Pre-validation of Nuclear Power Plant Control Room Design

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Abstract. Evaluation of the design of complex automation and control room systems is an essential phase in the design process in the nuclear field. For example, in order to meet the nuclear regulatory requirements, the new control room systems have to be evaluated in full-scope simulators to achieve a validation of the systems. We have developed a specific approach for the pre-validation of human-system interfaces and applied the method to evaluate the control room designs of a Finnish nuclear power plant. Some lessons learned from previous tests are provided. The paper will also discuss some open questions concerning the use of pre-validation test data. One of the most interesting questions is how pre-validation test data can be used in the final validation of a system, and how a set of pre-validation tests can support the validation by providing cumulative evidence of the functionality and usability of the system.

Keywords: Verification & Validation, Pre-validation, Control Room, Concept of Operations.

1 Background

Verification and validation (V&V) of complex automation and control room (CR) systems is an essential phase in the design process in many industries. For example, in the nuclear field, in order to meet the regulatory requirements, the new control room systems have to be evaluated in full-scope simulators to achieve a validation of the integrated system.

We have developed a specific approach for the integrated system validation (ISV) called Contextual Assessment of Systems Usability (CASU) [1]. ISV tests provide a final evaluation of the integrated system; before them, prototypes of the individual subsystems are evaluated through small-scale usability tests. Since complex systems are typically designed in a modular fashion, the designed systems are also evaluated in a stepwise manner. We have coined the term 'pre-validation test' to refer to these small-scale usability tests that precede the final testing. Even though there is a lot of literature on ISV testing, there is little research in the nuclear field on these pre-validation activities.

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In this paper, we first describe the development of the pre-validation test methodology; then we give examples of the application of our approach and of how evidence of the system usability of the CR human-system interfaces (HSIs) is gathered based on the results of these tests. Typically, this phase also includes verification of design documents against standards and guidelines and verification of the design against design documents, but in this paper our focus is on the description of the pre-validation activities.

2 Development of Pre-validation Methodology

2.1 Requirements for Testing

There are some critical requirements for pre-validation testing. A key requirement is that the tests really support the iterative design of a system. Therefore, they should be carried out cost-effectively and quickly enough so that the input is delivered to the design process without delay. But at the same time they should be such that they truly assess the validity of the system i.e. they somehow remain independent from the immediate design solutions and also evaluate what kind of impacts a fully developed system would inflict in the future work. In addition, the tests should also be comprehensive enough to cover all the subsystems and their functionalities.

Timing has to be carefully planned, and testing of the system should be scheduled at the right time, i.e. at the moment when the design work has not yet been completed, and there is still time to take into account the recommended changes and fix them. If simulator tests at an engineering and design (E&D) simulator are included in the assortment of pre-validation activities, the plant model implemented in the simulator must also have been developed to a sufficient stage.

2.2 Selection of Pre-validation Methods

Different methods and techniques can be used in the evaluation of systems usability. Some of the most typical techniques are usability test, expert evaluation, cognitive walkthrough, focus group and usability questionnaires. We have adapted and refined most of these techniques to the evaluation of systems usability of complex technical systems, and they form the basis of our method assortment. The primary aim of a usability test is to improve the usability of a technical system through practical tests with users [2]. The participants who use the system represent real users, and they do real tasks. The personnel who are accomplishing the test observe and record what the users do with the system, how they communicate and how they co-operate. The data is analyzed and possible problems are identified. Based on the analysis, recommendations are given on how to improve the system and fix the problems. Expert evaluation is a kind of usability inspection method in which experts evaluate a HSI with a reference to a specific set of criteria, identify and rank the usability flaws according to their severity. In cognitive walkthroughs possible end-users of the system go through a sequence of actions with the user interface that is tested and evaluate its functionality and usability. Focus groups are group discussions in which

participants tell their experiences and opinions about the usage of the system. Focus groups are quite often used in the early phases of the design work to probe possible users' attitudes and beliefs. A usability questionnaire is a list of items asking questions of the usability of a system.

