

Symptom Identification, Modeling, and Context Observation Data Mining System for Analysis of Cognitive and Decision-Making Errors in a Full-Scale Simulator

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Abstract: The purpose of this paper is to describe the scope, approach, methods, models and algorithms for the development and implementation of a data mining technique using the symptom identification, modeling and context observation (SIMCO) system. It is designed to analyze cognitive and decision-making errors during the regular training sessions of the main control room crews on the full-scale simulator for a pressurized water reactor, type VVER-1000. The pilot implementation of the SIMCO system at the Kozloduy nuclear power plant, through experimental testing, validation and verification of the methodology, will also enable the automated data mining of offline and online assessment of the symptom-based emergency operating procedures and crews' practical skills. To prevent or minimize the impact of the introduction of SIMCO on the goals and efficiency of regular training, the extraction of data will be automated to the maximum extent using the existing capabilities of the full-scale simulator for registering operational information from the conducted exercises and archiving this data. In the absence of critical information that does not allow for the correct determination of the context probability or contexture of the human failure event, they can be supplemented with standard and other tools of studying human behavior. The scope of the methodology is not limited to the activities of collecting data for human reliability assessment, processing and analyzing these data to assess the human error probability in a mode and format for their integration in the probabilistic safety analysis of units 5 and 6 of the Kozloduy NPP. This can also complement the quality assessment of human factors engineering and the efficiency of the human-machine interface under normal and abnormal operating conditions, as well as operators' knowledge and abilities, making the personnel testing and licensing process at the Bulgarian nuclear regulatory agency more systematic and objective.

1. INTRODUCTION

The taxonomy of human failure events (HFEs) in PSA is based on the way in which the preliminary, indirect and direct cognitive or decision-making errors affect the safety and efficiency of the nuclear power plant (NPP). NPP interactions are complex and difficult to track, identify and assess, and those related to the control and management of human factors (HFs) can be clarified only after retrospective tracking of the events that occurred. Such complex technologies, facilities and activities, carrying hazards, risks and uncertainty for people and the environment, are described and analyzed as socio-technical systems (STSs). Human actions (HAs) in STS are most often judged expertly through performance shaping factors (PSFs). Such subjective guessing introduces additional uncertainty into the extraction, interpretation, and assessment of data, which requires the extensive use of data from operational experience or their acquisition, mostly experimentally, with the help of simulators [1].

Standard practices for identifying, classifying, and obtaining data on the several modes of operators' HFEs are conducted through conventional "measurements" of human behavior - a checklist, debriefing of the exercise, filling out a questionnaire, describing observations, interviews, etc. However, classifying the cognitive error probability (CEP) is more difficult using these traditional methods, as operators' cognitive processes during a scenario are typically routine and unconscious. Furthermore, operators often forget the context of the situation or fail to identify the stages of the scenario's development when HFEs occur. Therefore, collecting and evaluating data on the HA of the main control room (MCR) obtained during training on the full-scale simulator (FSS), is the key to understanding human reliability and performance in the relevant context [2]. The STS context could be determined

and evaluated by the Performance Evaluation of Teamwork (PET) method on the basis of the observed states of the STS, which are described and determined, qualitatively and quantitatively, by the symptoms of the object (unit/station), recognized through images by the subject (operator/crew), in the specific situation of the technological task and work organization. This can be achieved by using an automated system for fixing, registering, and identifying critical symptoms with standard technological control (audio, video) and non-standard (supplementary) devices. On their basis, the context of the played normal, unusual and accident scenarios should be tracked deterministically, modeled probabilistically, and assessed qualitatively and quantitatively. The contexture or context probability (CP) serves to "measure" workload the processes of perception, cognition, decision-making, and execution. For a consistent and effective assessment of human error (HE), it is necessary to develop an automated SIMCO system, technique and methodology. The use of the SIMCO system should be accompanied by explaining, predicting, and evaluating the influence of the STS context on the HA functions and processes of cognition, communication, judgment, and execution of the MCR operator crews during their regular training on the FSS of VVER-1000 at the Kozloduy NPP (FSS-1000).

2. SIMULATOR DATA EXTRACTION

2.1. A Holistic, Dynamic, Symptom-Based and Human-Centered Approach for SIMCO System

The most common human-centered conceptual approach to safety management in risky technologies is based on monitoring, "measurement" (expert judgment) and management of independent PSFs to reduce the HEP. However, this approach does not allow for a direct, explicit, dynamic and holistic study of interactions in the STS through a qualitative and quantitative assessment of the context [2]. Therefore, alongside this expert-based approach, another symptom-based approach to improving human performance is widely used in the management and control of the nuclear power [3]. It tracks the behavior of the entire STS as a changing number of symptoms that are present, recognized, reported and resolved, and which are characteristic and significant for it. When relevant information is available, symptoms can be grouped and weighted according to their significance. The symptom-based approach is recommended for both nuclear accident and incident management and routine situations at NPPs. It is also used in the SIMCO system, as it appears more promising for data extraction using simulators, and as an HRA method in PSA [4].

2.2. Data Collection from Simulators and Operational Experience

In contrast to the accumulated operational experience and the available formal rules for identifying mode A (pre-accident) and B (initiating) HFEs, the possibilities for identifying mode C (post-accident) HFEs from practical experience are very limited. The reason for this is that the scenarios associated with this mode of HFEs rarely occur and there is not enough data. In addition, mode C, like other modes, is specific to each NPP due to differences in the facilities – specific structures, systems and components (SSC) for a given reactor type – and in the activities – specific requirements of the regulatory body, the operating organization and the national mentality. For this reason, monitoring the training on the FSS-1000 is the most appropriate way to identify and accumulate a representative sample of mode C HFEs. Thus, the quality of PSA models can be improved considering facilities and activities at Kozloduy NPP.

