectual journey, ranging from cognitive models, interface design, human error definition and human reliability, to accident investigation and socio-technical modelling. Several scientific disciplines are concerned including engineering, psychology, safety management, and the cross-disciplinary field of cybernetics. Secondly, the article shows how his thoughts and writings have influenced many key researchers in the field, indicating the importance of his ideas in the development of more recent ones. Authors with different disciplinary influences (e.g. psychology, management and sociology) and orientations in the field of safety (accident investigation, safety assessment, man–machine interface) have indeed incorporated in different ways Rasmussen's ideas into their studies, building upon different aspects of his research over several decades. In doing so, they have used, extended upon or criticised some of these ideas.

1.2. Preliminary remarks

Some preliminary remarks are in order. Epistemologically, philosophically or historically oriented papers in the field of safety, such as this one, are important, even if they do not have the practical focus that many safety scientists expect in an applied field of research. Despite living in a world of restricted resources in which the question "so what?" is inevitable, coming from one of the different participants in research institutions and industry who

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expect "practical" results, I am convinced of the value of this type of paper. A historical account of Jens Rasmussen's research is necessary. In my view, there are indeed several good reasons to do so.

First, the time has come to begin writing a history of safety science (oriented here on safety-critical systems). One way to establish a field and to delineate its boundaries for institutional reasons as well as its societal needs (e.g. preventing the repetition of technological disasters) is to look back at its founding fathers. One can easily find a similar approach in other fields (e.g. sociology, management, etc.). A second reason is to identify the issues and concepts found in the early phases of the history of a field which have become the basis for current research. It is important for a discipline to be able to agree and to reflect on the core scientific and philosophical topics that lay at the foundation of its own developments. Thirdly, I wish to reflect personally on where I stand intellectually and consider the direction of my own research in a cross-disciplinary topic. Looking back at the trajectory of authors can help us look forward. I seek to better understand how my ideas have been shaped by scientists in the field, a reason that is obviously interconnected with the two previous ones.

Fourthly, an investigation of the genesis of thought from the angle of the history of science allows us to understand how ideas take shape in their institutional context, be it scientific communities (e.g. safety science) or societal and industrial interests (i.e. research funds), as well as the historic scientific and philosophical context of theories and concepts (e.g. cybernetics in the case of Rasmussen). It also facilitates the understanding of how ideas take shape and the time scale of their genesis. Fifthly, this paper is aimed at promoting cross-disciplinary research. One difficulty for studying safety is its multidimensional nature and the need to find ways to combine models from different research traditions, including engineering, psychology, sociology, etc. There are many obstacles: cognitive (one must take the time to master models from different research orientations), social (a cross-disciplinary approach creates identity problems for researchers) and institutional (i.e. appreciation of interdisciplinarity by established disciplines, e.g. engineering, sociology, etc.). Finally, this paper offers safety science students an overview of the scientific contribution of an important author, Jens Rasmussen. In so doing, I seek to avoid simplification or misinterpretation of the author's views, understand current developments in the field, review new developments in the light of existing concepts, identify the extent of the author's legacy, but also the limits of his propositions and the opening of new perspectives.

2. Methodology

Methodologically, I identified the core themes and concepts in his writings, beginning with his early papers (i.e. Rasmussen, 1969, 1976) through the later ones (i.e. Rasmussen, 1997a; 2000) To do so, I have read not only Rasmussen's published journal articles but also chapters in books (see Rasmussen's references). I have not included in this review books authored by Rasmussen (or those written in collaboration), nor the Risø reports (except one), as I believe all his essential ideas would have been published in his articles. Whereas the Risø reports may provide more conceptual and historical elements, their study is not necessary in this context. Indeed, Rasmussen's legacy is for the most part a product of his published articles, easily accessible to the community of safety scientists. Only a very restricted readership has access to these reports.

In reviewing the published articles, I focused on five aspects. First, I traced the introduction of new ideas, principles, concepts and models. Many quotes from Rasmussen are thus used in this article in order to provide readers direct access to his expressions and ideas. Second, I have tracked the evolution of principles, concepts and models. I have tried to understand how one concept in a domain was translated or transferred to another. I have also paid attention to the analogies or metaphors employed, whether they were borrowed from engineering, physics, biology, or psychology, etc. This is an important part of any scientific work, as we know that induction and deduction are to be understood in relation to abduction (analogy), a pattern recognised to be at the heart of scientific intuitions and creativity. Selected figures illustrate some of these evolutions. Third, I have taken note of the empirical approach used to ground model development, be it primary or secondary data, normal operation or accident, experimental or real life studies, qualitative or quantitative approaches, etc.

Fourth, I have identified the various topics addressed throughout the papers (e.g. interface design, human error, etc.) and tried to understand how shifts in subjects could be related to specific historical circumstances (e.g. major accidents, global evolution in safety concerns, development of research communities or networks). For these three steps, I have proceeded chronologically. I determined a timeline and a global pattern of how his research interests and focuses evolved over the years, but also how some of these shifts could be understood in relation to what I know of the historical context. Finally, I have tried to take a step back and look for main influences behind Rasmussen's ideas. I tracked what I thought to be a core intellectual matrix explaining the diverse models and concepts presented in the articles. To do so, I considered both concepts but also authors frequently mentioned in his writings, who were cited earlier or later in his research (this final aspect will be treated separately, in a second article with a different subtitle 'behind and beyond, a 'constructivist turn').

In conjunction with these steps, I have identified authors in the field of safety science who have used Rasmussen's principles, concepts and models. To do so, I have primarily focused my research on human and social science journals related to safety as well as safety related books. These authors are sometimes critical of his ideas; they have sometimes transformed, applied or expanded upon them. I have selected some of these authors for this article in order to give a notion of his legacy. This study is not exhaustive. I seek to be representative, not comprehensive. Finally, I have reflected upon my own approach in regards to his legacy.

2.1. Article sections

Based on the methodology described above, in Sections 1–7 of this paper, I introduce and discuss the key and enduring available concepts of Jens Rasmussen in the field of safety (box 1). For each of them, I present their genesis and some of the debates surrounding the issues that they introduce. I select and refer to authors in safety science who criticise, employ or develop Rasmussen's legacy.

Box 1 List of key concepts from Rasmussen discussed in the paper.

1. Modelling process plant operator in relation to display engineering,
   a. human data processing mechanisms,
   b. ladder of abstraction and levels of behaviour 'SRK'.
2. Conceptualising 'human error' as an "*unsuccessful experiment with unacceptable consequences*",
3. Contrasting technical and human reliability/safety analysis,

Box 1 (continued)

4. Producing a new vision of accident and safety,
    a. The fallacy of in-depth defence,
    b. Degree of freedom, self-organisation
    c. The 'normal accident' perspective,
    d. Major Accidents as an organisational migration toward the boundary of acceptable performance.
5. Investigating accidents,
    a. Causality versus relations,
    b. Stop rules and goals,
    c. A distributed decision-making view of accidents,
    d. Accimaps.
6. Creating a bigger picture,
    a. A socio-technical perspective derived from a control theory,
    b. Safety science as cross-disciplinary, problem-driven research and convergence of human sciences paradigms via information processing metaphor.

Thus, this paper explores issues related to safety science, specifically the intellectual itinerary or journey of Jens Rasmussen, its importance as well as its limitations, to the extent that I have been able to understand and interpret it from my own experience, primarily through his published papers.

3. Modelling process plant operator in relation to engineering issues

3.1. Genesis of the model

The 'skill-rule-knowledge' (SRK) model is probably the most well-known model in the human factors field. Publications in the late 1960s-mid 1970s (Rasmussen, 1969, 1976; Rasmussen and Jensen, 1974) introduced the concepts that were developed into their final form in the beginning of the 1980s (Rasmussen, 1982, 1983). Several decades later, this SRK model is still widely referred to in man–machine (computer) interaction (e.g. Kolsky, 1998; Vicente, 1999; Sheridan, 2002; Boy, 2010; Naikar, 2012) as well as in ecological (or naturalistic) approaches to cognition (Hoc and Amalberti, 2007). An indication of the importance of this model is the fact that a book has been dedicated to Rasmussen's contribution to cognitive engineering (Goodstein et al., 1988).

It was also obviously endorsed in Reason's landmark contribution to "human error" (Reason, 1990, more about this specific topic in the next section dedicated to Rasmussen view of 'errors'). The success of this model is probably mostly due to its ability to encompass basic mechanisms that can be easily understood by a broad public (in particular designers with an engineering background). Fig. 1 presents its main principles: skill-based behaviour functions on automatic or unconscious processes that have been internalised through experience. They are triggered by sensory inputs. Rule-based behaviour corresponds to explicit, known rules that operators consciously activate to perform specific tasks. Knowledge-based behaviour is the ability in new circumstances to find responses that are not directly available in the operator's repertoire and that require considerable attention and concentration.

The genesis of the SRK model can be traced back to the 60s. By then, Rasmussen had already distinguished, based on a study of error reports, four different cognitive 'states' or 'levels' of behaviour:

1. Normal working routine – automatic, or unconscious.
2. Conscious pattern identification – alternative response based upon trained co-ordination.
3. Conscious tradeoffs between scientific, operational and safety goals.
4. Conscious activity for unforeseen conditions requiring very detailed physical and technological properties of the plant.

This categorisation was illustrated with a first model. One can easily see it as an earlier version of SRK, although there are in this version four instead of three states. This first categorisation was very much dedicated to recommendations of 'display' design, a research orientation that would be later known as '*cognitive engineering*,' '*engineering*' referring to the practical purpose of the models. Automation and computerisation (implying new kinds of interfaces between operators and technology) were then becoming more and more part of operations of high-risk systems (e.g. aviation, nuclear).

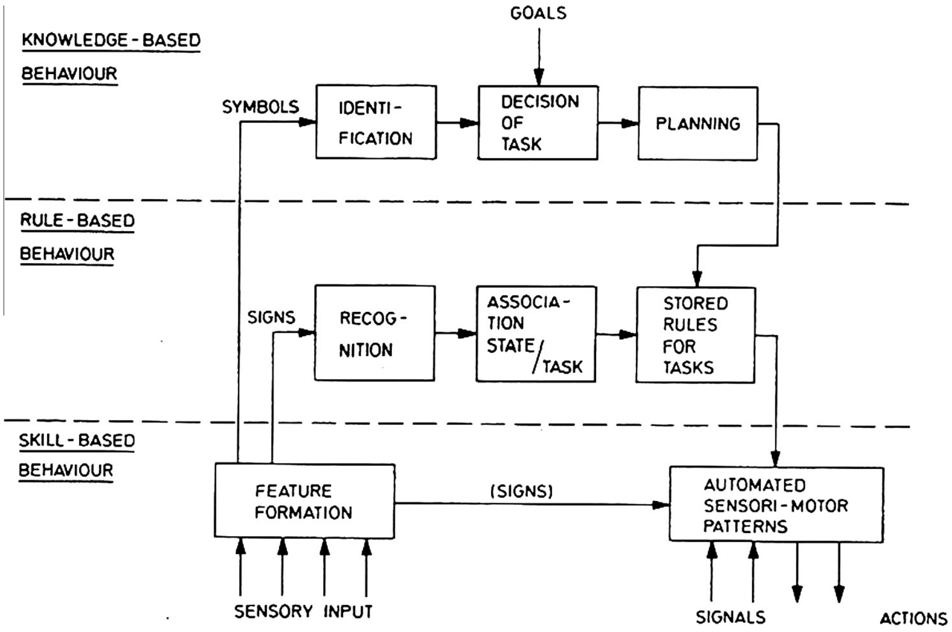

Fig. 1. SRK model (Rasmussen, 1983).

