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USE OF NUCLEAR-REACTOR CONTROL ROOM SIMULATORS IN RESEARCH & DEVELOPMENT

Jacques Theureau

CNRS / Université Technologique de Compiègne, 60206 Compiègne, France

Abstract: Simulator studies are powerfull means to know, design and manage the complexity of nuclear-reactor control, if they are correctly designed for that purpose. This contribution to an international state of the art precises the trends and novelties in the use of the results, in the theories and methodologies and in the construction of the simulated situations, i.e. in the conditions for an efficient use of the techniques of simulator design.

Keywords: Complex systems, Design, Ergonomics, Modelling, Nuclear reactors, Power control, Simulators.

1. INTRODUCTION

The interest of the use of simulators in Research & Development concerning nuclear-reactor control rooms stems from the necessity we have today to design and manage their living, social and cultural complexity. For that purpose, we must know sufficiently the underlying dynamics of this complexity. The knowledge of the deviations it shows from what is prescribed by the management helps to set up the problem but not the solutions. What do we mean by “living, social and cultural complexity” in matters of nuclear-reactor control? We characterize this way the system made of the control room, including its diverse operators. In fact, if we consider the control room, the classical definition of complexity (many elements and many different kinds of relations between them) is not sufficient. We need at least the Santa-Fe Institute definition: “systems with many different parts which, by a rather mysterious process of self-organization, become more ordered and more informed than systems which operate in approximate thermodynamic equilibrium with their surroundings”. And it’s itself not enough to take in account the presence of human actors who have the peculiarity to be autonomous, i.e. to have at every moment a subjective view of the whole system, including themselves, i.e. of what we can call the “situation at hand”, and who interact at this moment with elements of this situation which have been shaped as relevant by their past interactions up to that moment. Such a living, social and cultural complex system can’t be breacked up into simpler sub-systems to be studied apart from each other and aggregated afterwards to get the complex system, or, anyway, these breacking up and aggregation are drastically unsufficent. The complexity gives rise to important phenomena which can be missing in the simpler sub-systems studied separately.

Hence the three steps of the best use of simulator studies from the point of view of the scientific knowledge and management of the underlying dynamics of living, social and cultural complexity of the control room: (1) systematic studies of natural situations, that is of the real complexity to manage; (2) systematic studies of full-scale simulated situations, with simulators and scenarios designed especially, and operators chosen especially to match the characteristics proved essential in natural situations; (3) systematic studies of part-task simulated situations designed in the same way, where, thanks to their greater flexibility and lower cost, design alternatives can be tested. Still from this point of view, to proceed another way, performing only one or two of these steps, or performing them in the reverse order, can give only an illusory or inoperative knowledge, or at least a poor one, on which can be based only a poor management.

During each of these three steps, we need also, in the present state of the cognitive science, to practise both inductive and deductive method. Inductive methods proceed from data to concepts by descriptive generalization. Deductive methods proceed from an a priori mathematically organized view of the tasks to be performed to the concrete concepts describing the empirical systems. If we stuck to the first one, we take risks of getting pure clinical analysis, that is poor generalization. If we stuck to the second, we take risks of misplacing concreteness, Alfred North Whitehead's expression, that is of taking the a priori for the real, of finding in the real what we have put a priori in it. Concerning such a living, social and cultural complexity, in the present state of cognitive science, inductive methods mean process tracking methods, and deductive methods mean dynamical systems modeling.

These considerations shape the interpretative frame of a contribution we made recently to an "international state of the art review on the use of simulators in hazardous industries for purposes other than training", asked by the Human Factors Group of the Reliability Studies Department of the Direction of Studies and Research of EDF, the french electrical power public company (Theureau, *et al.*, 1997). In using this contribution here, we will put the emphasis, not on the techniques of simulator design, but on the epistemological conditions for an efficient use of them.

2. USE OF THE RESULTS

The results of the studies in full-scale simulators or in sufficiently rich and relevant part-task simulators, like those of studies in natural situations, are by construction, multi-uses: design of control rooms and of their organizations, devices and procedures (human-machine interfaces, paper or computer driven procedures, operation manuals); Probabilistic Human Reliability Studies (PHRA). Nethertheless, a few of these uses are dominant and increasing: (1) An increasing number of simulators studies aim at preventing potential negative effects of automation; (2) There exist more Verification & Validation studies than studies integrated in the design process, in spite of the possibilities open by part task simulators; (3) More interest exists in the improvement of training and certification; (4) More emphasis is put on qualitative aspects of Human Reliability Analysis than on its quantative aspects; (5) Still a poor interest is expressed, at least in the litterature, in testing the design of procedures, yet drastically changed and computerized in different ways all around the world since Three Miles Island events.