2.3 Measuring Systems Usability

By applying the above-mentioned methods and techniques different aspects of human performance can be measured. It is assumed that if a system is usable humans can perform well with it. Typical factors of human performance evaluation are, e.g., personnel task performance, situation awareness, workload and teamwork. We have recently presented a slightly different classification of measures, based on the idea that different measures provide evidence of different perspectives of behavior. Performance measures are quantitative measures that give information of the outcome of human activity; practice measures give information of the core-task orientedness of activity; and user experiences give information of, e.g., the promisingness of the system for future work. Each of these classes of measures is needed when estimating the functionality and usability of a complex technical system.

3 Pre-validation Test Description

Five main phases can be identified in the pre-validation of CR HSIs, planning, modeling, data collection, analysis and assessment (Fig. 1). In the following, these five phases are described from the perspective of the consultant that is responsible of the evaluation of a new design.

3.1 Planning

In the planning phase the aim is to get familiar with the system that will be evaluated, formulate goals and constraints for the evaluation, and define the relevant methods and measures that will be used.

Training and Familiarization. Training of participants and personnel conducting the test is carried out before testing. Designers provide training on the new concept of operations, on new features of the HSI and on modifications of operational procedures. Technical feasibility of the simulator runs is also tested beforehand. It is important that demonstrations and simulations that are used in training are different from those that are used in actual simulator tests.

Defining Goals and Concerns. An important task in the planning phase is to determine the main focus of the pre-validation activities: 1) what systems are included in testing; and 2) from what perspective they are studied. For example, since operating procedures are typically tested together with the new HSIs, the target of a pre-validation test is not only a specific HSI element, but a set of operational activities that can emerge in a particular task.

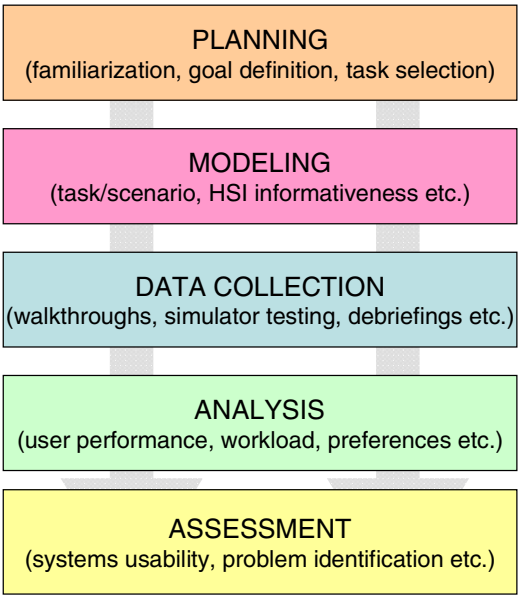

Fig. 1. Main activities of a pre-validation test

Task Selection. The main task in pre-validation testing is the functional testing of HSIs in a simulator environment. Tasks and scenarios should be selected from the point of view of the systems to be tested. They should cover all the features of the HSIs that are included in the test, and a representative set of situations should be selected. If possible, there should be small-scale tests of particular features of the HSIs, and large-scale tests of the whole system. Ideally, the task selection is carried out in collaboration with designers, process experts and usability experts. But quite often, in the pre-validation phase, the usability experts do not participate in the selection of tasks.

3.2 Modeling

Since simulator testing of the proposed systems is a central task in the pre-validation of CR HSIs, tasks and scenarios for the simulator tests are modeled. In the modeling, the aim is to develop a conceptual basis for the assessment, and understand, analyze and describe the task-specific requirements for operator activity. A test scenario or a task is hierarchically analyzed to specify the task structure. For example, in a hierarchical task analysis, the main goal of the task is divided into the sub-goals to achieve it, and they can be further divided into lower-level goals if needed. Operating procedures can be used in the development of the hierarchical task breakdown structure. After the breakdown of the tasks, it is defined what information is presented on different display screens and other HSIs at different phases of task execution.