The results of the analysis of the simulator training recordings, together with feedback from the debriefing and interviews with the trained crews, can show potential shortcomings in both the training programs for the MCR operators and in the content, format and implementation of the symptom-based emergency operating procedure (SB EOP). Such an analysis can also help to more specifically select the FSS-1000 training scenarios, improve the diagnosis of specific events and situations, and provide a quantitative assessment of the efficiency of the training to deal not only with rare emergency scenarios, but also with normal routine operations. The detailed study, recording and analysis of the symptoms in the SB EOPs can provide useful information for identifying EOO (errors of omission) and EOC (errors of commission). The latter are the biggest challenge for the HRA, given the need to include them in the PSA models of the Kozloduy NPP.

2.3. HRA Methods Used at the Kozloduy NPP

The following HRA methods are used in the level 1 and 2 PSA models at Kozloduy NPP to estimate the HEP of three modes of HFE and decision errors (DE) [5]:

- A. ASEP (Accident Sequence Evaluation Program),
- B. THERP (Technique for Human Error Rate Prediction),
- C. CBDT (Cause-Based Decision Tree) method and THERP via EPRI HRA Calculator®, as well as the HCR/ORE (Human Cognitive Reliability/Operator Reliability Experiments) correlation.

The assessment of HEP for HE or DE of mode C, with these methods, is carried out through a subjective qualitative description of the PSF at the discretion of the modeling expert, who compares and assigns values for them from the tabulated factors of the relevant HRA method. Such an approach does not allow for an objective “measurement” through qualitative and quantitative identification, description and assessment of the HEP for EOO/EOC based on the context/symptoms of the simulated scenarios. Therefore, it is necessary that the qualitative criteria for the different modes of HEP, described and applied in the CBDT and HCR/ORE methods for their classification, be expanded and upgraded with additional criteria (qualitative and quantitative) from other methods. Alternative techniques such as HEART (Human Error Assessment & Reduction Technique), NARA (Nuclear Action Reliability Assessment), HDT (Holistic Decision Tree) and PET have been presented and discussed at Kozloduy NPP as applicable for collecting data on HFE [1], [2], [4] and [6].

3. SIMCO METHODOLOGY

3.1. Purposes

The general purpose of SIMCO is to collect, systematize and archive (automated, offline or online) various data related to the work of operators. The specific purpose of developing the SIMCO is to be used to improve the awareness and efficiency of operators in performing their tasks at the MCR of VVER-1000 within the existing FSS-1000 interface.

The development of the SIMCO technique requires obtaining a lot of different data to reliably, dynamically and statistically assess the performance of the operator crews. These data are related to the human response to various symptoms (stimuli for operator action), describing the behavior of the STS (object and subject in each situation). This can be achieved by using an automated system for fixing, registering and identifying critical symptoms with standard and non-standard (supplementary) devices. On this basis, the scenario's context must be deterministically monitored, probabilistically modeled, and qualitatively and quantitatively assessed. The contexture (CP as a STS context) is presented and evaluated based on the observed states of the STS [7] and [8]. The estimated CP serves to "measure" the processes of perception, workload, cognition, decision-making and execution.

3.2. Models and HEP Integration and Application in HRA of PSA

Figure 1 shows the SIMCO system models for obtaining HEP for use in HRA PSA. How HEP is integrated and applied in HRA PSA is shown in Figure 2.

3.3. Brief Description of SIMCO Methodology

The methodology for collecting, processing and obtaining data from FSS-1000 for the purposes of the HRA and integrating them into the PSA encompasses a process with 9 sequential, interdependent and iterative stages, which are illustrated in the diagram in Figure 3. The process is guided by the data needs of the PSA by compiling archives with databases (DBs) for the different modes of HE (*Stage 1*). When specific and new data are required in the PSA that is not included in the archives, then in *Stage 2* it is established whether these data can be obtained from a simulator.

The collection of primary data from the simulator with standard devices and tools is done by selecting the analog and discrete parameters from the FSS-1000, which must be fixed for automatic registration,

recorded and archived (*Stage 3*). In *Stage 4*, these data are processed and prepared according to criteria for correspondence between the parameters used in the SB EOP and the symptoms used in the HRA methods, to obtain secondary data. These data must be suitable for qualitative and quantitative modeling, assessment and analysis of the different modes of HE encountered on the FSS-1000. Data generation in the initial version of the SIMCO system is mainly based on the capabilities for automated data collection with the standard tools of the FSS-1000 (*Stages 3 and 4*). Secondary data are prepared for their application in the HRA methods by identifying, classifying and counting the symptoms (*Stage 5*). For each mode of HE, appropriate HRA methods can be proposed by combining their capabilities and criteria for classification and assessment in *Stage 6*. The combination of different HRA methods allows the processing of data with HRA methods to obtain useful and complementary dynamic and qualitative characteristics in *Stage 7*.

