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# The Effect of Psychotropic Drugs as a Performance Influencing Factor on Human Reliability Assessment

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**ABSTRACT** The increasing use/abuse of psychotropic drugs is an alarming social phenomenon with repercussions in many areas, especially in reliability engineering. The aim of this paper is to present a method developed by a multidisciplinary team composed of ergonomists, psychiatrists, information technologists, and reliability engineers to quantitatively consider the impact of psychotropic drugs on the assessment of human reliability of Operation and Maintenance (O&M) personnel of a hydroelectric plant. To achieve the proposed objective, the first step was the identification of drugs that affect the psychic-cognitive/sensory and motor functions as a side effect and the frequency (probability of occurrence) of the effect. This was done mining public and private drug databases. A qualitative (symbolic) scale later translated into numerical values was used to quantify the impact of each drug on the affected functions. At the same time, O&M tasks were broken down into observable activity sequences, recording the frequency of each activity on each task (Task Analysis). Then, the relationship between each activity and the sensory- cognitive-motor psychic functions was established, based on the knowledge and experience of the team involved. Again a qualitative (symbolic) scale was defined and later transformed into a numerical scale. As a result, the first version of a drug effect - task knowledge database (KDB) was built with the symbolic and numerical values assigned to all relationships between the different model elements. Although the KDB needs to be systematically reviewed and updated by a broader network of ergonomists and psychiatrists, it has served as proof of concept and a starting point for the development of a human risk management tool for hydroelectric power plants. The last step was to calculate a new Performance Shaping Factor (PSF) due to Psychotropic Drugs Use (PDU), for each drug in each of the O&M tasks. In a preliminary assessment of the inclusion of PDU-PSF with three common methods of Human Reliability Assessment (HRA), we found an increased risk of human failure ranging from approximately 15% to 35%, depending on the HRA method. The case study used to illustrate the method considered a routine operator inspection task using an antidepressant drug. The proposed method can be updated for new drugs and can be refined/customized for other high-risk human activities such as oil and gas and petrochemical industries, nuclear power plants, aviation, and surgery, among others.

**INDEX TERMS** Human error analysis, reliability, task analysis, psychotropic drugs, human reliability.

## I. INTRODUCTION

In operation and maintenance (O&M) of industry, workers are exposed to many different and sometimes conflicting natural and constant stressors. As a consequence, it is increasingly common for them to use psychotropic

drugs [1], [2]. However, many, if not all tasks require concentration, attention, quick reflexes, speed, dexterity, accuracy, visual-spatial coordination, and decision-making abilities that can be affected by drugs taken before and during service [3].

Human Reliability Assessment (HRA) methods estimate the *Human Error Probability* (HEP) taking into account factors in the work environment, the work task and the

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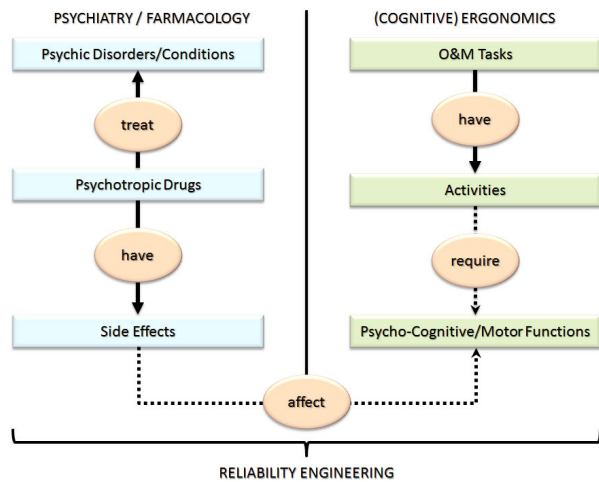


FIGURE 1. Entity-Relationship Diagram of the Scope of the Project.

worker itself that influence human performance, called either: Performance Influencing Factors (PIFs) [4], Performance Shaping Factors (PSFs)<sup>1</sup> [5], [6], Error Producing Conditions (EPCs) [7], [8] and Human Error Inducing Factors (HEIF) [9]. Company aspects, the personal characteristics of the worker and his/her qualification/training, the complexity of the tasks under existing environmental conditions (temperature, noise, lighting, smells, etc.) and the human-machine interface are some of the PSFs normally considered [5], [6], [10]–[13].