These new technological developments had to rely on principles of how operators worked with technology in real-life situations in order to reflect and translate them into new technological designs. In a paper published in 1969, Rasmussen already warned that "*a designer should be careful not to design display coding to his own mental models (...) the diagnostic procedures applied by system operators are different from those of system designers*" and that for instance "*integrated analogue or graphic display seem to be more appropriate than alpha-numeric displays*." In 1976, he published a paper with a much higher level of cognitive conceptualisation that presented much more explicitly the theoretical background for the 'SRK' model.

Between the two papers, he observed troubleshooting maintenance engineers at work (Rasmussen and Jensen, 1974). This very detailed empirical study, based on observations and verbal protocols, revealed the variety of strategies that operators activated in the course of their interactions with technological systems. "*Different operator's strategies can be observed ranging from use of professional training and experience to procedure requiring detailed knowledge of the specific system and the laws controlling its internal functioning*" (Rasmussen and Jensen, 1974). It showed the wide range of views – mental models – operators have on technological systems, including topographic maps, functional understanding or physical representations of the technological parts themselves (pumps, valve, etc.). Although Rasmussen and his colleague observed local trial-and-error type strategies at odds with what designers might expect in troubleshooting tasks, they explained that "*working memory issues, mental load from the procedure, fixation in routine search procedure and subjective formulation of task and performance criteria all contribute to shape a behaviour to be understood as rational given tasks and environment constraints*" (Rasmussen and Jensen, 1974).

This detailed study, most likely triggered by the first findings in the 60s from error reports, provided him with enough data to move ahead with a much more elaborate conception of cognition for display design than that the initial 1969 paper. In 1976, two important models were described (Rasmussen, 1976). The first one is a hybrid model of the process operator, relying on an information processing model of cognition available at the time (Newell and Simon, 1972). Rasmussen combines the idea of a slow and serial data processor cooperating with a high capacity, parallel processing subconscious processor related to perception, sensory-mentor responses. This cooperation between the two processors is based on a mental model of the plant (a "*dynamic world model*") allowing for variability in strategies in different environments. This first idea is illustrated by a first graphical model, while a second one complements it (Rasmussen, 1976). The second is a new version of a decision-making process, as mentioned above. As commented by Rasmussen, *"the diagram resembles a 'ladder of abstraction'. One leg upwards for analysis of a situation, another downwards for planning of the proper actions. Short cuts from habits and rules connect the two legs of the ladder"* (Rasmussen, 1976).

It is on the basis of these previous models (levels of behaviour through error reports, conscious/unconscious processors coordinated through mental representations of plants associated with the principle of shunts or shortcuts in the decision-making process) that the distinction between three cognitive levels of description, skill-based (SB), rule-based (RB) and knowledge-based (KB), was elaborated. In order to stabilise and ground this choice of categorisation, he compared it with works offering similar three-dimensional views of cognition, among which Whitehead's philosophical proposition, which distinguished between "*instinctive*," "*reflex*" and "*symbolic conditioned*" actions, as well as Fitts's more psychologically oriented contribution on learning, discriminating "*early*," "*intermediate*" or "*associative*" and "*final*" or "*autonomous*" phases (Rasmussen, 1983).

An important aspect of this model is that it is associated with its practical purposes from the very beginning. "*In considering the human data processor as a system component, it is necessary to describe mental processes in a frame of reference compatible with the decisions to be made by the interface designer*" (Rasmussen, 1980a,b). This feature of the model is very interesting as it introduces the importance of the observer's purpose when modelling phenomena. It demonstrates that an observer never observes from a neutral point of view but always with a specific purpose. It also illustrates very well in this specific field the intertwined aspects of 'fundamental' and 'practical' research, and contributes to the blurring of these distinctions (Galison, 2006).

3.2. Hollnagel's critique of SRK[1]

Although the SRK model was praised and endorsed by many authors (Goodstein et al., 1988), some have challenged its rationale, most notably Hollnagel (1983), 1984, Hollnagel (1992), who was an early collaborator of Rasmussen (e.g. Hollnagel et al., 1981). For Hollnagel, SRK represents a procedural and normative model of cognition, in the sense that "*it implies that one sequence of actions represents a more natural way of doing things than others, or that a certain sequence or ordering is to be preferred*" (Hollnagel, 1992). This idea is represented in Fig. 2a.

In these circumstances, the observer is tempted to be driven by the model rather than by the situation under study. Hollnagel then contrasted this approach to cognition with a contextual one that "*implies that actions are determined by the context rather than by an inherent sequential relation between actions*" (Hollnagel, 1992). For Hollnagel, it is relevant to separate the control model and the competence model, which are otherwise associated in the SRK model in a normative manner. Mobilising such a normative model is too restrictive for the study of the reliability of cognition (Fig. 2b).

Whereas this was certainly an influential and decisive critique that could lead to potential shifts in design strategies, in my view, it is one that is better understood in relation to the attempt to produce a taxonomy of errors, rather than to denigrate Rasmussen's global contribution. As explained above, the SRK model is indeed the product of a broader approach, which includes an understanding of process operator strategies where context does play a key role. In fact, a close reading of Rasmussen's writings reveals that the contextual nature of process operator's cognition has always been taken into account by Rasmussen. For this reason, he emphasised from nearly the beginning the importance of studying real life situations instead of relying on experimental data to understand cognition. "*A model of operator behaviour related to plant reliability and safety cannot be obtained by adding together results from isolated psychological experiments. It must be based upon study of the performance during the actual, real-life work condition*" (Rasmussen, 1976).

He was also acutely aware of the difficulty of conceptualising real-life situations in normative simplistic terms or a model: "*great difficulties will appear when verbalization is used to study highly trained tasks implying parallel processing of information by pattern recognition and subconscious routines as well as tasks calling for complex reasoning*" (Rasmussen and Jensen, 1974). The naturalistic, ecological or macro view of cognition as it was described later (Klein et al., 2003), including the importance of context in shaping cognitive strategies, was therefore shaped early by Rasmussen's principles of cognitive engineering (Hoffman and McNeese, 2009).

I therefore believe that to better understand Hollnagel's criticism, it is important to introduce the next topic, the issue of "human

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[1] I would like to thank Ludovic Moulin for our fruitful discussions on this topic.

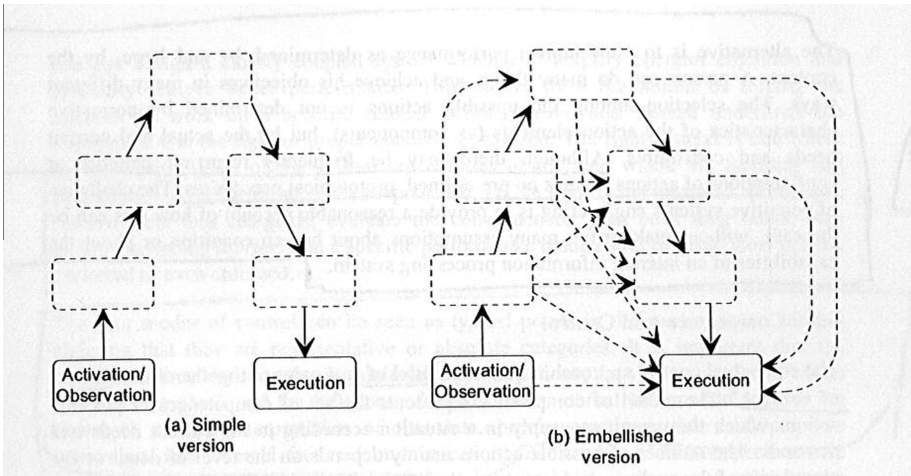

Fig. 2a. A critique of the normative side of SRK's rationale (Hollnagel, 1992).

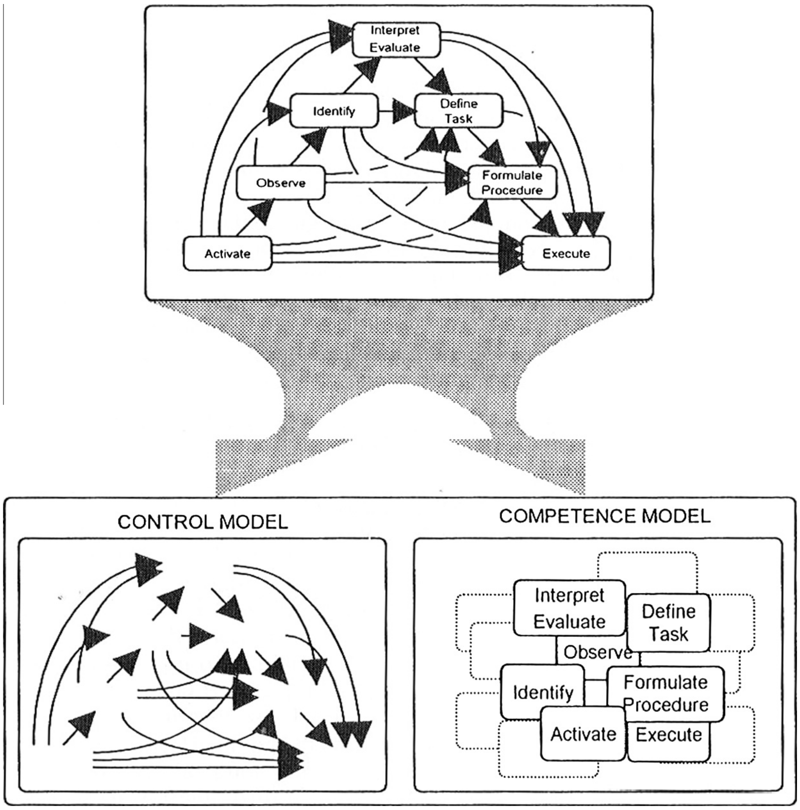

Fig. 2b. A critique of the normative side of SRK's rationale (Hollnagel, 1992).

error." His criticism can be seen as stemming partly, without grossly oversimplifying (I leave aside here the issues of time and control[2]), from Hollnagel's rejection of the usefulness of the notion of "human error" from a cognitive point of view (Hollnagel, 1983). Characterising an error requires defining a normative (cognitive) reference against which one can qualify the error as such. Accident investigations create these norms retrospectively, from the position of hindsight. During studies of cognition in normal operations, "errors" are part of normal variability in performing tasks, and an external observer struggles to distinguish between the correct from the proper action unless a norm is defined. In my view, this rejection of the utility of the concept of human error is not in fact unlike Rasmussen's own position. In order to see this, one needs to delve into the history of error explanation.

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[2] Even if neither the time dimension nor the operator as an active agent are absent in Rasmussen models e.g. "*Attention may not always be focused on current activities, and different levels may simultaneously be involved in the control of different tasks, related to different time slots, in a time sharing or in a parallel processing mode.*" (Rasmussen, 1990a); "*These errors mechanisms are consequence of the fact that data in the environment cannot be considered input information to a passive data processor (...) interpretation he uses depends on an active choice and error mechanisms are related to his bias or fixation for his choice*" (Rasmussen, 1982). 'An operator cannot be considered merely as a data channel transforming input information into actions. Instead, in a specific situation, the input transformation synchronizes the internal model, and complex responses may be generated from primitive inputs' (Rasmussen, 1980).