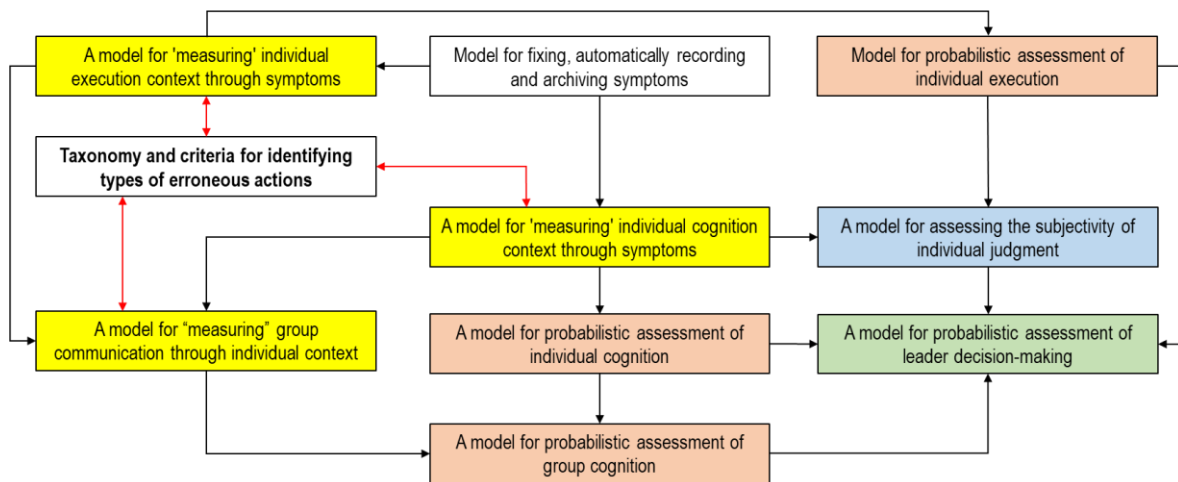


Figure 1: SIMCO system models for obtaining the HEP for application in HRA of PSA

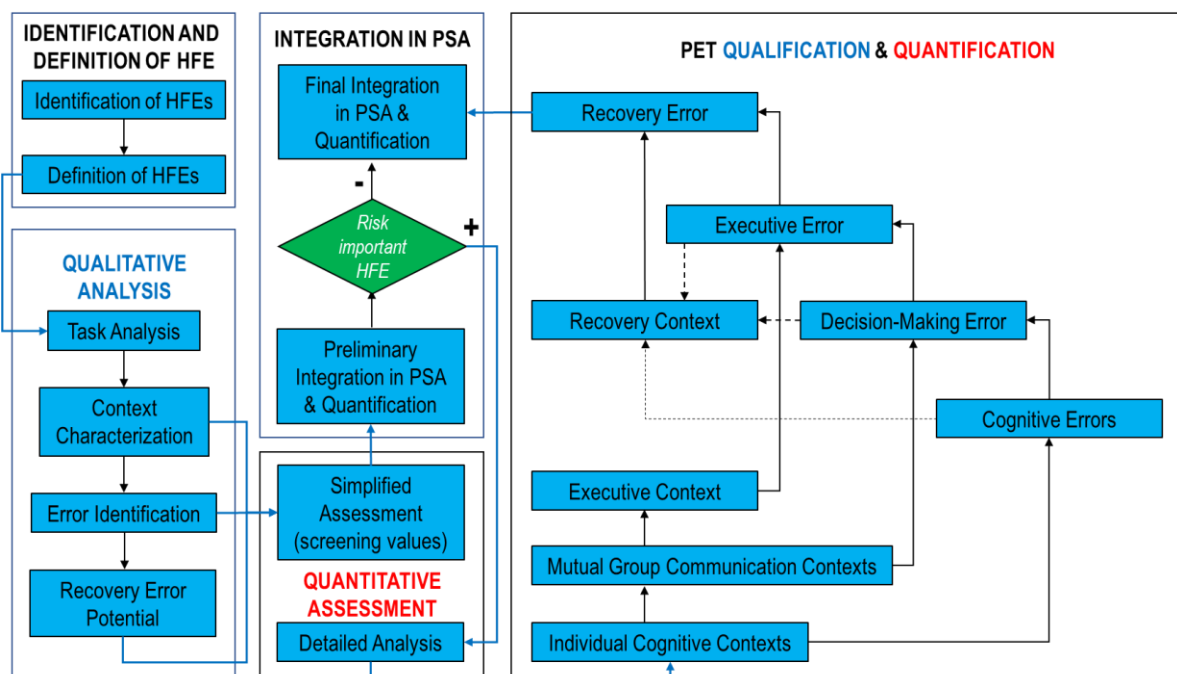


Figure 2: Defining HFE, identifying HE, HRA and integrating into PSA.

In this methodology, quantitative dynamic assessments of CP and HEP are obtained based on the symptoms of each scenario using the PET method. These assessments complement and quantitatively

verify the qualitative criteria for the mode of HE obtained by other methods of HRA used at Kozloduy NPP. This sequence of stages allows the data to be supplemented and upgraded by:

- 1) real data from the units,
- 2) calculations and analyses with other HRA methods, and
- 3) application of additional devices and tools, expanding the possibilities for collecting data on human reliability during the regular training of FSS-1000.

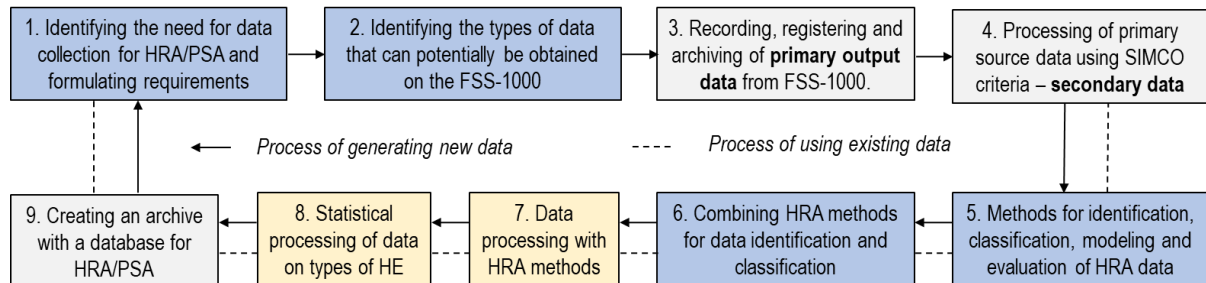


Figure 3: Overview of the stages of implementation of the methodology.

Statistical processing and evaluation of samples of collected data on the modes of HE can serve as the basis for the creation of an HRA/PSA DB at Kozloduy NPP (*Stage 8*). If such DB is created (*Stage 9*), it can be further improved and developed. The results of applying this approach would provide additional analysis for improving the regular training program for operators.