As the essential purpose of studies on nuclear power plant control room simulators is often to provide data for Probabilistic Human Reliability Analysis (PHRA), we will consider more thoroughly this point. Many studies continue to implement the conventional methodology initiated by A. Swain, which bypass the operators'cognitive activity. Different research and development teams tend to query the relevance of this conventional methodology in various ways. At VTT-Espoo, a recent objective of the psychological research group is to integrate cognitive analysis of control activity into the new stochastic dynamic model called the "marked point process" (Arjas and Holmberg, 1995). It matches well with the idea by which one should analyze the construction of the action and not model it in some way as a predefined sequence. At Westinghouse-Pittsburg, the human factors research group works upline of PHRA by implementing a checklist of cognitive task requirements produced from simulator tests (Roth, *et al.*, 1994). At OECD-Halden, Erik Hollnagel integrates a similar concern to a structured approach for contribution to PHRA, called CREAM (Cognitive Reliability and Error Analysis Method). The principle of the approach is to combine two interpretation methods, the first of which is a logical progression of the customary behaviourism of PHRA, and the second a logical progression of cognitivism, (Theureau, *et al.*, 1997). It is a clear recognition of the kind of complexity which is involved in nuclear power control.

3. THEORIES AND METHODOLOGIES

Much work is being done practically everywhere on innovation and development of data-collation and analysis methods. This work can be characterized by: (1) a reduction in the ambitions of cognitive simulation and a return to process-tracking methods; (2) a trend towards eclectism, that is the coexistence of heterogeneous or even contradictory theories and methods (which can be both an hindrance to research and a recognition of the complexity of the problem and of the limits of each of the theories and methods available), and search for theoretical and methodological complementarities; (3) a tendency to go beyond traditional cognitive psychology by means of the still-confused notion of situation awareness coming from human factors research in aircraft piloting; (4) a tendency to consider cognitive aspects of co-operation within the control crew, with distributed computerized information, and to develop the corresponding methods and theories; (5) an important issue only tackled in VTT-Espoo is the evolution of operators' competence and confidence in the automated systems, which requires longitudinal studies. All these trends or novelties are different ways to deal with the complexity of nuclear power control. We will insist here on points (1) and (3) which provoque the more discussions.

Just a few years ago, cognitive simulation—computer modelling of control activity, based on a symbolic representation of the task and considerations derived from experimental psychology—was the lode star for simulator studies. It still is today, but instead of expanding, this perspective vanishes. For example, the series of studies by (Roth, *et al.*, 1994) was developed within a broader project undertaken by the Nuclear Regulatory Commission (NRC) to study the performance of the control crew during simulated emergencies and develop a cognitive simulation of the cognitive activities involved. In a past series of studies, two variants of an ISLOCA (leak from the high pressure reactor coolant system to the low pressure residual heat removal system) were studied on a full-scale simulator. But generalization of the results of this study encountered many limitations: (1) solely ISLOCA incidents; (2) control crews made up of training staff and not actual operators; (3) only one crew for each ISLOCA variant; (4) control crews made up of two persons, and not the usual three to five. The simulated situation was far removed from a real full-scale situation as far as the composition of the control crew was concerned. Also, the cognitive simulation developed dealt only with "certain" of the cognitive activities engendered. It was therefore decided to develop a new, more extensive series of empirical studies with richer simulated situations. It was planned to at the same time develop the cognitive simulation, but on the NRC's recommendation it was decided to first focus on the empirical study because of the difficulties, cost, and time entailed. To our mind, this postponement implicitly reflects the relative failure of cognitive simulation in its current form, with respect to both knowledge of activities in complex dynamic systems and to design and management. We feel that at the moment use of this tool is of interest only if: (1) it develops in connection with a systematic analysis of activities and not on the basis of symbolic representation of the task and general considerations derived from experimental psychology; (2) it is restricted to modest objectives in both theoretical and practical terms. This is the case, for example, in collective activities in an emergency rescue service or in air-traffic control, as presented in (Pavard, 1994).