4. The conceptualisation of 'human error'

4.1. Two independent fields, 'psychology' and 'cognitive engineering'

The study of error started in fact in two independent fields. One was based on a psychological tradition, the other on (cognitive) engineering. Within what I consider to be an acceptable level of simplification for the purpose of this paper, the first may be said to be represented by Reason, the second by Rasmussen. Reason, with co-author Micielska, published a book in 1982 on "*absent minded slips*" (Reason and Mycielska, 1982). There is no mention of Rasmussen in this book. And, up until 1982, there is no mention of Reason's work in Rasmussen's papers (Rasmussen, 1982). For more than 10 years, the two lines were unknown to each other until an international interest in 'human error' was aroused by the Three Mile Island nuclear accident in 1979. Two international conferences, one held in 1980 and the other in 1983, contributed to the establishment of the two networks of researchers, institutes and universities that were so active during the 80s and 90s (Senders and Moray, 1991) and the links between the study of human error in the two fields.

Reason and Micielska's background and approach were different than Rasmussen's, but they proved later to be highly compatible. Three main aspects distinguish the two. First, Reason and Micielska consider error from a psychological angle. With James and Freud as major influences throughout the book, the two authors saw errors as a way to theorise psychology, with the help of new metaphors available in the field, including an analogy with computers and information processing. They consider the importance of the subject of '*absent minded slips*' in light of technological accidents (in particular aviation, with a description of pilot errors), but this preoccupation seems to remain somehow a bi-product of a psychological investigation, to be adapted for practical purposes. As they express it "*As Freud understood very well, the most interesting feature of absent-minded slips is not how to avoid them, but what they reveal about the secretive workings of the mind*' (Reason and Mycielska, 1982). Influences such as James and Freud are absent in Rasmussen's investigation, as he is committed to producing models for engineering purposes rather than psychological ones.

Second, Reason and Micielska focused on types of errors related to automatic or unconscious cognitive processes that could be categorised as 'slips' or 'lapses' ('*absent minded slips*') (Norman, 1981).[3] Rasmussen's orientation was radically different from the start. For him *"most of the accidents are initiated during periods with non routine operations (...) the majority of the failures can be attributed to the human operator in complex, non-routine situations when he has to adjust his procedures while taking many parameters into consideration (typical of landing operations on bad weather)"* (Rasmussen, 1969). The engineering angle was consequently to help operators to "*cope with complexity*" (Rasmussen and Lind, 1981), including conscious problem solving to be supported by proper interface design. This focus manifested in the need for further research, including empirical studies of real-life situations of operators based on verbal protocols (Rasmussen and Jensen, 1974) in order to better understand how these situations could be translated into design requirements.

The third aspect is thus the absence of detailed empirical study of real-life situations of operators of technological systems in the theoretical approach of Reason and Micielska. Thus, although they provided a generic framework to conceptualise their findings gathered from an array of various methodologies (e.g. psychological experiments, a variety of natural observations of errors in everyday life and literature, including accident reports, etc.), their study lacked the support of a grounded model based on real life observations, such as reported in Rasmussen and Jensen (1974). '*Their study was drawn largely from diary studies by members of the public recording occasions when they found themselves in unintended situations or conducting inappropriate actions in everyday life. This biased the conclusions to the slipses and lapses end of Reason's later categorisation, with few 'mistakes' or 'violations', which came from later studies. The errors were self defined by the diarists. This is in marked contrast to the data Rasmussen used at the time, which came from observations and reports of work situation*'.[4] This empirical posture of Rasmussen held considerable advantages compared to a strategy relying on error descriptions from scattered sources (whether experimental or even natural), as discussed above.[5]

4.2. An early 'naturalistic' perspective on 'human error'

Because of these three aspects, when human error became a focus of attention following the Three Mile Island accident in 1979, Rasmussen, who relied on his empirical observations and models to conceptualise errors, had an entirely different approach than the taxonomic approach of the psychologists. In his opinion, "*to optimize performance, to develop smooth and efficient skills, it is very important to have opportunities to perform trial and error experiments, and human errors can in a way be considered as unsuccessful experiments with unacceptable consequences. Typically, they are only classified as human errors because they are performed in an 'unkind' environment. An unkind work environment is then defined by the fact that it is not possible for a man to observe and reverse the effects of inappropriate variations in performance before they lead to unacceptable consequences. When the effect of human variability is observable and reversible, the definition of error is related to a reference or norm in terms of the successful outcome of the activity*" (Rasmussen, 1982).

I think that this definition has not aged, and has been instead comforted. Rasmussen emphasised that "*when performance can no longer be judged with reference to a stable normal performance, the definition of 'human error' becomes dubious*" (Rasmussen, 1987a). Unfortunately, in industrial and organisational environments, "*if a short cut is successful, the person is clever, if not, it is an error and he is blamed*" (Rasmussen, 1987a). Although he did provide a sort of taxonomy for errors (Rasmussen, 1982, 1987b) based on the SRK levels of behaviour, he understood error as part of the normal process of operators performing tasks within their specific contexts, leading to adaptation and variability in their (cognitive) strategies. I would argue that Rasmussen's approach to errors in relation to industrial accidents has not really been a taxonomic one, whereas Reason's approach, as seen in his seminal book of 1990, remained engrained in a taxonomic vision, very much in the spirit of the 1982 book (Reason and Mycielska, 1982). In my opinion, the two fields (psychology/cognitive engineering) did therefore meet in the beginning of the 80s, but their trajectories diverged slightly thereafter throughout the end of the 80s into the 90s in the modelling of industrial accidents (i.e. Reason, 1997; Rasmussen, 1997), in part because of these differences (Fig. 3).

Indeed, Rasmussen's definition opened a distinct practical perspective to error rather than a typology, classification or taxonomy. A classification of errors can lead to the idea that once categories (including types and forms) of errors are identified, a possible

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[3] Freud is quite present in the book (see for example Reason's comments on Freud, Reason, 2000). The question of the difference of unconscious behaviour as approached in psychoanalysis and current cognitive sciences is a very contemporary one (Buser, 2007).

[4] This sentence is a direct quote from one reviewer of the manuscript, who constructively commented on this section.

[5] "*A model of operator behaviour related to plant reliability and safety cannot be obtained by adding together results from isolated psychological experiments. It must be based upon study of the performance during the actual, real-life work condition*" (Rasmussen, 1976).

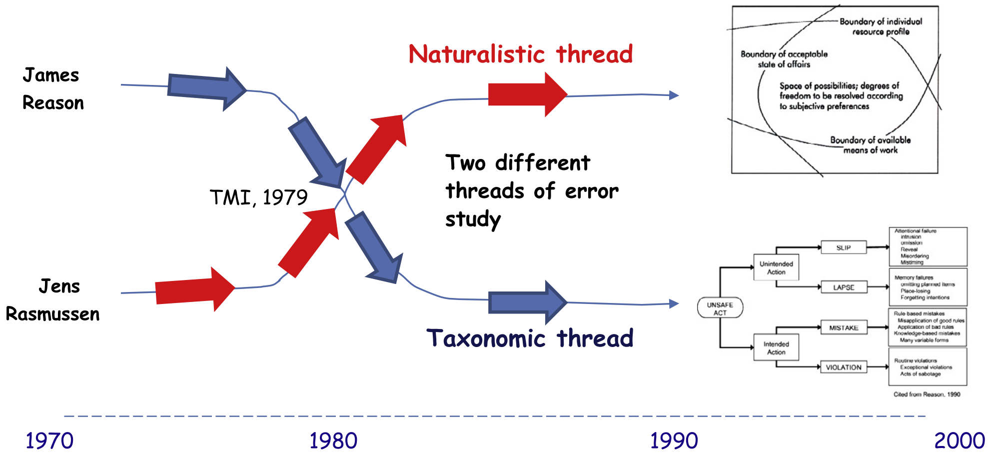


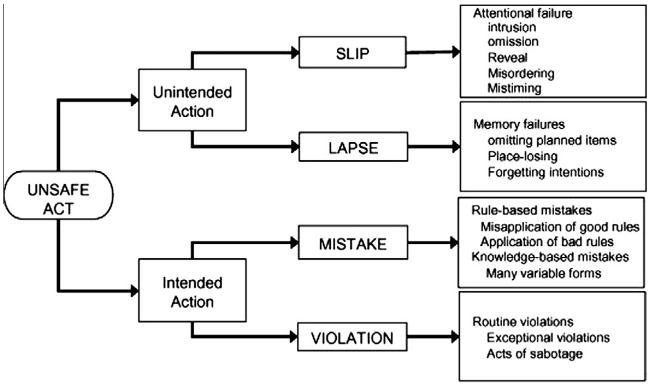
Fig. 3. Two orientations of error theory.

option is to try to eliminate them for safety purposes (for example, “context” in Reason’s book refers to the context that can trigger specific types and forms of errors, not a context shaping specific process operators strategies). Rasmussen’s definition indicates instead that “errors” are to be expected and that they are part of a natural or normal learning and explorative cognitive process (see Figs. 4a and 4b, for a contrast between the outcomes of the two threads in 1990, between taxonomic/naturalistic). Rasmussen’s practical orientation towards managing errors had as a consequence to “*be focused on an envelope including system resources which allows users to perform according to their ‘style’ without violating resource constraints*” (Rasmussen, 1993a,b).

This perspective on cognition and design recommendations for interfaces was endorsed by Amalberti (1996). It is in light of his work that I can to some extent understand Hollnagel’s criticism of SRK when it is used to classify error, as Reason did (Reason, 1990). Nevertheless, I find that it does not sufficiently acknowledge Rasmussen’s more global conceptualisation of cognition. Rasmussen’s specific approach to error provided a very fruitful springboard for theorising accidents from a wider (socio-technical) perspective in the 90’s, as it is presented in the following sections. But it also leads to a different appreciation of operators’ contribution to safety by acknowledging their expertise in finding viable solutions when coping with complexity and by identifying, understanding, recognising and nurturing their ability to cope with disturbances, e.g. by introducing the contemporary topic of resilience (Hollnagel et al., 2006; Reason, 2008).

5. The difference between technical and human reliability/safety analysis

In his papers published at the end of the 70s and during the first half of the 80s, drawing from his cognitive models and studies, Rasmussen always maintained a strong critical perspective on human reliability assessment (HRA). I will not explore this topic in depth as it is not at the heart of Rasmussen’s contribution to the field of safety science. Nevertheless, I see his rejection as an important theme throughout his scientific contributions with regards to the ‘qualitative versus quantitative’ approaches in the field of safety. The fact that Rasmussen never ventured into this area to propose quantitative methodologies suggests that he was very dubious about the feasibility of an adequate quantitative method in this. His empirical studies of both error and real-life work situations (Rasmussen, 1969; Rasmussen and Jensen, 1974) made him well aware of the level of qualitative complexity involved when attempting model cognition.



Cited from Reason, 1990

Fig. 4a. A taxonomic view of errors (Reason, 1990).

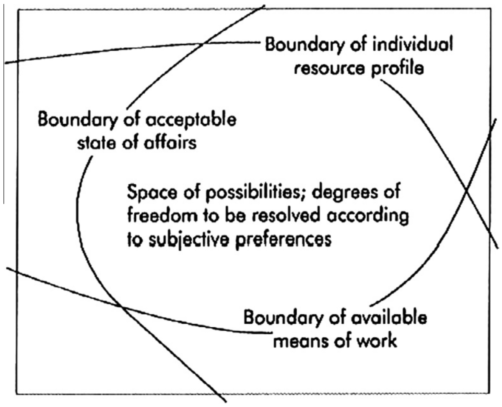


Fig. 4b. A naturalistic view of errors (Rasmussen, 1990a).