3.4. Algorithm and Criteria for Transforming the Input Data

This subsection describes conceptually and in the form of a data extraction algorithm the SIMCO system, which will be implemented in the FSS-1000 facility at the Kozloduy NPP training center. The SIMCO system upgrade could also include audio recording and video surveillance, which are already feasible, as well as voice recognition, eye tracking, and HE diagnosis using trained artificial intelligence (AI). Obtaining primary output data from FSS-1000 (*Stage 3*) and transforming it into secondary data (*Stage 4*) is carried out in accordance with the following algorithm and criteria (filters):

1. Based on the review and analysis of all SB EOP used during the regular training sessions, as well as the next scenarios and other procedures, the analog and discrete parameters are selected, which should be recorded in FSS-1000. These analog and discrete parameters are included in the *List of Symptoms for Registration* using **Criterion A**: *the presence of a given parameter/event in at least one of these documents (SB EOP and others)*. They are used to record the change in the state of the equipment, which is displayed on the MCR and registered by the FSS-1000 regular devices.
2. After each scenario played, **file a** (*.csv format) with the recorded parameters is archived and transmitted for further processing. This completes *Stage 3*: collection of primary output data.
3. The **file a** with primary output data is based on the complete *List of Symptoms for Registration*. It contains parameters that have changed or have not changed during the scenario. Therefore, through the following **Criterion B**, only the changed parameters that are significant, for the played scenario, are extracted. **Criterion B**: *the presence of a limit value or condition in the SB EOP, the played scenario or the technical specification (TS), which the given parameter has passed*. These limit values and conditions are also described in the *List of Registration Symptoms*. Based on this criterion, a **file b** is formed, containing the chronologically changed parameters over time. This **file b**, with the changed parameters during the scenario, serves as the source for determining the symptoms that appear during the scenario. **Criterion C** distinguishes and qualifies the symptoms in the scenario as a symptom or a violation of symptom in each group. *A symptom is a measurable cue in nuclear engineering, accessible to operator control, and can be considered as a combination of process parameters and signals that change the state of the nuclear power unit and require active actions (automation or*

personnel) [3]. There are 7 groups of symptoms: parameters (P), events (E), functions (F), transitions (T), goals (G), actions (A), resources (R); and violations of any group's symptom (V). The symptom contains a set of changed parameters (one or more), which are technologically and logically connected, and change the state of the STS. The filter allows for a chronological description in a table of all technological and logical conditions with an indication for change, in SB EOP and others, which are subject to monitoring and identification. The resulting **file c** represents a chronological description of the scenario in qualified symptoms, which is suitable for qualitative and quantitative assessment of the played scenario with the PET HRA method.

4. With the preparation of **file c** (chronological description of the scenario in the qualified symptoms), *Stage 4* ends. "Processing of the output data using SIMCO criteria" and secondary output data have been obtained, which are ready for use in *Stage 5* (Figure 3). This stage includes qualitative analysis, modeling and assessment of the CP of individual and group processes of cognition, execution, communication and decision-making using the PET method. The procedures, algorithms and software for these assessments are described in [7].
5. Identification and classification of the HE modes, based on the qualitative descriptions and criteria of the THERP, CBDT, HCR/PET, HEART/NARA, HDT methods, as well as through PET quantitative criteria: assessment of the CP of individual and group processes, as well as the availability of sub-processes and interval criteria for HEs are described below.

3.5. Qualitative and Quantitative Analysis with the PET method in SIMCO

The sequence and dependencies for qualitative and quantitative analysis of CP and HEP with the PET method in SIMCO is shown as a block diagram on Figures 2÷4 in [7]. Coordination between crew members is a dependent, interactive and iterative process. It can simultaneously affect different sub-processes of individual cognition, execution and communication in perceiving and interpreting symptoms in the parallel and recursive thought processes of the crew. It is assumed that these sub-processes are sequential in time and recursive for the context of each operator in the crew, but it always ends with a single decision-making and individual execution of operations for certain actions by each operator. Thus, the performance of each task and HA in STS is traceable through the symptoms that can be obtained from the files with registered points (analog parameters and discrete signals) in the FSS-1000 archive. To more accurately determine the time of onset, recognition, and reporting of a particular symptom, additional devices for tracking pupil position and voice recognition, as well as methods of audio recording, video surveillance, and communication analysis, can be used.

The current system for registering parameters of FSS-1000 has sufficiently large capabilities, which are used partially and episodically. In the presence of models, algorithms and software for automated processing, analysis and accumulation of statistics, this registration and archiving system can be successfully used both for creating a DB for the HE and for evaluating the training of crews. The initial version of SIMCO is based on archived files from regular training, but, if necessary, it can be upgraded with additional devices and methods for analysis. SIMCO will track the performance of the tasks in the training scenario based on the performance criteria in the SB EOP, predefined models and procedures for analysis and assessment of the context, and for identification and classification of the modes of HE. The initial accumulation, verification and validation of the data will allow for further automated evaluation and statistical processing to create a specific HE DB at Kozloduy NPP. SIMCO also plays the role of an automated tool for the HRA by reducing the burden on the analysts' tasks by improving the models, algorithms and procedures for data collection.

4. SIMCO PROCESS IMPLEMENTATION

4.1. FSS-1000 Process of Diagnosis, Measurement and Evaluation of the Crews Performance

The sequence and dependencies in the process of diagnosis, measurement, and evaluation of the performance of operators' actions were developed based on the models of "measurement" of individual and group processes of operators, which were shown on Figures 3 and 4 in [7]. The general process of

diagnosis, measurement, and evaluation of the performance of crews, as well as the classification of modes of HE is shown in Figure 4. The process includes three phases. **Phase 1** includes *Stages 3, 4* and *9* of the methodology shown in Figure 3 and refers to its practical part - the collection of initial data of FSS-1000 at Kozloduy NPP. **Phase 2** and **Phase 3** are theoretical in nature and are based on the described methods, models, procedures and tasks.