Tasks are often broken down into simpler activities in a process called Task Analysis, which is common in the ergonomic subarea of the production engineering, while in the medical / pharmacological literature, there is comprehensive information on the side effects of psychotropic medications [14]–[16] as well as the negative influence on the skills required for certain activities, such as driving vehicles [17]. Figure 1 shows the Entity-Relationship Diagram (ERD) [18], [19] of the problem addressed. According to IT nomenclature, Entities (underlined) are objects characterized by their stored data, and *relationships* (italic) are verbs that establish how data objects are interconnected.

This diagram has two parts. The left part belongs to the area of psychiatry and pharmacology, having as central entity the Psychotropic Drugs. Psychotropic medications *treat* Psychic Disorders / Conditions, but also *have* Side Effects. The right side belongs to Classical and Cognitive Ergonomics, having as main entity O&M tasks. The O&M task *has* Activities, and Activities in turn *require* Psycho-cognitive / Motor Functions to be performed.

Therefore, to be able to consider in the analysis of human reliability the risk arising from the use of psychotropic drugs, it is necessary to relate the left part with the right part. This can be done by establishing that the Side Effects on the left *affect* the Psycho-cognitive/motor Functions on the right as

<sup>1</sup> Denomination adopted in this article.

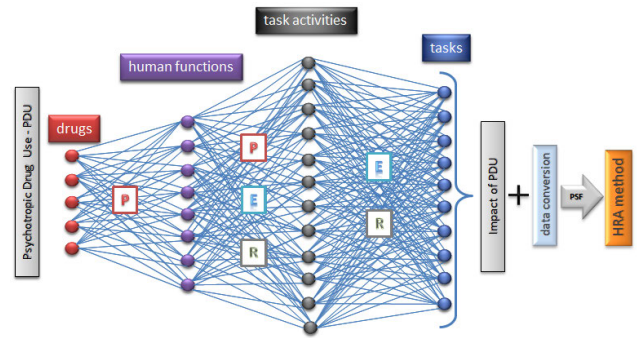


FIGURE 2. 4-layer hierarchical network model generating input for HRA methods. The areas of expertise that define the factors of connection between the layers are indicated as: P - Psychiatry, E - Ergonomics and R - Reliability Engineering.

shown with a dashed line in Figure 1. We use different types of lines for relationships in order to visualize what is new (dashed lines) and what was already known or relatively easy to obtain (solid lines).

The purpose and contribution of this paper is to provide a viable methodological framework for considering a new PSF that seriously affects human performance and that has become commonplace and is increasingly common in industry work environments: the use of psychotropic drugs (PDU) by the O&M staff. To illustrate its use, an example application was conducted using three HRA methods in a routine task in hydroelectric plants.

The developed model makes it possible to quantitatively estimate how much it would contribute to the increased likelihood of human failure while performing an O&M task when an operator has taken a particular controlled psychotropic drug. In this way, plant manager at the beginning of each work session can decide how to go about minimizing human error in order to increase operational reliability. For example, it may deny the operator's assumption of service, relocate staff among the intended tasks, or allocate another operator to assist the operator who used the drug, among other alternatives.

The model developed is structurally and functionally similar to a multilayer network without feedback, such as those used in deep learning, (see Figure 2) differing only in the way in which the weights of connections between neurons are estimated. In deep machine learning, the weights that connect the neurons of the various cascaded layers are computationally obtained [20]–[22] to obtain the best match between the data presented in the first layer (types of drugs used by the operators before and during work) and those presented in the last layer (occurrence of incidents / accidents while performing O&M tasks). In our approach these weights are estimated by human experts. Importantly, our approach to using human experts to set weights has two motivations: (1) There is no data to apply the machine learning version, nevertheless, the problem already exists in plant operation personnel and therefore needs to be addressed. (2) Even when there is sufficient data for machine learning, it is essential

to have a model created by human experts that can serve as a reference. Reference is needed for controlling machine learning, which is not always correct, and for correcting expert estimates, generating feedback for a reverse (human) learning process, every time the knowledge database built on this project is updated.

Following the established practice in the HRA field, we use expert estimates in all areas involved: psychiatry, ergonomics and human reliability. A multidisciplinary team produced their best weight estimates and stored in the first version of a parameterized knowledge database called the Psychotropic Drugs Impact on Human Reliability (PDIHR). We believe that, in matters related to risk control, it is better to apply some control method that depends on subjective factors, than not to apply any method for lack of more reliable values of those factors. Even though we know that the current PDIHR version serves only as proof of concept and as a starting point, the description and analysis of the current version of PDIHR will be published in an upcoming article.

Intra-layer connections may be the subject of future developments in order to take into account drug interactions [23] and dependencies between functions [24], activities and tasks [12]. Similarly, consideration of the dose and time since drug ingestion [25] may be additional elements to consider in the future.