3.3 Data Collection

Recruitment of Personnel. The validation team typically consists of two-three human factors specialists of the consultant who conduct the tests and gather the data. Designers will participate in the training of other participants; they will also answer questions and provide additional information during the pre-validation activities. In addition, at least one simulator expert is needed to run the simulator. Typically, two or three crews of CR operators are recruited for pre-validation testing. If possible, it is preferable if operators with different levels of operator experience are selected.

Equipment and Material. Simulator models are developed in the E&D simulator before pre-validation testing, and pilot tests are conducted to verify the functioning of the E&D simulator.

All the material for briefings, walkthroughs, simulator tests and debriefings is prepared based on the modeling work. Detailed scenario descriptions are prepared for each test, and detailed guides for researchers are prepared before pilot testing. The guides include, e.g., instructions for the placement of test personnel and video cameras in the simulator, actions that are carried out, measures that are used and questions that are asked.

Description of Test Activities. The following research activities to collect information are typically used in a pre-validation test. The activities are presented in the same order they are usually conducted.

Observation of training sessions. Previous validation activities have shown that during training important usability issues emerge. Therefore, observation of training activities is an essential part of the validation process. The representatives of the validation team participate in the operator training sessions and gather comments that can be further discussed in the interviews.

Expert evaluation. Usability experts systematically evaluate the design before simulator testing focusing on general usability issues such as the visual layout of a user interface, and navigation properties and functionality of control devices.

Structured interview before simulator testing. All the operators who will participate in the simulator tests are interviewed beforehand. A special emphasis in the interview is placed on the evaluation of their knowledge and understanding of the new HSIs and/or concept of operations.

HSI-oriented walkthroughs. In order to evaluate the usability of the new HSIs, walkthroughs are carried out by using screen/paper mock-ups. Operators are asked about their positive and negative experiences with the new displays, and suggestions for improvements are gathered. They evaluate the design from the CR operator's point of view, concentrating on issues such as the possible lack of critical process information, and problems in the functional division of the system into display pages. A special emphasis in the walkthroughs can be put on those displays that play a small role in the simulator tests.

Simulator testing. In order to evaluate the new HSIs and/or the concept of operations, simulator tests are carried out. Simulator testing includes small-scale simulation tests with CR operators, in which, first, individual functionalities are tested, and after that, representative realistic simulator test runs are carried out.

The detailed structure of the test varies from test to test, but the basic structure of each test is as follows. Instructions to the operators are given including a short description of the status of the power process and automation system at the beginning of the test. Since the aim is to test the operators' ability to understand the new design and make operations with the new HSIs, it is important that the instructors do not provide answers to those operational tasks that are tested, but the operators themselves have a possibility to try to find the solution to the questions and do the operations that are needed. During the implementation of the test, members of the validation team make observations, video-record the test and rate online the performance.

Process tracing interview. A process tracing interview is carried out immediately after the test: The performed test is enacted and discussed with operators, and a set of questions is asked on the usability of the new design. Overall, the aim is to clarify the perception of the state of the process on which the operator's actions are based. In the interview, operators are asked to describe, e.g., 1) the process events that occurred in the test run; 2) what operations were associated with particular events; 3) what the meaning of each event was from a holistic process point of view; and 4) what information or user interface element the detection of a particular event was based on. The questions are modified to suit each specific task.

Questionnaires. After the complete simulator runs, the operators also complete the workload questionnaire, and after all the simulator tests, they also complete a usability questionnaire providing information of the functionality and usability of the new systems. The questionnaire includes statements about the usability of the CR. The statements include items of the control room's 1) instrumental function (e.g., task effectiveness), 2) psychological function (e.g., efficiency and suitability for the user), and 3) communicative function (e.g., support for shared situation awareness and cooperation). The participant evaluates how well the statement holds true by checking one of the four options.