Phase 1 is related to the organization of the various sources of data for measuring efficiency, collected by each measuring device, after which they must be integrated into a common database. The data from the tools and devices are arranged in chronological order. The primary data for building the SIMCO system is the discrete and analog data, selected and fixed based on SB EOP, recorded through the FSS-1000 archiving system.

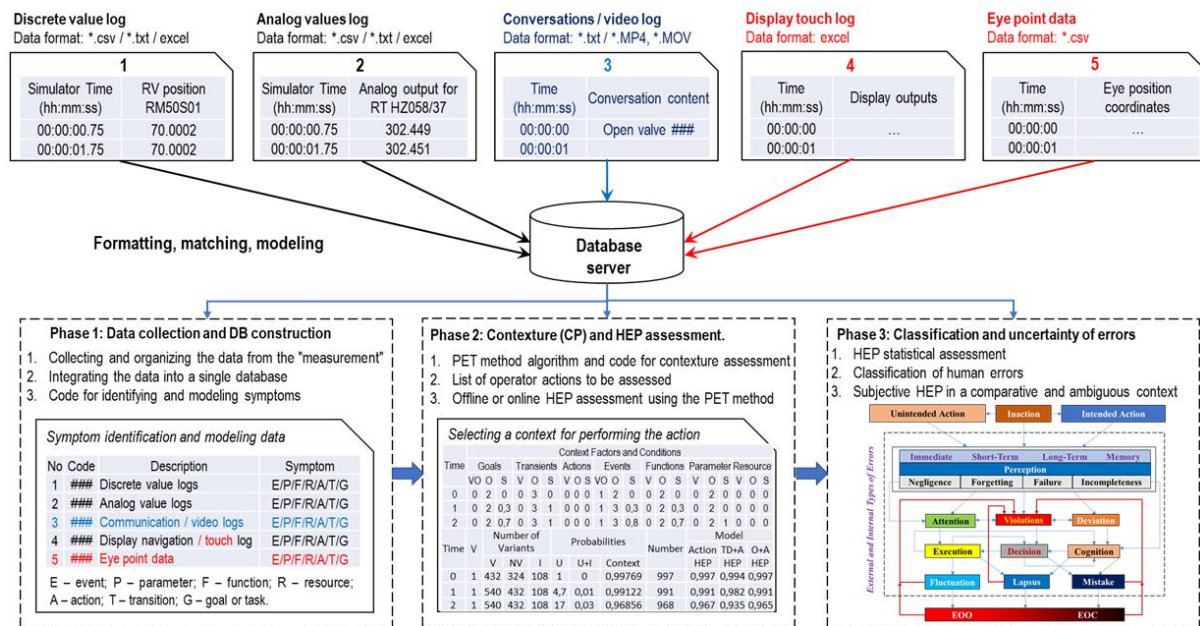


Figure 4: A comprehensive process of PET diagnosis, measurement, evaluation and classification of the efficiency of the MCR operator crews of the Kozloduy NPP.

Phase 1: Data collection and specific database construction

If necessary, data from video surveillance, interviews and surveys can be collected and used for clarification and confirmation. Typically, they are transformed into text so that symptoms can be identified as keywords during their assessment.

Data on eye position and/or touch on the display could also be included in the future, after an additional hardware upgrade of the FSS-1000.

In this way, the records from the measurement of cognitive processes can be unified, clarified and applied in a common algorithm for the holistic (non-selective) assessment of CP and HEP, conducted in Phase 2, and archived for possible study of the selectivity of the cognitive sub-processes.

Phase 2: CP and HEP assessment

Phase 2 applies the algorithms of the PET method to assess the crew's performance for each sub-process at the different level of the processes of cognition/execution/communication/decision-making by the operators and the crew. As a start, this phase uses the results (offline) of the identification and modeling of the symptoms from Phase 1. After experimental testing, validation and verification of the methodology, opportunities can be sought for a transition to automation and online assessment. The algorithms for assessing the crew's performance are developed and created based on the chronology of the detection and recognition of the symptoms that are identified during the development of a given training scenario, assuming the approximate speed of the thought processes. The tasks of the operators

are categorized based on the following sub-processes of cognition and decision-making, for which the context has a holistic influence:

- 1) **Activation (Act)** by primary symptom (signal or alarm);
- 2) **Observation (O)** of units and comparison of symptoms with those described in the SB EOP:
 - a) Monitoring of parameters and position/state of unit's SSC,
 - b) Detection and observation of alarms, signals and trends;
- 3) **Identification (Id)** of symptoms;
- 4) **Interpretation (In)** of symptoms;
- 5) **Goal Evaluation (GE)**;
- 6) **Task Definition (TD)**;
- 7) **Procedure Formulation (PF)**;
- 8) **Execution (Ex)** of the procedure:
 - a) Operations for switching on and off,
 - b) Management of processes by controllers (incl. interlocks and automation).

Administrative tasks, orders and reports for taking on duty, handover of shift, rounds, inspections and others are not covered in this assessment. Algorithms for evaluating individual and group performances are developed by studying the occurrence of symptoms and their recognition by operators and examining the communication and participation of operators during each sub-process of cognition through communication and group decision-making and execution of the task.

Phase 3: Classification and uncertainty of human errors

Context describes all external and internal aspects of the STS (unit and crew in each situation as a whole). Context enables the operator to ensure the crew fully and correctly performs their operational functions, and allows for the distinction and classification of error modes:

- A. errors of omission (EOO), which are associated with gaps in procedural execution, perception, attention, and procedural rules (caused by inconsistencies in memory),
- B. errors of commission (EOC) due to impaired, incomplete, or biased knowledge and decision.