For now, the proposed methodological framework was implemented in a computational tool (SARO - Sistema de Avaliação do Risco Operacional - *Operational Risk Assessment System*) currently in use in eight hydroelectric plants in Brazil. The tool purpose is collecting data of human errors in operation committed with and without psychotropic drug intake that will allow future validation and adjustment of the developed KDB-based inference model.

The knowledge database built, beyond the weights that define the interactions between the model components in a hierarchical form, was designed to store relevant metadata for human reliability studies, such as (i) active compounds and combinations of them in different drugs, (ii) the frequency of use of each drug and each active ingredient, (iii) average, maximum and minimum dosages, among other data relevant to the psychiatric field. Similarly, human error events will be logged, including (i) the task in which it occurred, (ii) the profile of the operator(s) who made the error, (iii) environmental conditions, (iv) time stamp (time, day of the week, month and year), (v) physical and psychological examination of those involved after the event, (vi) use of psychotropic medications and (vii) summary of the incident clearance interview, among other data.

The article is structured as follows: In section II we provide a brief review on related subjects in the fields of human reliability, ergonomics and psychiatry, called here *cognitive dimensions* of the problem addressed. In section III we describe the method, again differentiating the three knowledge dimensions, including the description of the specificities of three HRA methods used in the case study. In section IV we describe the case study and in section V its results. The article

ends with a discussion of the results (section VI), followed by the conclusions (section VII).

## II. BACKGROUND

According to data published in MHIDAS (*Major Hazard Incident Data Service*) [26], approximately 22% of refinery accidents are related to human failures, but this percentage grows to 41% in pipeline companies. In both cases 81% of human failures occurred in O&M activities.

In the *Failure and Accidents Technical information System* - FACTS ([www.factsonline.nl](http://www.factsonline.nl)) which contains data of more than 26,000 (industrial) accidents (incidents) involving chemicals from 1979 to 2006, has 33,042 listed causes, 9,379 (28.38 %) of them unknown. The three main known causes (among the 23,663 identified causes) are management failure (9,978 / 42.16 %), human failure (7,176 / 30.32 %) and technical failure (5,454 / 23.05 %). Considering that management failure is a type of human failure, the human versus technical failure ratio is approximately 3.04.

In power plants accidents involving chemical substances are not very frequent and only 34 such accidents were found in FACTS from 1979 to 2006. Of these accidents 13 (38.23%) have unknown causes, 12 (35.29%) occurred due to technical failure, 5 (14.7%) due to human error and 4 (11.76%) for management failure. This means that in this specific scenario (power plants and chemical accidents) human failures were responsible for 42.86% of accidents. Data on accidents of other nature in power plants could not be accessed in this research.

These statistics demonstrate the high incidence of human failure in accidents and high risk incidents in O&M activities in industries in general and in power plants in particular.

In the following sections, we present the context of the research, providing concepts and describing methods used to address the analysis of human factors in socio-technical systems from three different but complementary points of view, which we call problem dimensions: human reliability, ergonomics, and psychiatry.

### A. HUMAN RELIABILITY CONTEXT

According to [27]:

*“Human Reliability Analysis (HRA) is a method by which human reliability is estimated. In carrying out an HRA, it is necessary to identify those human actions that can have an effect on system reliability or availability... The person in a system may not only fail to do what he is supposed to do, or fail to do it correctly, but he may also do something extraneous that could degrade the system. The latter is the weak link in HRA. It is not possible to anticipate all undesirable extraneous human actions. The best anyone can do is to identify those actions having the greatest potential for degrading system reliability and availability. The assignment of probability estimates to extraneous actions is difficult and uncertain. Often the best one can do is to estimate very broad ranges of probabilities of human errors that one believes include the true probability”.*

Human reliability is an input for engineers to build reliable systems. HRA methods are designed to assess the probability of a human-originated system failure, commonly referred to as Human Error Probability (HEP). There is a long list of HRA methods including THERP [27]–[30], SLIM [31], CREAM [32], [33], ATHEANA [34], [35], IDAC [36], HEART [37], [38] SPAR-H [39] and HERA [40].

Although more than 50 HRA methods and variants have been identified in the literature review, we have selected to illustrate the use of the method described in this article, the THERP, SLIM, and HEART methods [33], [41]–[43] because they are best suited for power plants.