Debriefing interview. At the end of each test day, a debriefing interview is arranged with operators, designers and usability experts. A special emphasis in the interview is placed on the evaluation of the role of the new operating system in the operator's work.

3.4 Data Analysis

In the analysis phase the data is processed in several successive phases. Pre-validation test data is analyzed mainly through qualitative analysis methods, but also quantitative analyses are carried out. Specifically, in the quantitative analysis of video data, behavioral research software is used. The video analysis is focussed on communications of the operators, directions of gazes, and operations and movements.

3.5 Assessment

The pre-validation activities provide both evidence of the validity of the concept of operations, the usability and functionality of a particular set of user interface elements and the adequacy of the training activities. In the following, these three areas are discussed separately.

Evaluation of Operational Concept. Both observational data and data gathered through interviews provide information of the effects of HSI changes on operator practices. Aspects of operator performance that are registered are 1) task completion (whether the operator could perform the action/task), 2) errors in performance (fault actions), 3) fluency of performance (amount and type of repetitions, interruptions and hesitations), and 4) communication and collaboration (number and content of speech acts).

By interviewing operators, we gather information of 1) operators' understanding of the concept of operations (e.g., their understanding of the function and meaning of the new systems), 2) operators' understanding of the differences between the new and old solutions, and 3) operators' situation awareness (concerning the status of the power process/automation system). Interviews also provide information of subjective experiences and preferences, e.g., subjective estimates of performance, situation awareness, and mental workload. They also provide information of the adequacy and promisingness of the new concept of operations, and recommendations and suggestions for improvements.

Based on the above-mentioned qualitative and quantitative evidence, an early assessment of the effects of the new HSIs on operator work practices is derived.

Evaluation of the Usability of HSI Components. Observations, interviews and walkthroughs provide evidence of the functionality and usability of the HSI components included in the scope of the pre-validation. HSI-oriented walkthroughs provide information of the main dimensions of usability, e.g., visual clarity, visibility, consistency, familiarity, flexibility and error prevention.

By observing operator performance we gather information, e.g., of task completion accuracy, fault actions and fluency of performance providing indirect evidence of the usability of the new design. Interviews, in turn, provide evidence of 1) operators' understanding of the use of information presentation formats (e.g., meaning of symbols and colour codes, logic of element groupings and display hierarchy), 2) user satisfaction with the new information presentation formats (e.g., use of symbols and colour coding, relevance and adequacy of element groupings and display hierarchy and navigation) in comparison to the old design, and 3) suggestions for improvements. Also the usability questionnaire that is completed at the end of the pre-validation session provides information of the functionality and usability of the new HSIs.

Based on the above-mentioned evidence, a preliminary assessment of the usability of the new design can be derived, and a list of possible problems and challenges can be prepared with suggestions for their solution.

Evaluation of Operator Training. Since operator interviews also give information of the relevance, adequacy and desired volume of training, some suggestions for the operator training can be given and a preliminary training concept can be outlined.

4 Example of the Application of the Method

A pre-validation test of a large screen display (LSD) pilot of a Finnish NPP was carried out at the E&D simulator in which the aim was to gather preliminary information of the usability of the prototype and gather experiences from participating operators [3].

Three members of the VTT research team carried out an expert evaluation of the displays before the functional tests. Since the expert evaluation was based on screenshots and paper images of the displays, the evaluation concentrated on basic design features of the displays. More complicated issues such as how these displays are integrated with the other displays in the CR and how they are controlled and managed were not considered.

Three crews of operators (pairs of operators) participated in the simulator test. For all the crews, the same set of six scenarios was provided. Detailed instructions for briefing the participants were developed. Before the usability test, a one-day training session was arranged, in which the aim was to familiarise the operators participating in the test with the key principles of the design concept and with the pilot, and to gather some first comments on the design solutions. During the first half of the training session designers gave presentations introducing the background and central ideas of the new display concept.