Therefore, the detection and classification of errors such as EOO and EOC is important to be based on the taxonomy of the HE. It is assumed that operators would not make EOC if they had correctly identified and understood the context of the entire STS. This context is identified, observed, perceived, interpreted, and recognized as a set of past, present, and future states of the STS. In EOC, the operator does not miss an action for which she/he has a skill or an appropriate rule, but makes a wrong judgment and takes an unnecessary action in the given situation due to an incomprehensible, misunderstood or ambiguous context as a result of misconceptions and prejudices [6] and [7].

4.2. SIMCO development tasks

The tasks and tools for detecting and classifying symptoms for the processes of cognition, execution, and decision-making in the SIMCO system are described in Figure 4. It provides practical information about the standard tools of the FSS-1000 for registering analog and discrete parameters, video surveillance and audio recording, as well as more modern tools such as those for eye tracking using gaze maps. It shows the detection of symptoms of STS, their understanding, and solving used for individual or group cognition and decision-making. The last stage of the overall process of assessment and classification of errors modes is completed by applying the proposed taxonomy, shown bottom right.

The tasks of SIMCO are to “measure” the operator’s familiarity (awareness) with the context (workload – mental and physical) in the operational situation (emergency or not) and to assess the interactions in the STS. The mental load caused by cognitive tasks is dominant over the physical load, especially in the MCR digitalization conditions. The used HRA method is crucial for identifying cognitive HEs in addition to procedural/executive HEs.

The STS interface for a standard VVER-1000 MCR consists of specialized consoles, monitors/displays for operators, that they use to monitor and control the relevant process systems. These consoles and systems are grouped to facilitate operational control by the relevant MCR operators as well as supervisors. For individual crews, this is accomplished as follows:

- The *Senior Reactor Operator* (SRO) 1 and SRO 2 controls systems related to the reactor and the primary circuit,
- The *Senior Operator (SO)* and *Senior Operator of Turbo Feed Pumps* (SOTFP) controls systems related to the turbine and secondary circuit,
- *Supervisor* manages all unit operations, monitors the unit's status (symptoms), controls the actions of the operators, the displays at the rear location and the station's workplaces, and maintains communication with the operators in the MCR, making decisions based on the operating procedures.

Operating procedures are provided on paper or computer. In the case of a *computer-based procedure* (CBP), it is also displayed on monitors/displays on the operators' consoles.

4.3. Qualitative analysis of context through symptoms

The symptoms describe the development of most technological, automatic, manual and mental processes in the STS. They are objective signs of the STS's behavior in each situation, insofar as they reflect the properties and state of the object. But since the subject (operator) perceives, interprets and recognizes them individually or in groups, they also manifest themselves as subjective images. Symptoms can be placed in the appropriate group according to their distinctive characteristics. Usually, 2 to 7 groups of symptoms are sufficient, with the simplest division into two groups - relevant and irrelevant symptoms. Usually, symptoms are modeled as indistinguishable (with equal importance) within a group, which facilitates the probabilistic interpretation of the context. But if we have enough information (e.g., frequency of occurrence in the SB EOP), they can be weighed up within the group and between groups.

The emergence, recognition and reporting of technological parameters and signals by operators can be traced over time and described in chronological order. Based on this timeline of unit behavior, a qualitative retrospective analysis and assessment of the change in the unit states is carried out.

Each group, over time, is described in 3 sub-columns (V, O, S), as shown in Table 1, where:

- V represents the number of violations (deviant symptom images) in the group,
- O is the objective number of symptoms in the group (objectively occurring/measured cues),
- S is the subjective number of group symptoms (subjectively recognized cues by the operator).

Each symptom manifested by the object or recognized by the subject during a given time interval is added as 1 to the sub-columns with the number of objective or subjective symptoms (o/s), respectively, in the corresponding group. The recognition process in this interval is a random variable and can be quantitatively described by a probability distribution function. Once a symptom is recognized and considered in context, it may disregard from the subject's (operator's) working, short-term, or long-term memory within another time interval, which can also be quantitatively described by a probability distribution function. The proposed model for qualifying and quantifying the context of cognition with the PET method uses from 2 to 7 groups of symptoms and their violations.

Table 1: Initial data with symptom groups of the PET method [7].

time, s	Goals			Transitions			Actions			Events			Functions			Resources			Parameters					
	V	O	S	V	O	S	V	O	S	V	O	S	V	O	S	V	O	S	V	O	S			

The calculation of the CP for each operator and the *communication* CP (CCP) between operators in the crew is performed according to the procedure outlined in [7] and [8].

The PET method procedure for CP in [7] is supplemented with one more step using the individual cognitive model to obtain the estimate of the individual CEP, *execution error probability* (EEP), *CEP recovery error* (CRE), and *EEP recovery error* (ERE), respectively. Using the Rasmussen SLM and its formula (3) in [9], the HEP_C of the HFE mode C is calculated as follows:

$$HEP_C = (1 - CEP_1) * EEP_1 * ERE_1 + CEP_1 * (1 - CRE_1) * EEP_2 * ERE_2 + CEP_1 * CRE_1 \quad (1a)$$

$$HEP_C = (1 - CEP_1) * EEP_1^2 * CP_2 + CEP_1 * (1 - CP_2 * CEP_1) * EEP_2^2 * CP_3 + CEP_1^2 * CP_2 \quad (1b)$$

where $i = 1 \dots 2$ is a number of iterations, $i+1$ is a number of considered *contextures* (CPs) and in (1b) $CRE_i = CP_{i+1} * CEP_i$, and $ERE_i = CP_{i+1} * EEP_i$ are used for simplification.