Most input data for HRA methods are provided by Human Factor Methods (HFM) intended to describe human performance under actual operating conditions [30], [32], [35], [44]–[46]. The HFMs were developed to analyze systems with humans and equipment, integrating the technical, individual, collective and organizational (social) processes [12], [47] that happen concomitantly and intrinsically related in what is called the socio-technical system [4], [5]. The influence of such factors is represented as PSFs. In summary, HFM allows specialists to identify and characterize PSFs and convert them to a numeric scale for use in the HRA method. [9], [31], [42], [48]. Reliability engineers have set HEP nominal values [49] and consider PSFs as multipliers greater or smaller than one if the effect is detrimental or positive, respectively [44], [50]–[52].

Therefore, to perform an HRA, the analyst needs specific knowledge of the fundamentals of human performance, in particular human cognition, PSFs, and organizational influences on the behavior of task performers. There are four main challenges in this procedure:

- 1) Identify the PSFs,
- 2) Mapping all the factors contributing to each PSF,
- 3) Based on the factors acting in an event to attribute a numeric value (normally between 0 and 10) to each PSF, and
- 4) Translate each PSF into a multiplier of the nominal HEP.

To illustrate the diversity of PSFs considered, the method SPAR-H [39] developed for a Nuclear Power Plant (NPP) context considers 11 PSFs:

- 1) Available time
- 2) Stress and stressors
- 3) Complexity
- 4) Experience and training
- 5) Procedures (including job aids)
- 6) Ergonomics and human-machine interface
- 7) Fitness for Duty
- 8) Planning / Scheduling
- 9) Supervision / Management
- 10) Conduct of Work
- 11) Problem Identification & Resolution / Corrective Action Plan

**TABLE 1. Number of contributing factors (CFs) to PSFs in HERA.**

PSF	CFs	Example CF
Available Time	3	Inappropriate balance between available and required time
Stress & Stressors	1	High stress
Complexity	20	Demands to track and memorize information
Experience & Training	12	Individual knowledge problem
Procedures & Reference Documents	4	Document technical content less than adequate
Ergonomics & HMI	7	Displays less than adequate
Fitness for Duty/Fatigue	7	Unfamiliar work cycle
Planning/Scheduling	4	Inadequate staff/task allocation
Supervision/Management	11	Frequent task re-assignment
Conduct of Work	35	Failure to apply knowledge
Problem Ident./Resol. & Corrective Action Plan	16	Evaluation less than adequate
Communication	5	Communication not timely
Environment	8	Lighting less than adequate
Team Dynamics & Characteristics	3	Team interactions less than adequate
TOTAL	136	

but the *Human Event Repository Analysis* (HERA) [40] database and system includes three more PSFs adopted from *Good Practices for Implementing HRA* [53]:

- 12) Communication
- 13) Environment
- 14) Team Dynamics / Characteristics

Most HRA methods, including SPAR-H and HERA, have been developed to identify the causes of accidental or even risky events. To do this, each event is subdivided into subevents and for each subevent is investigated which of the various definite and verifiable *contributing factors* (CFs) belonging to each PSF previously contributed to the occurrence of the subevent. In other words, “the PSF contributing factors selected for a subevent should not describe the subevent in question, but should identify factors that contributed to the subevent under analysis” [40].

To illustrate the complexity and level of detail of the socio-technical system model in the HERA method we show in Table 1 the number of CFs considered for each PSF along with the description of a single but representative CF due to space constraints. More detail can be seen in the reference cited.

In addition, to evaluate the 16 CFs of the above *Problem Identification and Resolution / Corrective Action Plan* PSF, a two-part HERA Human Cognition Model (HCM) is used.<sup>2</sup> HERA’s HCM first part considers four steps of Human Information Processing (HIP) occurring in the human decision making process:

- 1) Detection: Recognition of a problem,
- 2) Interpretation: Understanding the causes and consequences of the problem,
- 3) Planning: Structuring a response to the problem,
- 4) Action: Executing the planned response.

<sup>2</sup>A recent review of cognitive models in human reliability analysis is done in [54]



In each subevent, each step of human information processing can be evaluated as: (1) correct, (2) incorrect, or (3) correct, but based on at least one previous step not correct. Operators can make mistakes in any of these steps. For example:

- Incorrect detection error: A problem is not recognized as such and the necessary subsequent actions are not taken.
- Correct detection but misinterpretation: An observed problem is misclassified and subsequent corrective actions may be ineffective or counterproductive.
- Correct detection and interpretation, but incorrect planning: An incorrect plan can make the situation worse or render the actions ineffective, ie the execution of the planned actions is very unlikely to meet expectations.
- Correct Detection, Interpretation and Planning, but Incorrect Action: Errors committed in the execution of planned actions nullify the effect of all previously performed actions, leading to the same or even worse risk situation than before the problem was detected.