His addition is therefore only qualitative, although it does sometimes refer to specific quantitative techniques. He reviewed for instance possibilities for introducing human error into technical risk assessments, including and distinguishing both reliability and safety analysis (Rasmussen, 1979). There are, in many places in his papers of the 80s (Rasmussen, 1979, 1980a,b, 1982, 1985a,b), very strong statements against attempts to apply a technical rationale to the specificity of human behaviour. One can imagine in the aftermath of the Three Mile Island incident there was a clear demand for quantitative methodologies, a subject that Rasmussen was very about a keen to. The 1979 paper is certainly to be understood as a position paper on this topic, following TMI.

One comment demonstrating this sensitivity is the following "*In some areas, particularly in reliability engineering, several premature attempts have been made to quantify human performance due to the pressing need for prediction. (...) In this effort, we have to consider that humans are not simply deterministic input–output devices but goal oriented creatures who actively select their goals and seek relevant information. The behaviour of humans is teleological by nature*" (Rasmussen, 1983). Rasmussen rejects the idea that the rationale of these technical risk assessments could be translated to human performance assessment without taking into consideration the specificity of humans as system components; by nature much different than the technical ones. He wonders about the ability of accessing reliable sources of data on the probability of human error and introduces his own findings about cognition. "*This technique must be used however with extreme caution. The operator is in many respects a holistic data processor responding to total situations rather than individual events or system states. Complex functions may be performed by skilled operators as one integrated and automated response*." Fig. 5 illustrates these ideas (this figure is not original and results from the combination of two separate ones).

While these early attempts were focused on "human factors," the prospect of applying these quantitative techniques to "organisational factors" was also explored n the years by authors including Embrey or Paté Cornell). Although it was too early for Rasmussen to identify this trend and to offer criticism, one finds premonitory warnings about this tendency *"It lies in the nature of oversights and errors of management that they are tied to human errors, but it also lies in the variety and complexity of organisations and design activities that quantitative risk modelling in this areas is practically impossible"* (Rasmussen, 1979). It seems indeed natural to expect great difficulties in moving from individual to organisational levels, especially given the already great limitations at the individual level, as Rasmussen expressed: "*simulation of causal chains of events in entirely technical systems is eased by their well structured and relatively stable anatomy (...) This is not the case for the activity of people with free will, mobility and subjective goals"* (1988b).

One can see in these sentences his preoccupation with the importance of the use of mathematics and quantification as a "proper" science, as defined by the community of engineers of the time and still by many today. With this in mind, one could expect a strong tendency to attempt to quantify human (and then social) dimensions, as engineers represent a very powerful profession in the operation of socio-technical systems and in the research of reliability and safety (not to mention a managerial tendency to believe that adequate management depends only on metrics, indicators and quantification, a problem that Rasmussen also identified). This continues to cause problems to this day when trying to promote qualitative approaches to safety assessment based on social science inputs. Safety and risk dimensions are very often taken seriously in some circles only when numbers or equations start to appear. This is an epistemological theme that he explored both for human reliability assessment and for accident investigation. I believe this to be of great significance for understanding the challenges of improving safety today.

"*Science and engineering depend on a representation of the laws of nature in control of the behaviour of physical systems. This representation can take different forms. (...) The breakthrough of modern science was due to Galilee and Newton who replaced observations of events by measurements of variables and causal laws by mathematical relations among variables (...) the quantitative, mathematical representation of the physical sciences and engineering has been so successful that the qualitative concept of causality has been discredited by scientists*"(Rasmussen, 1988b). Such epistemological concerns can be found in many of his papers, and they underlie the themes to come. A later section will be dedicated to his epistemological or philosophical explicit (and implicit) preconceptions. This next section, which considers in depth Rasmussen's new vision of safety and accidents, includes many of these considerations.

6. Intermediate comments

As I progress in this paper with the different concepts introduced by Rasmussen through time, it seems important to mention that at the end of the eighties (from 1987 onward) there is a clear shift in the topics that he addressed. Whereas up to the mid 80s all his papers dealt principally with cognitive models, interface design, human error and human reliability assessment, a new era clearly unfolds later for the reader as the author takes a more macro perspective on safety and accidents. Although the ideas, concepts and models elaborated in the 70s and 80s shaped considerably these new concerns, his thoughts encompassed a

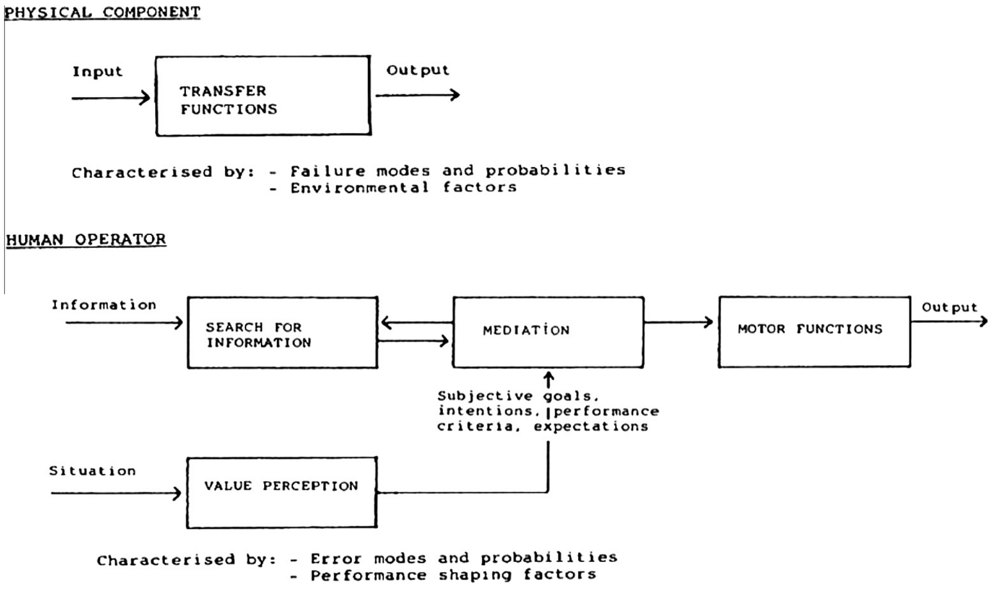


Fig. 5. Contrast between a physical component and a human operator (Rasmussen, 1982).

much wider scope. In a series of six papers (Rasmussen 1987a, 1988b,c, 1990a,b; Rasmussen and Batstone, 1989), the basics of a new research program and agenda are put together and pursued in the 90s.

One key event in the genesis of this shift seems in retrospect to be the international workshops organised by 'The World Bank,' in which Rasmussen was deeply involved as a co-organiser with Michael Batstone (Rasmussen and Batstone, 1989). This is undoubtedly at least in part consequential to the major industrial accidents of the 80s in various technological areas (e.g. transport, nuclear and petro-chemical industry), including Bhopal, 1984, Challenger, 1986, Chernobyl, 1986, Zeebruge, 1987, Clapham Junction, 1988, Piper Alpha, 1988. The accident investigation reports contributed to divert (cognitive) researchers away from local problems solely associated with human error and technology to open a much wider field of enquiry. It is clear that the range of discussions involved, including a variety of experts from both Europe and US with different disciplinary backgrounds (engineering, psychology, social sciences, law), created a very productive environment for developing new ideas related to accidents and safety.

Rasmussens's 1989 paper is probably one of the best available testimonies of this intense intellectual activity, in which he summarises the interventions and conferences of a great number of authors in the field including Baram, Brehmer, La Porte, Meshkati, Moray, Nertney, Otsberg, Reason, Rochlin, Rouse, Sheridan, Swain, Westrum and Woods. This writing opens a window on Rasmussen's own developing ideas at that time, in particular his attempt to incorporate various strands into a unified feedback loop framework, a problem which has always driven his research and on which he will write quite extensively in the late 90s (Rasmussen, 1992, 1993b, 1994, 1995, 1997a, 1997b, 2000), and to which a section is dedicated below. For now, the papers from 1987 to 1994 are primarily under consideration. From these papers, many intertwined new concepts must be introduced. While a new vision emerges, it is clearly based on his previous research findings. In the following paragraphs, several of these key concepts are introduced, including the degree of freedom of operators and self-organisation, the fallacy of defence in depth, the perspective ot accident normalcy, and the model of accidents as migration towards the boundaries of acceptable performance.

With this move, one can observe a shift from a basic vision of accidents as "*low probability situations which typically are related to complex situations caused by several coincident abnormal conditions and events*" (Rasmussen, 1979) to the view that "*there seems to be a natural migration toward the boundaries of acceptable performance in any active work organisation*" (Rasmussen, 1993b). And, Rasmussen oscillates at times between accidents understood as 'normal': "*catastrophic system breakdown is a normal feature of systems which have self-organising features and at the same time, depend on protection against rare combination of conditions which are individually effected by adaptation*" (Rasmussen, 1990b) and foreseeable ones: "*in many cases, as judged after the facts, liabilities and losses could reasonably be anticipated, accidents were foreseeable and obviously preventable*" (Rasmussen, 1995).

7. A new vision for accident and safety

7.1. Degree of freedom, self-organisation and defence-in-depth fallacy

One important idea behind a move from a micro view of accidents to a macro (socio-technical) one is the degree of freedom of individuals in accomplishing their tasks. This principle is found very early in Rasmussen's the concepts of his writing and constitutes a building block of the wider perspective for safety and accidents to be described below. "*In a real-life situations, a large degree of freedom is left to the human even though the overall goal is stated unambiguously*" (Rasmussen, 1980a,b). This sentence reflects the findings o empirical study of electronic troubleshooting (Rasmussen and Jensen, 1974) and has implications for a macro approach of safety and accident. The notion of self-organisation, from the development of the cybernetics movement in the 60s, makes up the next building block, which will stand with the degree of freedom principle.

The principle of self-organisation is of great contemporary significance (in many fields including physics, biology and social sciences and expanding through the science – and philosophy – of complexity) and that he recognised it early in his career as being extremely valuable for the field, which is quite prescient. His manner of associating degree of freedom and self-organisation is articulated: "*it follows directly from this discussion that the structuring of work processes through on the job training by an individual will be a self-organising, evolutionary process, simply because an optimising search is the only way in which the large number of degrees of freedom in a complex situation can be resolved*" (Rasmussen, 1990b).

The interesting twist is when he then associates these self-organising properties and degree of freedom with the principle of defence-in-depth. In the period of reflection following the technical disasters of the eighties, it is apparent that the defence-in-depth concept was in the air, as Reason, for instance, had ruminated over the subject of catastrophe beyond human error by providing what is probably the most renown and advocated model in the field for accident investigation (which became known as the 'Swiss Cheese' image). Rasmussen had already discussed the notion in a 1987 paper (Rasmussen, 1987a) in which he suggested a comparison between technology that relied on feedback to improve design over time (e.g. aviation) to new modern technology that had to rely on risk assessment in a feedforward process to anticipate without much learning about possible failures (e.g. nuclear). According to him, the principle of defence-in-depth allowed to build this strategy for modern technologies if one monitored the defence-in-depth status during operation.