4.4. Diagnosis and measurement of the MCR crew performance

The diagnosis and measurement of the group cognitive processes and sub-processes of the operators of the MCR crew is shown in Figure 5, where each of the sub-processes can be individual or group. These sub-processes can be combined into three stages of detection, understanding and decision-making, including execution. Among the human senses (i.e. vision, sound, smell, taste and touch), vision and sound are the main senses for detecting MCR symptoms [10].

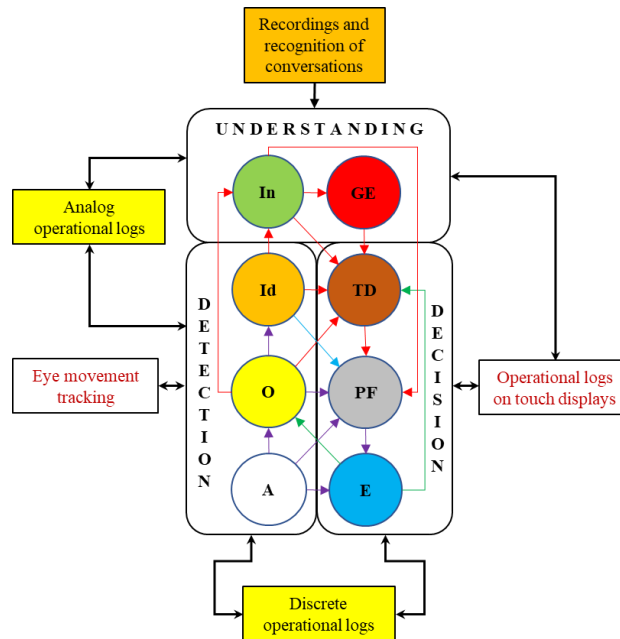


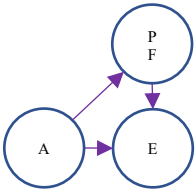
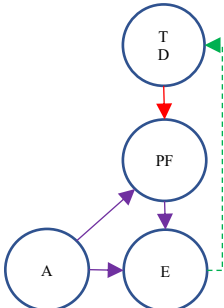
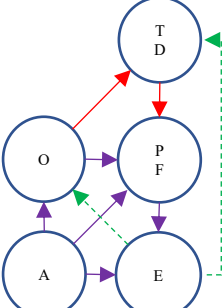
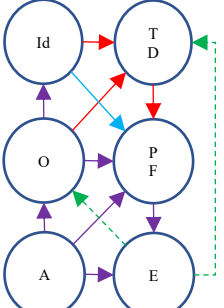
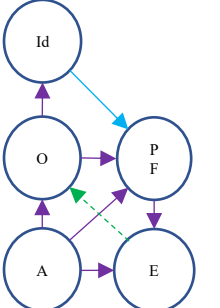
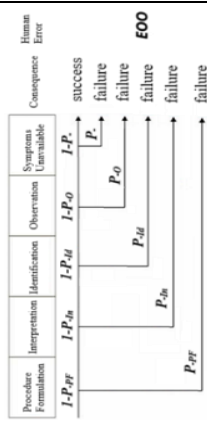
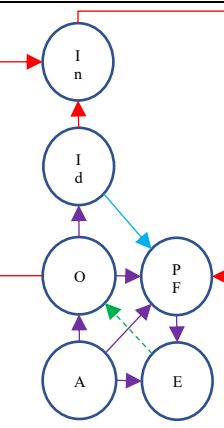
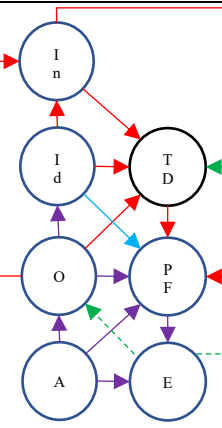
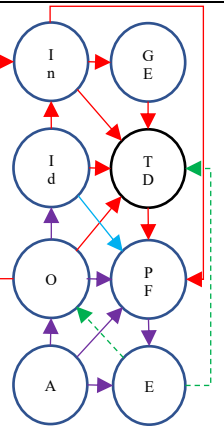
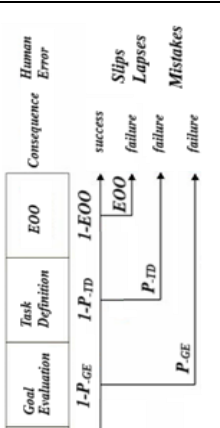
Figure 5: Methods of diagnosis and measurement of operator actions.

For the diagnosis and measurement of operator symptom detection, we need to focus on the visual senses – the eyes. The eye pointer measurement system is applied to observe and record eye movements during diagnostic operations for the detection, understanding and decision-making of operators. The communication (verbal exchange of information) between operators can be recorded in the speech recognition system and used to assess the role of communication in the crew in the process of understanding and decision-making [10].

4.5. Automatic identification and classification of the HE modes

The combined criteria, models and logics for detecting the mechanism/mode of HFE and automatically identifying and classifying HE defined in THERP, CBBDT and PET are shown in [10]. Table 2 shows that, based on qualitative and quantitative analysis of the context of the different HE models, interval HEPs can be obtained within the bounds for each model, where index “lf” is logic fallacy [11].

Table 2: Models and logic for identification and classification of HE modes in SIMCO [10, 11].