This limitation on the ambitions of cognitive simulation raises the problem of seeking out new channels for modeling, taking inspiration from the mathematical theory of dynamic systems, for example, together with the problem of replacing the paradigm of"man as an information-processing system" by a new paradigm of cognition. In any case, at the moment it is leading to a renewal of what some authors call "process-tracking methods". These process-tracking methods are related to the methods of French-language occupational ergonomics analysis, and more specifically to those of course-of-action analysis and their collective interlinking (Theureau and Jeffroy, 1994). This is not entirely fortuitous since, like course-of-action methods, they go back to (Newell and Simon, 1972) who, at the dawning of cognitive psychology and Artificial Intelligence as we know it today, developed a new fashion—in psychology in any case—for validation of theories and models which stresses systematic description of verbal protocols collated at the same time as the activity was in progress and which gives a secondary status to conventional experimentation and statistical analysis. The essential instruments of this new fashion for validation of theories and models are the problem-solving graph and computer simulation, the ancestors of process-tracking methods and cognitive simulations. The decline in the ambitions of cognitive simulations results in process-tracking methods being reinstated to a position they had lost since (Newell and Simon, 1972), except in certain French-language research in ergonomics. Let us look at another example of development of process-tracking methods: the "realistic" approach developed in studies on the VTT-Espoo full-scale simulator. As is explained in (Hukki and Norros, 1994), the approach is contextual (including the social situation), dynamic (acts are not considered as isolated events) and subject-centred (the operators' point of view is considered to be essential). The researchers speak of situation activity or socially constructed activity, or quite simply of activity in the sense of Vygotsky. Their fundamental concepts are “activity”, “orientation”, and “how to do things”, associated with process-tracking methods .

The notion of situation awareness (SA) that came into being in aerospace studies is invading the nuclear field. It has become emblematic of the presence of man in highly automated technical systems. Still, situation awareness is unanimously considered to be a vague notion which has multiple definitions and gives rise to multiple complementary or alternative methods. A recent congress (Garland and Ensley, 1995) gives testimony to this. The definitions that follow are just two chosen from a multitude of others and felt to be exemplary of their radical theoretical heterogeneity: “the condition of the knowledge of the persons or the mental model of the situation around them”, or “perception of environmental elements in a volume of time and space, understanding of their meaning, and projection of their condition into the near future” (Ensley); “dynamic cognitive coupling of an agent and a situation” (Flach). According to Meister, situation awareness is thus “a concept for aggregation rather than for analysis”. According to Billings, it is “too clear, too holistic, and too attractive” a construct about which one might wonder if its utility compensates its complexity. For Charniss, situation awareness is a “default construct”, i.e. we appreciate it most when it is absent: “when someone loses his situation awareness, the result is a crash”. Some authors in the same congress stress the ‘family resemblance’ between the notion of situation awareness and that of work load, especially mental work load : same fuzziness, same practical necessity in the absence of better established notions, same measurement problem. In fact, the notion of situation awareness reflects both the incapacity of traditional cognitive psychology to answer the practical questions of control of complex dynamic systems, and the efforts to go beyond this traditional cognitive psychology, whereas no alternative has yet fully asserted itself. Its fuzziness is evidence of a scientific crisis that has not yet been resolved, but its very existence evidences the need to give the designers of complex dynamic systems if not criteria, then at least a principle concerning the relationships to be established between human operators and automatic systems: maintain the situation awareness of operators. This new principle results in a search for synthetic criteria to replace the usual analytical performance criteria. It is therefore worth examining what can be done to clarify this notion.

In (Sarter and Woods, 1991), a preliminary clarification of the notion is made by showing that it cannot be the equivalent of “effective conscious knowledge”, for “that would suggest that only the information in work memory could be considered to be ‘aware’”, and by considering that “any definition of situation awareness must refer to the information that is available or that can be activated, when it is relevant for evaluating a situation and dealing with it”. If one agrees with these authors, the notion of situation awareness can be assimilated to that of potential actuality proposed in the course-of-action theory (Theureau and Jeffroy, 1994) as part of an human cognition paradigm alternative to that of “man as an information-processing system” most authors dealing with situation awareness continue to refer to. The definition of potential actuality is close to Flach's definition of situation awareness mentioned previously. Flach considers that the theoretical precision of situation awareness requires a “ theory of the field of cognition” inspired by the mathematical theory of dynamic systems—although he wonders if such a theory is possible. It is precisely this theory that is the synthetic lode star of the course-of-action theory. The “potential actuality” at a given moment is considered to be co-produced by the situation and by the “agent's involvement in the situation” at that moment. This “agent's involvement in the situation” is the product not of the situation itself but of the entire course-of-action up until that point. The notion of “potential actuality” is thus built up in a way that is strictly the converse of the usual notion of situation awareness. Along this usual notion of situation awareness, what comes first is the “situation” independently of the person involved or “agent”, whereas along the notion of potential actuality, what comes first is the “involvement in the situation” inherited from the past course-of-action, independently of the instantaneous “situation”, with its characteristics of “ orientation ” or “ confusion ”.