Rasmussen was clearly aware of Reason's use of barriers in 1989 at the latest as his synthesis of the workshops of that year includes a summary of Reason's participation. "*Reason introduces the discussion of the key problems of industrial safety by an emphasis on the sensitivity of the 'defence-in-depth' design philosophy to combinations of human failures' (...) 'Two important conclusions emerge from Reason's review: first, disasters are rarely caused by any one factor, either mechanical or human; second, most of the significant root causes are present within a system long before an accident sequence is identified. In short, violations very likely turn into 'resident pathogens' to use Reason's very illustrative medical metaphor*" (Rasmussen and Batstone, 1989).

However, instead of sticking with the medical metaphor, Rasmussen combined self-organisation and defence-in-depth together to characterise what he called the "fallacy of defence-in-depth" (here one can see an illustration of the difference of the two threads (i.e. taxonomic, naturalistic, see Section 3). "*One basic problem is that in such a system having functionally redundant protective defenses, a local violation of one of the defenses has no immediate, visible effect and then may not be observed in action. In this situation, the boundary of safe behaviour of one particular actor depends on the possible violation of defenses by other actors*" (Rasmussen, 1997b).

7.2. A 'normal accident' perspective, as the product of organisational migration toward the boundary of acceptable performance

From there, two consequences follow, one is that it is possible to see accidents as normal, in the sense that "*catastrophic system breakdown is a normal feature of systems which have self-organising features and at the same time, depend on protection against rare combinations of conditions which are individually effected by adaptation*" (Rasmussen, 1990b). Another is that this adaptation, based on the self-organisation and degree of freedom of local agents at the level of operations, can indeed be transferred to different actors (e.g. managers) within high-risk systems. "*Analogy can be drawn between the adaptive mechanisms involved in the skill attainment of individual (...) and the role of management decisions – which may be errors in a safety point of view – in the adaptation to efficiency measures of an organisation. Errors in management and planning are intimately related to organisational attempts to adapt to the requirement of a competitive environment.*"

This helps define a model of migration towards the boundary of acceptable performance served by an analogy from the domain of physical sciences. *"Activity will be characterised by local, situation induced variations within work space calling to mind the 'Brownian movements' of the molecules of gas. Such variability will give the actors themselves ample opportunity to identify an 'effort gradient' while management is likely to build up a 'cost gradient"* (Rasmussen, 1993b). This is an analogy and a translation, first from a physical phenomenon to techno-social one, second, from a vision of operators as self-organised agents with degrees of freedom to a (macro) vision of safety as a global migration of a system (Fig. 6).

This translation is well illustrated by two figures found in papers published 3 years apart (Rasmussen, 1990b, 1993b) then finalised in the 1997 paper (as shown in Fig. 6). Concerning this introduction of Rasmussen's new vision of safety and accident, two points are discussed in the following paragraphs. One point concerns Rasmussen's "normal accident" interpretation. It is relevant to distinguish three lines of interpretation of the normality of accidents, three main tendencies or dominant schemes taking shape in the 70s/80s. I believe that Rasmussen initiated one of the three. The other point concerns the great influence these ideas have had in many recent developments in the field, in particular with the introduction of the rhetoric and vocabulary of (the science of) complexity in the past 10 years (e.g. self-organisation, emergence, edge of chaos, sensitivity to initial conditions, etc.).

First of all, although it is fair to see Perrow as the author who brought the question of the 'normality' of accidents to the forefront, the roots of this idea are found earlier. Recently, the work of historians of technological disasters during the industrial revolution in France and Britain (Fressoz, 2012) has revealed that a similar sort of argument was already present at this time. Indeed, to explain nineteenth-century train derailments, contemporary commentators would refer to the rhetoric of a simple cause producing big effects and the impossibility of foreseeing such events. One may legitimately see in what Fressoz found in his historical research an anticipation of the 'normal accident' argument that arose a century later with the advent of new technologies, and more specifically for Perrow, the nuclear industry. Although Perrow contributed greatly to making this domain a concern for the social sciences, this idea about accidents had been around at least since the technological revolution of the 19th century.

7.3. Rasmussen's 'Ashbyan' version of normal accidents

One could argue that Rasmussen's earlier definition of accidents was inspired by this kind of idea of a level of unpredictability of accidents: "*low probability situations (...) are related to complex situations caused by several coincident abnormal conditions and events*" (Rasmussen, 1979).[6] Indeed, it is relevant to bear in mind that there exists many subtleties when it comes to this topic. I distinguish for this reason three different somewhat overlapping tendencies (Fig. 7). The first one is technological. It is Perrow's version of the normal accident, of the tight coupling and complexity of technical systems that will at times defeat all efforts of societies (civil society, private companies and states) to prevent them.

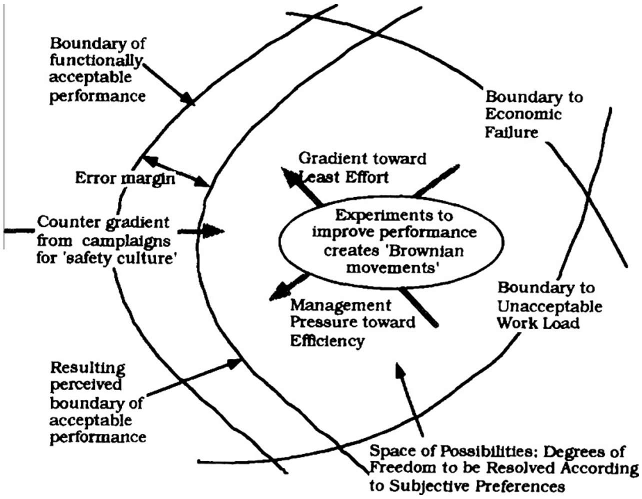


Fig. 6. Migration towards the boundaries of safe performance (Rasmussen, 1997b).

This corresponds to a certain idea of technological determinism as found in the writings of philosophers during the 70s, for example Winner (1977), who was inspired by authors who introduced the debate on the autonomy of technology, such as Ellul (1954, 1977). Ellul considered that technology had become, since the industrial revolution, a major influence on modern societies. For this author, technology had the ability to shape these modern societies as an independent influence, colonising practices with a certain degree of autonomy, out of human control. Technology could be seen, along these lines, as considerably shaping societies, in a subversive way. But he was not the only writer concerned by the spread of technological systems in the 1960s, as Thomas Hughes describes, in US, '*numerous other academics and professional writers similarly considered omnipresent technological systems out of control*'.[7] Although this view has been subsequently criticised by social constructivists, in this paper one can see how it makes sense to characterise Perrow's emphasis on technology out of control as an 'Ellulian' perspective on normal accident, even if he never refers to this author. Accidents happen because technology escapes human control.

The second tendency is epistemic or constructivist. It can be traced back to Turner's "failure of foresight," endorsed and then developed by Vaughan (1996, 2005). This one has Kuhnian roots in the philosophy of science (Khun, 1962). The central idea is that institutionalised views prove at times to be inadequate because they are unable to consider the possibility of events or to integrate anomalies early enough to be modified accordingly before an accident. These (cognitive/cultural) frameworks that communities of individuals construct while interacting with their worlds are always in principle temporary ones. They are challenged with anomalies, precursors or signals (whether mixed or weak) that make sense only in retrospect, in what has been described by Turner as "incubation periods." During these periods, these anomalies do not challenge sufficiently the worldviews held by the different agents. Although it should be seen as a cultural-cognitive phenomenon, the question of power is also associated.

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[6] The expression '*several coincident abnormal conditions and events*' reminds the philosophical reader about conceptualisation of the unpredictable by Cournot during the 19th century. In times of science seen as the search of the deterministic law of phenomena (e.g. Comte's positivism), this French philosopher of the 19th century conceptualised novelty and fortuitous events as the unexpected encounter of two (or more) deterministic independent trajectories. It turns out that Cournot's view was very much influenced, as asserted by Fressoz (2012), by the debates surrounding the train derailments at the time!

[7] Hughes, 2005. 89.

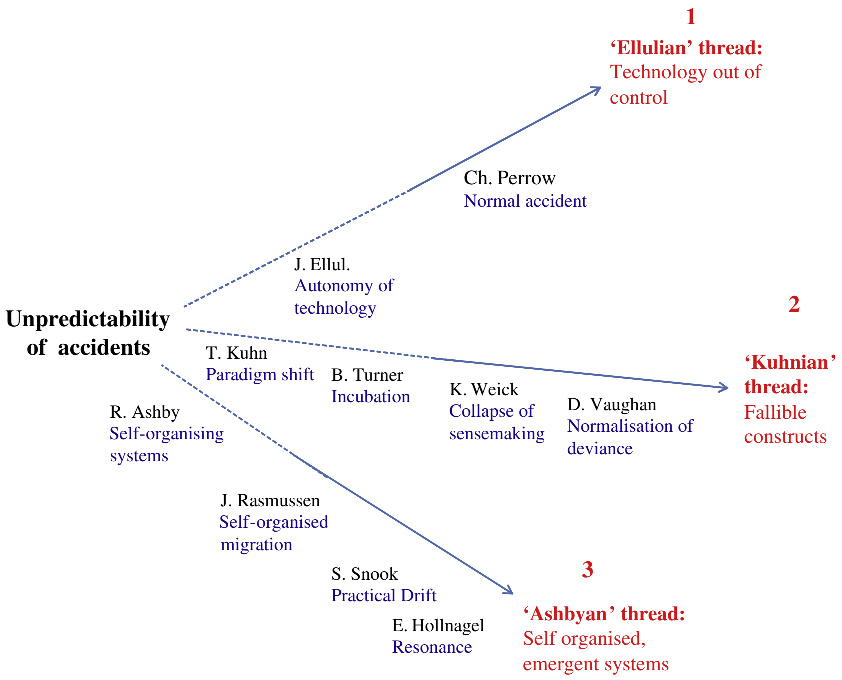

Fig. 7. Many 'normal accident' threads.

The third is the question of complexity. Some might find this distinction strange as Perrow clearly included a type of complexity in his interpretation of the unpredictability of accidents. The fact is that complexity is polysemous; it has different meanings. Rasmussen's use of complexity is not straightforward, but it is quite clear that one of his dominant uses of the term is related to the principles of self-organisation as introduced by cybernetics thinkers, and most notably in Rasmussen's writings, by Ashby (1956, 1962). Although Rasmussen had not identified the broad movement and developing field of the science of complexity (one thinks of the activity of the Santa Fe institute which began in 1984) and despite not being unaware of recent approaches (e.g. catastrophe, chaos theory)[8], Rasmussen can be seen as a pioneer of this version of the normal accident. It is his knowledge and use of the writings of Ashby (one of the precursors of the science of complexity) that gives this prescient flavour on complexity to Rasmussen's writings.

I am inclined to classify an author such as Snook (2000) into this third line of thought, which was promoted by Rasmussen and could also be called the 'Ashbyan' strand of the normality of accident. This author refers directly to the original writings of Rasmussen on self-organisation applied to accident and safety. One cannot help but think of the "defence-in-depth fallacy" when reading Snook's presentation of "practical drift" (Snook, 2000). Snook stood back to produce a big picture of "friendly fire," which he investigated in order to revise the official report of this accident. "Practical drift" consists of localised drift in an individual's practices. Whereas the organisation is at first designed to ensure the consistency of the whole by proceduralising the behaviour of the parts, in fact these parts (individuals) slowly drift from their expected course to create a path for an accident. This is no different from Rasmussen interpretation of the Clapham Junction accident, applying his new vision of safety and accident and its "defence in depth fallacy" (see box 2).

Box 2 Rasmussen's Clapham Junction interpretation.