<i>Human error modes, models and boundaries of HEP: 1÷5 and 6÷10</i>				
<p>1. $P=P_{ca}$ There are no symptoms available to explore.</p> 	<p>2. $P-o=P_{cb}$ Symptoms for situational awareness are present but not addressed.</p> 	<p>3. $P_{-Id}=P_{cc}$ The symptoms for getting to know the situation are misinterpreted or transmitted.</p> 	<p>4. $P_{-In} = P_{cd}$ The available symptoms for recognizing the situation are misleading!</p> 	<p>5. $P_{-PF} = P_{ce}$ Steps are omitted, executed or reordered incorrectly in procedures.</p> 
$CP \geq P \geq P-o$	$P \geq P-o \geq P_{-Id}$	$P-o \geq P_{-Id} \geq P_{-In}$	$P_{-Id} \geq P_{-In} \geq P_{-PF}$	$P_{-In} \geq P_{-PF} \geq P_{-TD}$
<p>6. EOO [13] “failure to perform an assigned action.”</p>	<p>7. $P_{-TD}=P_{cf}$ Errors made when interpreting instructions</p>	<p>8. $P_{-GE} = P_{cg}$ Errors made in interpreting diagnostic logic. A goal was chosen that does not lead to a resolution of the situation.</p>	<p>9. $P_{SLM} = P_{ch}$ The error is the result of an incomplete or violated cognitive process. The crew intentionally violates the procedure.</p>	<p>9. EOC [13] “incorrect performance of an assigned task, or performance of an extraneous task that was not assigned, which may contribute to accident progression or cause an initiating event”</p>
				
$EOO=1-(1-P_{Slips})*(1-P_{Lapses})=1-(1-P_{-})*(1-P_{-o})*(1-P_{-Id})*(1-P_{-In})*(1-P_{-PF})$	$P_{-PF} \geq P_{-TD} \geq P_{-GE}$	$P_{-TD} \geq P_{-GE} \geq P_{SLM}$	<p>for $CP < 0,5$: $P_A \geq P_{SLM} \geq P_{O-A}$</p> <p>for $CP \geq 0,5$: $P_A \geq P_{SLM} \geq P_{TD-A}$</p>	$1-(1-P_{Slips})^* (1-P_{Lapses})^* (1-P_{Mistakes}) \approx P_{SLM} \geq P_{SLM}^* P_{If} \geq EOC$

$$CP \geq P.(P_{ca}) \geq P-o(P_{cb}) \geq P_{-Id}(P_{cc}) \geq P_{-In}(P_{cd}) \geq P_{-PF}(P_{ce}) \geq EOO$$

$$EOO \geq P_{-TD}(P_{cf}) \geq P_{-GE}(P_{cg}) \geq P_{SLM}(P_{ch}) \geq P_{If}^* P_{SLM} \geq EOC \quad (2)$$

However, these probability intervals may overlap depending on the current contexture of the action, the number of iterations and the recursive recovery actions. They should also be considered in relation to

the time available for the cognitive, judgmental and executive sub-processes for the respective routine or non-routine actions.

5. CONCLUSION

This paper describes the SIMCO methodology, tasks and tools for detecting the symptoms of a given scenario. The behavior of the nuclear unit, and the corresponding STS, is fixed, detected and interpreted by observing, comparing and identifying the relevant trends of parameters, signals, alarms, functions, goals/tasks, procedures and actions during the scenario.

Despite the disputed reliability, feasibility and validity, FSS reproduce not only complex physical, chemical and technological processes, but also complex decision-making processes at the individual, group, mental, psychological, cognitive and organizational levels. They act as natural laboratories for studying these processes, allowing us not only to observe and investigate them, but also to collect useful data for improving models of processes that cannot be reproduced by traditional methods.

In short, the SIMCO system can automatically track and identify symptoms. Based on an algorithm and criteria, transform input data and provide a qualitative and quantitative assessment of context by the PET method. The SIMCO taxonomy enables classification of HFE modes and collection of objective data for HRA/PSA, as well as assessment of crew performance and improved operator training.

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References

- [1] A. Spurgin and G. Petkov, "Advanced Simulator Data Mining for Operators' Performance Assessment," chapter in book *Intelligent Data Mining: Techniques and Applications*, Physica Verlag, A Springer-Verlag, (2005), pp.543-572.
- [2] G. Petkov, V. Todorov, T. Takov, V. Petrov, V. Vladimirov, K. Stoychev, and I. Chukov, "*Safety Investigation of Team Performance in Accidents*", Journal of Hazardous Materials, (2004), ISSN: 0304-3894, Vol. 111, pp. 97-104.
- [3] IAEA Safety Reports Series No. 48. Development and Review of Plant Specific Emergency Operating Procedures, Vienna, 2006.
- [4] A. J. Spurgin and G. I. Petkov, "*Power Plant Simulators: Data Collection and Insights from Data*", Journal of Safety and Reliability 'Human Performance Data Collection Edition', Vol. 26, No. 2, Summer 2006, p. 47-67, ISSN 0961-7353.
- [5] 30.00. PP.MT.69, *Methodology for Developing a Data Collection System for Human Reliability Analysis of FSS-1000 at Kozloduy NPP*, 2025.
- [6] B. Kirwan, H. Gibson, J. Edmunds, G. Cooksley, R. Kennedy, and I. Umbers, "*Nuclear Action Reliability Assessment (NARA): A Data-Based HRA Tool, Safety and Reliability*", June, 25(2):38-45, 2005.
- [7] G. Petkov, "*Symptom-based context quantification for dynamic accident analysis*", Safety Science, (2018), <https://doi.org/10.1016/j.ssci.2018.02.027>.
- [8] G. Petkov, "*Risk Contextualization for Nuclear Systems*", Journal of Nuclear Engineering, (2025), 6 (1), 1; <https://doi.org/10.3390/jne6010001>.
- [9] IAEA, Safety Report Series No. 127, Human Reliability Analysis for Nuclear Installations, 2025.
- [10] K. Mashio, F. Tanaka, Nuclear Power Plant Operator Performance Measurement System for Human Reliability Analysis, PSAM17 & ASRAM2024 Conference, #1269, Sendai, Miyagi, Japan, October 7-11, 2024.
- [11] G. Petkov, "*Misjudgement Explanation in Ambiguous and Comparative Contexts*", PSAM17 & ASRAM2024 Conference, #1157, Sendai, Miyagi, Japan, October 7-11, 2024.