During the simulator runs the crews operated the plant as they were instructed and as they would have done in any other simulated or real situation. The whole scenario was recorded on four video tapes. Two of the video recordings provided an overview, and two of them were recordings produced with the head-mounted cameras. The evaluation team also took notes during the scenario in order to provide topics for discussion in later interviews.

In debriefing the main phases of the simulation were discussed through together with the operators. The aim of the interview was to find out what events the users considered most important in the simulated scenario, and what kind of information they used in order to manage the event. After all simulation runs, the operators were interviewed on their experiences about the displays that they have used in the test.

Some dimensions of operator performance (e.g., duration of time to event detection for each scenario, source of the first deviation detected and percentage gazing time to different information sources and number) were measured providing quantitative information of the use of LSDs. All the results of the pre-validation test activities were presented in a final report some weeks after the test sessions.

5 Conclusions

We have applied the pre-validation approach to several validation tasks in Finnish NPPs. Some of the lessons learned from these cases are the following:

- Pre-validation tests serve further development of the designed system. They provide information of whether the design work is proceeding according to agreed plans. Therefore, it has to be considered whether optimal design phase is selected for testing. The designed system must be complete and detailed enough in order for the testing to be feasible. In addition, the smooth functioning of the simulator model is important. It is hopeful that a large part of the target system has been simulated.
- Typically, in the pre-validation phase, systems are tested in a modular fashion, individual tests focus on a specific set of CR HSIs, and the HSIs are not tested as a part of the whole CR system. Since there is no certainty of the usability of the integrated system, we must be cautious in making inferences from pre-validation tests about the new concept of operations.
- The question of reference is a key issue in the evaluation of technical systems, since it is difficult to present arguments about the usability and functionality of the design, if there is nothing on which to base one's judgments. In the evaluation of individual features of HSIs the evaluation is based on the usability experts' judgment. In addition to that, standards and guidelines can be used. In the evaluation of concept of operations, the expertise of simulator trainers and experienced operators are needed, which may be difficult to obtain.
- Usability experts' independence from the design team is important also in the pre-validation phase, and its importance increases as the design process progresses. It is preferable that the usability experts are responsible for all the main activities of testing. In our cases, however, the representatives of the design team have been mainly responsible for the planning phase. Even though this does not compromise the reliability of the pre-validation, it is preferable if the usability experts could participate in the selection and modeling of tasks and scenarios.
- It seems to be that modeling and assessment are the most important and challenging phases in pre-validation. If there are not detailed enough models of the tasks, it is not possible to attend to key activities during simulation runs and ask relevant questions during process tracing interviews. In the assessment phase, a real challenge is to assess the safety implications of the design, or its impact on the concept of operations.
- In the assessment phase, our aim is not only to count usability problems and categorize them according to their scope and severity, but to evaluate how well the new system fulfils the functional criteria of systems usability (instrumental, psychological, communicative) [1]. In analyzing the instrumental function it is investigated to what degree the new systems support operational demands. In analyzing the psychological function it is evaluated how well the operators' coordination with the tools and procedures, and orienting to the core task demands, have succeeded. In the communicative function the focus is to judge whether the overall significance of singular events were comprehended and shared within the crew.
- A request that is included in our wish list is that a representative set of test scenarios are selected, and they cover all the tasks to which the new HSIs will be used. It is also desirable that a sufficient number of complete crews of operators with different levels of expertise are recruited, and the selected operators are a representative sample of the operating crews of the plant.

– Validation of NPP CR systems is typically considered as one distinct and integrated activity at the final stage of the design and Human Factors Engineering (HFE) process [4]. On the other hand, pre-validation activities are distributed along the design process, and they are tightly connected to many other activities (e.g., training, procedure design) of the HFE process. Therefore, we propose that a new kind of approach to V&V is needed, in which the evaluation is seen as a longitudinal and distributed activity in an integrated design process. The series of pre-validation tests conducted can thus support the more integrated validation of the CR HSIs by providing cumulative evidence of their systems usability.

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