> *"The Clapham Junction railway accident presents a clear example of how a safe work procedure for signal system modifications, including multiple precautions against human errors, gradually degenerates due to adaptation at all levels of the organisation to locally more efficient work practice (...) safety checks following modifications of signal system wiring were planned to be independently performed by three different persons, the technician, his supervisor, and the system engineer. Work force constraints and tight work schedules, however, led to a more 'efficient' division of work. The supervisor took part in the actual, physical work and the independent check by him as well as by the engineer was abandoned. In addition, the technician integrated the check, i.e. a 'wire count' into the modification task although it was intended to be his final separate check. In short, adaptation to a more effective division of work under time pressure causes the redundancy required for high reliability to deteriorate"* (Rasmussen, 1994).

Snook pushed further this idea of the normality of accidents in his book (an interpretation endorsed by Perrow, 1999) through the catch phrase that it was *"a normal accident in a highly reliable organisation"* (Snook, 2000), but adding that *"it was normal because it occurred as the result of normal people behaving in normal ways in normal organisations"* '(Snook, 2000). System thinking and complexity references pervade Snook's explanations. There are also direct references to Rasmussen when it comes to issues of stop rules and causality in investigations (a point discussed in the next section). But Hollnagel distinguishes himself (Hollnagel, 2004). Whereas Snook relies on an empirical case study, in which the concept of 'practical drift' only comes after a grounded analysis based on qualitative data, Hollnagel is deliberately both more conceptually and practically oriented.

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[8] One can read for example in a 1989 paper '*The question is raised whether modern approaches to system science such as catastrophe and chaos theories can contribute to the analysis of the potential for systematic break-down of self-organising socio-technical systems*' (Rasmussen and Batstone, 1989).

Building on ideas similar to those of Rasmussen and Snook, he moves to another level of conceptualisation by introducing the principle of "resonance." It is an analogy with a physical sciences phenomenon that, as its counterpart the 'Brownian' analogy from Rasmussen, seeks to support the identification of unwanted patterns creating paths to disasters.[9] The concept of emergence (versus resulting) is then added to advocate a non reductionist approach to the problem of safety. Although bringing a next level of conceptualisation with practical ambitions (i.e. functional resonance accident model), Hollnagel's ideas have strong affinities with Rasmussen's. In my view, Snook and Hollnagel show the relevance of exploring safety and accident through the application of self-organisation, emergence and complexity. They explore and extend the Ashbyan thread opened by Rasmussen.

These three tendencies – 'Ellulian' (with an emphasis on technology), 'Kuhnian' (with an epistemic or constructivist tilt) and 'Ashbyan' (with inspiration in self-organised complex systems) – are obviously not exclusive. They are found intertwined in the works of many authors. A good example is Turner, who owed much to a constructivist approach and to system complexity thinking (Turner, 1995). However, one thread can sometimes become too dominant in one's thinking. This is not without consequences. For instance, both the Ellulian technological and the Ashbyan complexity thread contain asocial tendencies. The interplay between actors, institutions and society as seen through sociology, political science or anthropology can as a result be minimised by authors influenced by these two threads. This depends on the background of the researcher and his or her intellectual inspirations. For example, I will argue further in the second article that the overly strong influence of the thread that Rasmussen created prevented him from introducing into his work the epistemic or constructivist ones, which derive much more from the social sciences and entail the use of other concepts (e.g. power, culture). Although Rasmussen's research program throughout the years is cross-disciplinary, in reality, the social sciences have remained peripheral to his own propositions and models. This is a good example of a thread taking over.

8. Investigating accidents

8.1. Causality, stop rules and goals

As a user of error reports (Rasmussen, 1969) and as a designer of methodologies for an exploitation of events from the human side (Rasmussen, 1982, 1987b), Rasmussen explored in increasing detail investigation principles in a paper published in 1988 (Rasmussen, 1988b). First, he contrasts the different rationales between risk assessment (foresight) relying on mathematical and relational properties based on our engineering knowledge of technological systems and the causal structure of explanations for understanding events after accidents (hindsight). A well-ordered reality in foresight is replaced in hindsight by a much 'messier' picture in which mathematical and relational statements are replaced by causal descriptions of discrete events related to each other and including many different dimensions, from technical to organisational aspects. This constitutes the background for future developments in accident analysis. "*The preconditions for formal, mathematical analyses of system function also break down and the formal methods are replaced by different methods for analysis of accident based on causal representation*" (Rasmussen, 1988b).

Second, he introduces two intertwined concepts necessary to the understanding of issues related to the investigation of accidents: stop rule and goals of investigations. These two concepts are related to the epistemological question of what it means to describe an object or a situation and whether or not it is possible to do so in an objective manner. For Rasmussen, it is not possible to be objective when applying a causal mode of explanation (as opposed to relational or mathematical ones, as introduced above). "*Causal explanations describe objects which interact in chains of events. Neither the objects not the events can, however, be defined objectively. Their identification depends on a frame of reference which is taken for granted and causal explanations are only suited for communicating among individuals having similar experience who share more or less intuitively the underlying definitions*" (Rasmussen, 1988b).

Because "*there is a tendency to see what you expect*" (Rasmussen, 1988b), in accordance with the lack of an objective posture as described above, it is therefore fundamental to be clear about the purposes of an investigation as well as the models used to support this purpose. Rasmussen identifies three goals for investigations: explanation, allocation of responsibility and analysis of system improvement. Depending on the goal pursued, the type of data collected and interpreted will differ, as will its exploitation. Investigations are not the same when they are performed in order to find people to blame, when they are performed to elaborate recommendations or when they are conducted in order to explain (or theorise). The mindsets of the investigators, the relationships between the investigators and the actors who are interviewed, as well as the timing of the investigation are very different for each goal. Stop rules are therefore closely linked to both a frame of reference and the goals of investigations.

8.2. Accimap

In line with his distributed cognition approach of safety and accident (Rasmussen, 1991, 1993a,b), Rasmussen moved in collaboration with Svedung toward a graphical approach explicitly representing a predefined type of landscape for a causal mapping including several actors (Rasmussen, 1997; Rasmussen and Svedung, 2002). One can imagine that the graphical inspiration for this proposition results from a combination of the socio-technical representation (to be discussed in the next section, Rasmussen, 1988c) and the Zeebruge figure showing that "*the individual decision makers cannot see the complete picture and judge the state of the multiple defences conditionally depending on decisions taken by other people in other departments and organisations*" (Rasmussen, 1993b). Graphical approaches of accidents have always been very important tools both for formalised, quantitative approaches and qualitative ones. The interest of Rasmussen and Svedung's (2000, 2002) contribution is its explicit introduction of a much higher number of potential dimensions than those restricted to technical and human error, and also its attempt to organise a 'messy' reality with many sources of interactions between technology, actors, functions and institutions.

This framework, called Accimap, was applied to the cases of Zeebruge, Clapham Junction and some other less known accidents and was intended to be a proactive tool for safety management, and not simply a support tool for investigations. The original idea of Rasmussen and co-author Svedung, as indicated in the previous paragraph, was derived from a principle of distributed cognition. Accimap is initially a tool designed for mapping the distributed nature of decision-making shared by actors located at different moments in time and geographical positions in the daily operation of socio-technical systems. The creators make this explicit: "*In contrast to the conventional cause-consequence chart, the analysis for development of an AcciMap should not only include events and acts*

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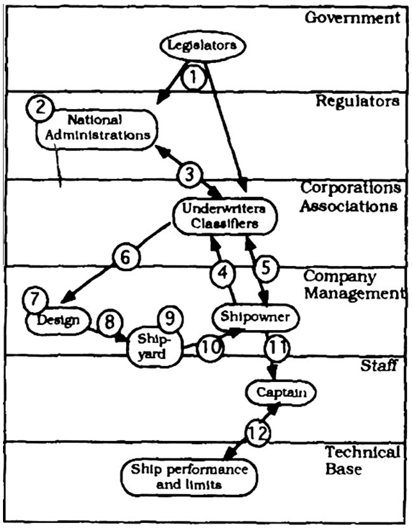
[9] Both these models, the 'Brownian movement' (Rasmussen) and 'Resonance' (Hollnagel), as identified by a reviewer of this article, '*seem to suggest that the movement is random rather than the result of purposive explorations of alternative decisions and actions (but above all knowable ones) aimed at definable personal and group objective*'.



Legend:

1, 2. The strategies for legislation appear to be inadequate during fast technological change.

3 Shipping industry's influence on legislators: Depressed shipping market of the 1980s leads to changes in its structure: Underwriters and National Administrations are neutralised by competition.

4. Ship owners influence classification societies.

5. Owners and classifiers co-operate and do not inform legislators adequately.

6. Communication from classifiers to designers inadequate.

7. Design based on established practice inadequate during period of fast pace of change:

8. Inadequate specification and documentation from design. Shipyards rely on established practice during period of rapid technological change.

9. Quality assurance of shipyard questionable.

10. Inadequate communication between design, manufacturing and operating communities:

11, 12. Inadequate guidance to captain, learning by doing inadequate during fast pace of technological change.

Fig. 8. Simplified Accimap. Zeebruge accident (Rasmussen, 1997a,b).

in the direct flow of events. It should also serve to identify all decision makers at the higher level in the socio technical system who have influenced the conditions leading to accident through their normal work activities" (Rasmussen and Svedung, 2002). By understanding distributed cognition from a situated perspective, a specific time and place, one can in theory better understand how systems behave the way they do, but also how they may at times create a path to disaster. One can also support the design of information systems that would materialise the boundaries of safe operations by indicating how decisions can propagate within systems, something that the agents are indeed unaware of most of the time in real life (Fig. 8).

Some authors adopted the Accimap layout very rapidly (Hopkins, 2000, Woo and Vicente, 2003a,b; Vicente and Christoffersen, 2006). These authors, however, have not applied the principles of mapping actors in relation to actors in distributed cognition decision-making processes. Instead, in some guidelines developed for introducing Accimap's use (Branford et al., 2009), categories of causes are associated to different levels (e.g. the external level: government including privatisation, outsourcing; organisational level: financial issues including cost cutting, including resource allocation problems, etc.), and principles for causal reasoning are also presented. However, the principles for introducing actors linked with their distributed cognitive decision-making processes are not provided. In this case, Accimap appears to be used as a graphical tool to open accident causality to higher levels and to visually communicate on the findings of an investigation. Distributed decision-making processes of actors are only implicitly present. Accident reports can contain more information about them depending on the quality of data and backgrounds of investigators. This kind of alteration from the original idea probably comes from the fact that Accimap can be seen as both an analytical tool for studying distributed cognition for risk control and as a tool for communication of investigation findings. Until now, the latter has been more successful than the former.

In fact, a series of problems derive from the analytical ambition to map actors in retrospect as one goes up and down the levels of the socio-technical system. Decision making at high levels does not always result from only one actor but from several actors debating, arguing and discussing. It is not always possible as such to explore cognition of one individual, but instead a collective decision-making process, which is not always easy to graphically decompose. Decisions about regulations involving multiple actors inside and outside private companies, decisions about change of organisational structures involving different actors of a company, decisions about adopting one technological design rather than another provoking debates between engineers and managers, etc. are never the act of an isolated individual but a highly interactive and collective process. This problem was partially dealt with in the representations when introducing function instead of actors (e.g. traffic planning, ferry design, e.g. Fig. 8).