This divergence between the current notion of situation awareness and that of potential actuality has important methodological consequences. If the situation does indeed come first, a method for documenting situation awareness which involves ‘freezing’ the simulator at certain times during the scenario and asking the operators to answer a questionnaire on the situation is legitimate. With the usual notion of situation awareness, it can be considered such a radical change to their "involvement in the situation" has little or no effect on the situation awareness they will express. If, on the other hand—as in the course-of-action theory—the "involvement in the situation" comes first, this sort of intrusion into the control activity is incapable of producing data reflecting the potential actuality. Potential actuality can only be reconstructed indirectly, through analysis of the control activity. For example, as part of the OECD-Halden international research and development programme, the SACRI (Situation Awareness Control Room Inventory) method was developed, which adapts to the nuclear power industry the SAGAT method (Situation Awareness Global Assessment Technique) developed in aeronautical studies. Both these methods are based on the principle of intrusion into the simulation that we have just criticized.

On the contrary, in (Roth, *et al.*, 1994), the question of situation awareness was re-examined following (Klein, 1995). While he does not specify the notion of "situation awareness", this author proposes to study it through the control activity, i.e. in the same way as one studies a "potential actuality". According to him, "Instead of studying the question of WHAT—what is the 'situation awareness' content of a person?—we can study the question of HOW—how does 'situation awareness' affect action? In this way, we can identify some important aspects of 'situation awareness'—those affecting judgement and decisions". Whence the stress on what these authors call 'process-tracking methods' which are very closely related to course-of-action analysis methods, as has already been said. Whence too a decision-support model said to be 'recognition-primed' which "models the way people make decisions in natural situations without having to compare options". The key to these decisions is " that people use their expertise to define situations and recognize typical courses of action that should be given consideration first " (ibidem). This decision-support model in fact implies a definition of "situation awareness" that brings it closer to what we call a "potential actuality". Klein's work is also among the essential theoretical and methodological references of the VTT-Espoo psychological research group referred to above.

4. CONSTRUCTION OF THE SIMULATIONS

Studies of human activity using simulators run into the problem of what it costs to conduct them, the problem of integrating them into the process of designing new systems, and the problem of relationships between the simulator and its scenarios and real situations. We observe: (1) More and more use of part task simulators, more and more rich and flexible and less and less expensive, due to the progress in computer techniques, in order to test alternative design options; (2) More use of usual training or certification simulated situations, with methodological cautions and limits and a consideration of training design issues; (3) More linkage of incidental/accidental simulator studies with retrospective incident/accident studies; (4) A growing (but still modest) interest for the study of natural, normally disturbed, situations, in order to insure a better relevance of the simulations and to know better the transfer made by the operators from the situations they usually live in to incidental/accidental situations; (5) A tendency to build simulation scenarios from theoretical hypotheses concerning control activity, and not only practical and empirical hypotheses. We will put emphasis on points (1) and (5) which exemplify the relation between scientific knowledge and design of complexity.

When people talk of simulators, they usually mean an ideal simulator, a "full-scale" one. The point of part-task simulators is to represent another ideal fulfilling another function. For example, at the NASA-AMES aerospace research centre, part-task simulation begins when pilots are not put in an exact replica of a real cockpit that reproduces the accelerations and movements of the actual aircraft. From this point of view, the HAMMLAB nuclear-reactor control room simulator of the international OECD-Halden programme is a part-task simulator. What is new is less the reality of part-task simulation (it might be said that traditional human-factors studies concern situations of this type) than the very notion of part-task simulation (as a simplification and reduction of full-scale simulation and not as a complication of psychological experimentation) and the fact that today's information-technology brings part-task simulation closer to full-scale simulation. Several considerations lead to studies being carried out on part-task simulators. The first two are the interconnected considerations of cost and integration into the design process: a part-task simulator costs less and is more quickly designed, transformed, or enhanced with new systems than a full-scale simulator. It therefore allows for easier comparison—from the point of view of control activity—of design alternatives for such new systems. The other considerations are of an ontological and epistemological nature, and imply two parallel trends.