This might be different in certain cases at lower levels, as when it comes to operators triggering local events at the time of an accident (such as a driver, pilot or process operator). However, here again, it is often a collective decision-making process relying on a very diverse range of artefacts. Unless one decomposes this collective process into units representing different individuals and their interactions with their material environment, it is aggregated in the representation within a box. Decisions, taken individually or collectively (even if one leaves this problem aside), can have a proximal or more distant relationship with the accident itself, both in time and space. It is not easy to include these dimensions in the graphical representation without greatly complicating the picture. For this specific reason, Rasmussen and Svedung suggested allocating numbers to the boxes of Accimap to direct readers through the report, permitting them to find explanations in the text (see a simplified example in Fig. 8).

Another issue meriting discussion is that of linear versus non linear causality in accidents, and whether non-linear causalities can fit within the Accimap format. One drawback for any graphical representation of an accident is the over-simplification inherent in going from a text to 'boxes and arrows', and from a complex network of circular causalities to much more simpler linear ones. It is for just this reason that the fields of cybernetics, general system theory and complexity have introduced non linear and circular causalities to make sense of complex systems. The point is that it is nearly impossible to make predictions because of the many interrelated events that defy certainty in anticipation. In fact, other graphical approaches to accident introducing the multidimensional and systemic nature advocated by Accimap can be found elsewhere, but which have not been directly influenced by the Accimap layout. These alternative approaches found their inspiration in soft system approaches (e.g. Waring, 1996; Waring and Glendon, 1998), system thinking, system engineering or system dynamics (e.g. Leveson, 2012) and grounded theory principles for treatment of qualitative data (e.g. Snook, 2000).

These other approaches exhibit a different kind of multi-circular causality with positive and negative feedback loops (e.g. system dynamics) which attempt to express the highly dynamic properties of complex socio-technical systems. One is entitled to wonder if a vertical top down retrospective causality translated in Accimap (e.g. Branford et al., 2009) does not participate indirectly to a form of hindsight bias, and therefore reproduces some of the drawbacks of the linear views of the too simplistic technical approaches of the past (e.g. fault trees, event trees). If accidents are to be understood as a highly dynamic feature of complex systems, ignoring the kind of circular causalities involved (meant to deal with the properties of intentional and adaptive systems) might be a problem. There is also the problem of the weighing of causes, discriminating those which contributed the most to the accident, but also determining if, in their absence, the other causes would have not been sufficient to provoke the accident. Despite its limitations, Accimap truly promotes a much more explicit socio-technical view of accidents and safety, a feature that owes much to Rasmussen's new view of safety and accident as developed beginning at the end of the 80s, a contribution to be explored in the following section.

9. 'The whole is more than the sum of its parts'

9.1. A socio-technical perspective based on feedback loops

Without a doubt, the greatest influence that Rasmussen's work has had on safety science over the past 30 years lies in its ability to produce imaginative models based on appealing illustrations and a synthesis of different concepts from multiple disciplines in relation to empirical data. This is true for the SRK model (and the hybrid model of process operator, Fig. 1), the idea of migration towards the boundaries of safe performance (Fig. 6) as much as it is for his socio-technical model, which is the focus of this section (Fig. 9). As with the other models, one can follow an interesting evolution from its genesis to its final development, as articulated in a paper of 1997 (Rasmussen, 1997b). The origin of this idea, as revealed by his papers; seems to be in a 1987 text, without illustrations (Rasmussen, 1987a), and then in a visual representation in 1988 (Rasmussen, 1988c). It is at first a description of feedback loops between different actors of a socio-technical system, then a column showing interactions between levels. From there, other alternative versions of this first model are made available, introducing a scientific discipline associated to a specific feedback loop level (Rasmussen, 1992), then a final version in 1997 (Rasmussen, 1997b) adding environmental constraints.

One of the most compelling characteristics of this model is certainly its ability to combine different levels together in relation to each other through feedback loops of information, scientific disciplines at different levels, and the dynamics of the environment (including the economy, technology, etc.). There are many other models addressing similar issues (Hale, 1985; Hale et al., 1997; Moray, 1994, 2000; Evan and Manion, 2002). They all have their strengths and weaknesses. Hale's perspective is to use a problem solving structure combined with a decomposition of safety management systems activities at several levels of description. Moray's version of the problem is represented through several layers instead of vertical levels, and it does not explicitly address

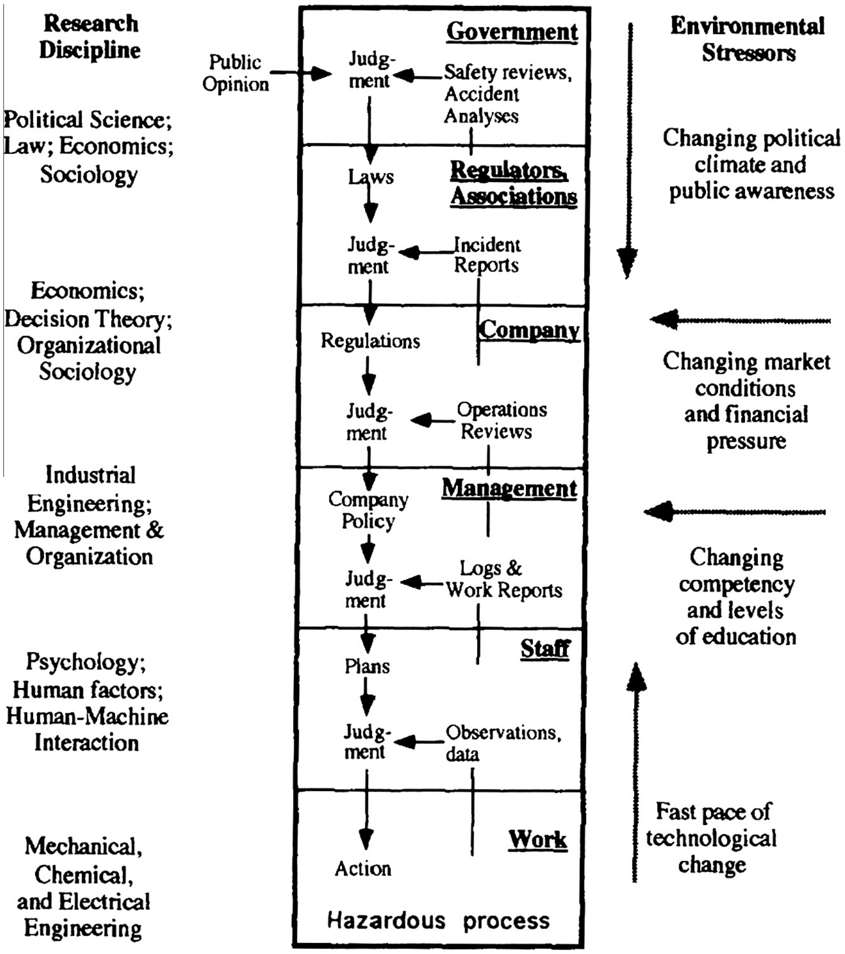


Fig. 9. Socio-technical model of Rasmussen.

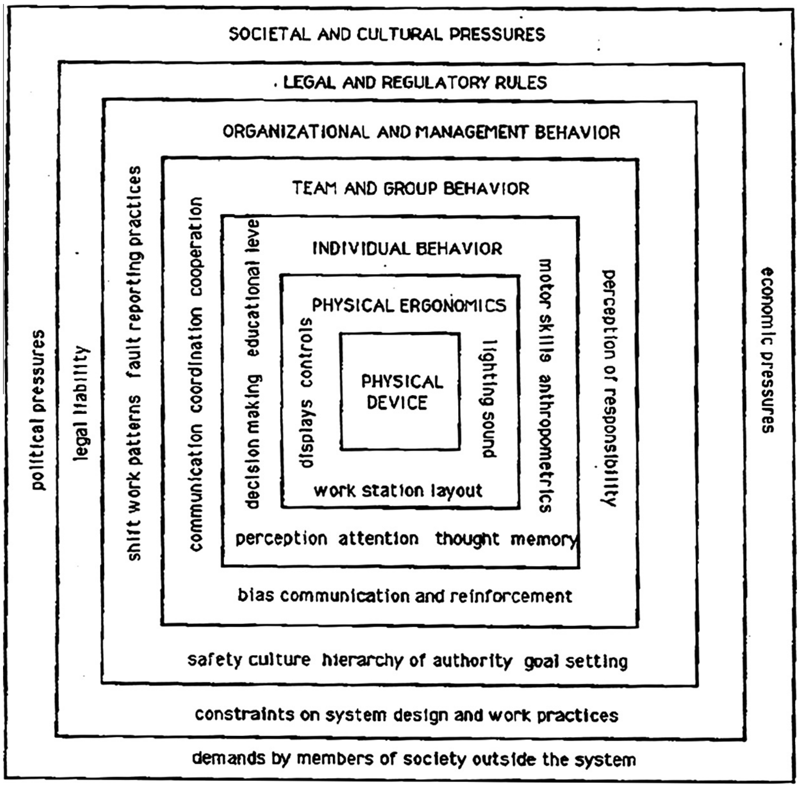


Fig. 10. System oriented approach to design and analysis (Moray, 1994).

communication between these layers (Fig. 10). Technology is at the centre of the figure, which gives the idea of an embedded technology that cannot be understood independently from society.

Evan and Manion distinguish four quadrants (reminiscent of Parsons') in a static manner, without implying the nested layers that Rasmussen and Moray do, instead putting technological, human, organisational and social dimensions at the same level, avoiding the idea of a hierarchy between levels. Hollnagel's representation of a joint cognitive system also has a layered approach but on a horizontal axis. There might be other models with similar purposes. Of course, they are only representations and in that respect need to be understood with the accompanying texts, which include the methodological, empirical and theoretical backgrounds. The discipline of the author – sociology, psychology or (cognitive) engineering – influences which system or view is advocated. This list is not exhaustive. It demonstrates the many different ways of representing safety from a global perspective. In my opinion, the strength of Rasmussen's model is its direct association with cross-disciplinary research, a feature of its later version.

For Rasmussen, the rationale for such a modelling attempt is most likely to be linked with the success of his previous research strategy when it came to modelling cognition in the 70s. In this previous research strategy, as discussed in Section 2, a real-life situation was empirically studied to produce a generic model of cognition, as opposed to local models of cognition (Rasmussen and Jensen, 1974). First, there is the analogy from micro to macro cognition with the concept of self-organisation leading the concepts of 'defence in depth fallacy'. Second, there is the idea that one needs an analytical framework to encompass a wide range of dimensions that have to be brought together to make sense of socio-technical behaviour. This is necessary, as much as it was necessary to produce a process operator model, because one cannot understand a system if analysed uniquely from its parts. Rasmussen opposes this line of thinking the structural (decomposing parts independently) and functional (abstracting the whole) approaches, which is somehow reminiscent of the distinction between experimental findings and a real-life study of cognition.

This assumption that Rasmussen applies a similar strategy when moving from cognition to organisation is confirmed by the following quote: *"For experiments in a laboratory, psychologists are very careful in describing the experimental conditions and informing the subjects about the goals to pursue. Flaws in such precautions, which prevent independent duplication of experiments, make the effort an unscientific enterprise. For field studies, careful instruction of subjects will make the whole study useless, the goal formulation and subjective value structure are key issues of an analysis"* (Rasmussen, 1992).

A bit further in the same paper, he concludes "*In fact, what we are looking for in our efforts to create a conceptual framework for the description of tasks, activities, work domains, etc., is a model framework, a framework for description which can serve to compare results from analysis made in different contexts and domains, which can serve to predict what kind of phenomena are to be expected in one work situation, given results from studies in other environment (...) the framework is, therefore, intended to be pragmatic and rigorous*" (Rasmussen, 1992).

9.2. Concerning the managerial issue

As for the role of managers in the socio-technical system, Rasmussen's expected a certain number of characteristics to be met by managerial practices for ensuring safety. He grouped these aspects into four categories:

- Information – boundaries of acceptable performance should be visible.
- Competency – decision makers should be competent.
- Awareness – decision makers should be aware of safety implications of their actions.

- Commitment – adequate resources should be present to maintain defences.

Some interesting and quite contemporary problems as they are now addressed were identified by Rasmussen, for example, that of the competency of top managers. He thought that the current situation could be the source of problems, for at higher levels competency is often inadequate on the topic of major accidents: *"This is the case partly because technical knowledge is not maintained during normal management activities at higher levels of the organisation, partly because high level managers often are law and business school graduates with a general financial background, not technically competent people promoted from the technical staff"* (Rasmussen, 1995). This interest for the organisational and managerial dimensions of socio-technical systems was part of his strategy to exploring complementary concepts from different disciplines. This strategy as applied to the socio-technical system is most apparent in a paper from 1991 (Rasmussen, 1991), whereas, in later years, this strategy is approached from a reflexive mode rather than carried out concretely. However, this cross-disciplinary approach characterises a pattern in Rasmussen's thinking that can be traced back to the earliest papers in the 70s.

9.3. Safety science as cross-disciplinary problem driven research and a convergence of human science paradigms

Thus, one can read in the 70s, "*It was important that the analysts have a background in engineering (...) on the other hand, a background in psychology is needed*" (Rasmussen and Jensen, 1974) *but also that "methods developed within different professions have to be considered (...) A truly interdisciplinary study has not yet been established and iteration between hypotheses, test of methods and detailed analysis is necessary*" (Rasmussen, 1976). These quotes remain scattered before the 90s; it was not until then that the question of cross-disciplinary study became a subject in its own right to be treated independently. In three published papers, two in journals and one in a book (Rasmussen 1997a,b, 2000) this theme was introduced and extensively discussed. These papers were based on the research program defined in 1995 (Rasmussen, 1995).

What can be retained from these papers is twofold. First, Rasmussen identifies a cognitive and an institutional problem. The cognitive difficulty concerns the time it takes to master concepts in different disciplines *"complex, cross – disciplinary issues, by nature, require an extended time horizon. It takes considerable time to be familiar with the paradigms of other disciplines and often time consuming field studies are required"* (Rasmussen, 1997). This cognitive problem meets great difficulties within the university environment, which constitutes the institutional problem. *"Such studies, quite naturally, are less tempting for young professors who have to present a significant volume of publications within few years to ensure tenure"* and *"different requirements to research emerge from teaching within the continuity of an established discipline and from analysis of the problems created by a turbulent environment. This difference is not a question of basic or applied research or of the degree of rigor and conceptual clarity called upon. It is a question of difference in aim and scope"* (Rasmussen, 1997).

However, he hoped that a current trend that he had identified in the human sciences could help overcome these obstacles. This trend in organisation and management science, decision science as well as major accident research and occupational safety is a move from normative approaches to more real life descriptive ones (Fig. 11). This would allow these different sciences to find

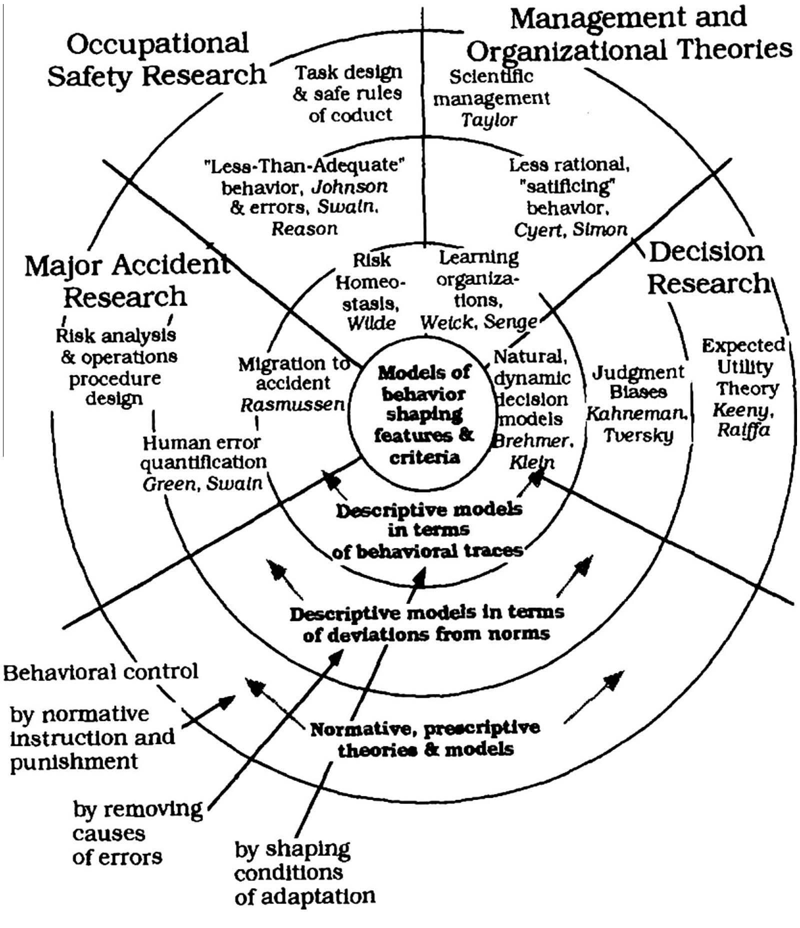


Fig. 11. Convergence of human science paradigms (Rasmussen, 1997a).

a common ground to project some potential cross collaboration in the future. I believe this approach is a bit misleading. Rasmussen projects the trends of the field that he is involved in (major accident research) onto other fields. Given the diversity of available work in these different fields, he could select authors in organisation, management, decision with a more descriptive orientation, compared to authors with prescriptive views. This does not make a global trend.

In any field of the human (and social) sciences, both tendencies exist with a tension between them, whether it be sociology, political or management sciences, for example. It will always be an endeavor for research to think both normatively and descriptively in a field like safety. The ambiguity is that the line between the normative and the descriptive is not always clear. For instance, stating that studying real-life situations should be the orientation of research for designing appropriate safety management strategies is in itself a normative statement. This will have consequences on the way things will be managed, based on new insights from descriptive studies. The question is nevertheless a very important one despite the lack of attention it has gotten in the field so far. I have not found authors rejecting, using or expanding Rasmussen's idea of a convergence between human science paradigms, although the distinction between normative and descriptive models is to be explored.

9.4. 'A strong program for a hard problem'

In my view, the socio-technical model associated with the principles of a functional approach (versus structural) as described by Rasmussen but also the clear cross-disciplinary research implications define what I call in this paper '*a strong program for a hard problem*'. The '*strong program*' is the cross-disciplinary challenge both from a conceptual and empirical point of view. It must reconcile the cognitive and institutional obstacles identified above. The '*hard problem*' is the ability to better understand but also anticipate accidents through a functional analysis going across levels (and therefore disciplines). Although the model is one of the most influential in the field of safety science, only a few authors have explicitly endorsed it in their research and attempted to apply it fully. I can nevertheless identify and discuss briefly two very different examples, as seen in the work of Vicente (2004) and Leveson (2004, 2012).

Leveson has in the past years developed an application of Rasmussen's research orientations into system engineering. STAMP (Leveson, 2004), an approach to investigate accidents, has been directly designed on the socio-technical model, and a risk analysis technique based on system dynamics has been applied to explore alternative ways for assessing safety. Feedback loops play a key role in representing systems and provide an example of how to concretely move from a structural to a more functional (or systemic) vision as advocated by Rasmussen (Leveson et al., 2005; Leveson, 2012). The '*hard problem*' is dealt with, but the '*strong program*' is not in the forefront. One cannot find much from the different disciplines in the loops in the system dynamics models. This is implicit rather than explicit. This stems from the engineering, prescriptive and predictive view taken and the methodological choices made, but also from a rather critical position toward social science descriptive inputs: *"Diane Vaughan, has written extensively about the NASA safety culture with respect to the Challenger accident, but her theory of 'normalisation of deviance' again oversimplifies the problem of engineering this type of system and does not provide much practical guidance in how to improve safety culture"* (Leveson et al., 2005).

Vicente (2004) has also endorsed Rasmussen's perspective, emphasising the '*strong program*' part, namely the need to embrace different disciplinary backgrounds in order to conceptualise issues at different levels of the socio-technical representation. I think it is fair to say however that the '*hard problem*' is somehow left a bit aside, and also that the approach remains more conceptual than empirical. First, the '*hard problem*' is not at the heart of the book, because the argument is rather descriptive and not predictive. Second, it is mainly a conceptual approach to the '*strong program*' because it is not empirically applied to a (or several) case study(ies). Part of the '*strong program*' is to observe empirically, in normal operation of a specific high-risk system, how the different levels are intertwined to produce specific behaviours. Let us indeed remember what Rasmussen had in mind; it *"is a model framework, a framework for description which can serve to compare results from analysis made in different contexts and domains, which can serve to predict what kind of phenomena are to be expected in one work situation, given results from studies in other environment (...)"* (Rasmussen, 1992). The need for real-life based description for the purpose of prediction is clear.

10. Conclusion

This article introduces selected elements of Rasmussen's legacy. One can contemplate a great number of fruitful insights in many different areas, as discussed in Sections 2–7. The number of authors who found inspiration and support for their own research in his work is impressive and clearly justifies seeing Rasmussen as one of the founding fathers of safety science. In very different domains, including the design of human machine interface, human error, accident investigation and socio-technical safety analysis, design or assessment, his propositions have shaped orientations that flourish today. Rasmussen's ability to develop models, which were always related to specific purposes (e.g. design of interfaces) is emphasised and described as a very good example of safety science research, in which the purpose of the researcher is fully acknowledged. Reality does not exist independently of the goal of the observer and empirical data does not determine the outcome of a study. However, observations of real-life situations remain crucial to the development of adequate models. The trajectories of the two different threads studying errors, one leading to a taxonomy of errors, the other to a naturalistic view of errors, show the importance of this. It is something that Rasmussen defines later as a problem driven research.

Rasmussen's creation of the 'Ashbyan' trend in the normal accident debate, along with the 'Ellulian' and 'Kuhnian' ones, reveals the importance of cybernetics as an underlying intellectual matrix. This is found very explicitly in the use of self-organising properties of complex systems that allow the conceptualisation of the principle of 'defence in depth fallacy'. This concept considers accidents to be the result of the migration of self-organised local practices outside the boundaries of safe performance, a feature to be linked with the degree of freedom of individuals in relation to their teleological nature. This was prescient of the new field of the science of complexity that pervades numerous current safety science works. The key role of feedback and feedforward control loops have to play in safety management is another influence of cybernetics. This requires the design of an appropriate framework. The socio-technical model is a response to this problem, based on several levels of loops linking together different categories of actors and institutions. It defined what I describe as a 'strong program for a hard problem.' To explore the new vision, new tools were developed, and chiefly, the Accimap representation, which was meant to analyse the distributed nature of decision making and cognition, a property found in the background of many accident reports.

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