The first trend arises explicitly or implicitly from a recognition of the living, social, and cultural complexity. For the supporters of such an ontology and epistemology, natural situations do not simply add complications to experimental situations. They add complexity and thus engender cognitive phenomena, some of which can be radically different. The resulting method for acquiring scientific knowledge of these cognitive phenomena starts from studies in natural or close-to-natural conditions (particularly when, as for certain emergency situations, it is absolutely necessary to use the simulator) in order to determine the cognitive phenomena involved. It works towards studies on part-task simulators intended to examine the cognitive phenomena more exhaustively and better validate them, but the pertinence and validity of these studies depend on the first studies. In the context of this recognition of the living, social, and cultural complexity, both full-scale and part-task simulators take on a scientific function instead of just a practical function or a role as ill-adapted substitutes for experimental situations in the laboratory. The researches of the Westinghouse-Pittsburg group, for example, are along these lines (Roth, *et al.* 1994).

The second trend arises out of an ontology (implicit) and epistemology (explicit) of “Lego” (internationally reputed children's building-block game) by which complexity is considered to be both capable of and having to be attained by putting together simple elements—or generic concepts of what is simple—produced by the laboratory situation studies. Part-task simulation is then thought out in relation to the ideal of laboratory experimentation. It is no longer thought out from the point of view of simulation. This is similar to traditional “human-factors” studies. The only difference between a part-task situation and a laboratory situation, from this point of view, is that because of the practical interests involved, researchers benefit from greater material resources than if they were to remain in their laboratory. A large number of studies on part-task simulators encountered in the literature result from this second trend. Their scientific interest is secundary relative to rigorous experimental procedures in the laboratory and field studies, full-scale simulator studies, or sufficiently rich part-task simulator studies developed from the simulator point of view. Nevertheless, their practical merits are not to be overlooked. They help demonstrate the interest of developing part-task simulators for integration of human factors into design processes. Their results can be re-interpreted in connection with an ontology and epistemology of complexity if one also has rigoutous studies in the natural situation or on full-scale simulator. At OECD-Halden, both points of view co-exist. In summing up 10 years of test and evaluation studies in (Folleso and Volden, 1993), it is considered that a high degree of realism was attained, to the detriment of systematic control of the experiments, and therefore suggested reducing realism in order to increase control, starting with the less realistic and more controlled studies in order to “demonstrate effects of vital aspects of the system”, and then using more realistic situations to more broadly test the validity of their hypotheses. On the contrary, in (Kvalem, *et al.*, 1996), it is suggested to put “less stress on well controlled experimentation and more on ‘simulated field studies’ to analyze complexity” as a long-term prospect for the use of the HAMMLAB simulator.

It is commonplace to design the simulation scenarios in order to test practical and empirical hypotheses, such as the hypothesis of performance improvements due to a given system, or various organizational arrangements for the control crew. What is new is the trend to build scenarios from theoretical notions in order to test theoretical hypotheses regarding control activity, and not only practical and empirical hypotheses. This trend is seen in certain full-scale simulator studies and in most of part-task simulator studies, both in those that tend to stick close to the epistemological paradigm of Lego and those that—more or less implicitly, it must be said—consider part-task work from the simulator point of view, in relation with the paradigm of living, social, and cultural complexity. The series of studies by (Roth, *et al.*, 1994), for example, dealt with two variants of ISLOCA (Interfacing System Loss of Coolant Accident) and two variants of LHS (Loss of Heat Sink) with eleven complete crews of real operators for each event. The model of cognitive activities linked to operator behaviour in the emergency situations involved comprises two components: situation assessment and response planning. Situation assessment is similar to situation awareness (see above). Response planning corresponds to the decision to take a course-of-action, bearing in mind a particular situation assessment. The two ISLOCA variants were especially designed to be difficult from the point of view of situation assessment. The objective was to create situations in which the control crews would have to identify and isolate the breach without explicit guidance. The emergency procedures did indeed include ISLOCA procedures, but it was possible to create situations where the control crews could not find the ISLOCA procedure through the network of emergency procedures. The specific dynamics of the event led the operators to a LOCA (Loss of Coolant Accident) procedure. As for the two LHS variants, they were designed to be demanding in terms of both situation assessment and response planning.

5. CONCLUSION

Such trends in the use of the results, in the theories and methodologies and in the construction of simulated situations, leave room to a more efficient use of the techniques of simulator design in matter of knowledge, design and management of the complexity of nuclear-reactor control.

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