The second part of the human cognitive model considers three levels of cognitive activities, known as Rasmussen's Skill/Rule/Knowledge Based cognitive levels [55]:

- 1) Skill-based: Activity performed during routine task execution, performed almost automatically, with sporadic progress checks.
- 2) Rule-based: Activity performed during the execution of a task that requires the conscious application of memorized or written rules, constantly checking whether the result is appropriate.
- 3) Knowledge-based: Activity performed during the execution of tasks that require a high level of abstraction, prior knowledge and logical reasoning to solve problems, usually arising in new tasks or situations.

It is important to note that a person can perform all three activities at the same time.

In this work we focused O&M tasks. According to HERA "Task refers to the goal-driven activity performed by the crew. Each task represents different activities and corresponding different goals necessary to complete an action". Since the description and analysis of tasks pertain to ergonomics, the next section is devoted to the ergonomic dimension of our problem.

## B. ERGONOMIC CONTEXT

Occupational ergonomics focuses primarily on work-related health and safety aspects of a system to reduce the rate of employee health problems. However, in recent years there has been a growing interest in what we call system performance ergonomics, both in the operation [56] and maintenance [57] of industrial systems. Sobhani *et al.* [56] provide a road map for assessing the impact of work-related risk factors, including physical and psychosocial aspects on system performance. However, its focus was on assessing the cost growth of a manufacturing system due to the low ergonomic design of the workplace rather than human failure

issues. Sheikhalishahi *et al.* [57] reviewed the current literature analyzing human factors in maintenance considering three main categories: (1) error calculation / human reliability, (2) human resource management and (3) workplace design / macro ergonomics. They found that even though most studies focus on macroergonomics, human factors in maintenance are a pressing problem, as reported in the few articles that dealt with ergonomic factors-induced human errors in maintenance.

Most HRA methods require the classification of tasks according to their specific activities, focusing on those in which mental abilities are critical [28], [32]. This procedure is based on the well known fact that most human errors are associated with some cognitive, conscious or unconscious aspect [55], [58]–[60], which is the subject of study of cognitive ergonomics [54], [61], [62]. It is assumed that under favorably working environment, with an appropriate time available to perform a single task the likelihood of human failure depends on the balance between operator's competence and task complexity.

A *task* is a unit of work prescribed by the organization, a set of patterns of operations that, either alone or in conjunction with other tasks, can be used to achieve a goal [58]. Human errors occur during task execution, so *task analysis* is critical to HFM. Task analysis refers to how a task is performed, including its characteristics (location, duration, frequency, complexity, schedule, performers) and resources (protective devices, instruments, tools), as well as description of manual and mental *activities* (performed through operations within actions), required to perform a specific task.

One of the key challenges for the expert observer who performs the on-site real-time task analysis process is to unambiguously classify the mental activities performed on each task [36], [46], [63]. For example, it is very difficult to differentiate just by looking at who performs the activity between monitoring, panning, scanning, verifying, and checking. Even though they seem synonymous, these activities have some subtle differences related to the kind of mental and physical (sensory) resources they require.

Note that the French ergonomics school adopts a different definition for *activity* [64], [65]. Here, the term activity is used as a subtask or a small part of a task, which may be part of other tasks. Thus, our activity is synonymous with *action* at the conceptual level. At the execution level, *actions* = *activities* are transformed into *operations* that depend on existing *conditions* when and where the action occurs. In this case, we consider that for the execution of each *operation* a certain combination of *sensory, cognitive and psychomotor functions* of the operator are used, reason why the use of psychotropic drugs (PDU) constitutes an element that shapes the working conditions.

As the characterization of psychotropic drugs and analysis of their therapeutic and side effects belongs to the area of psychiatry, the next section is devoted to the psychiatric dimension of our problem.

### C. PSYCHIATRIC CONTEXT

The balance between operator competence and task complexity depends on the operator's physical and mental state when performing O&M tasks. However, this is poorly handled in practice, even though most HRA methods make it possible to consider operator status at the time of task execution as a contributing factor to a PSF. For example, in the HERA method, this can be taken into account when estimating the PSF "Fitness for Duty". However, there is no established method for translating the operator's psychic and physical states into appropriate quantitative values of the associated contributing factor.

Worse still, previous use of psychotropic drugs by the operation and maintenance staff, an increasingly common daily practice, is neither monitored nor taken into account when analyzing the causes of human error. The use of sedatives, antidepressants and antipsychotics is growing even among non-ill people due to self-medication and easy access to various types of these drugs in Brazilian drugstores.

A drug is a chemical designed to produce a therapeutic (pharmacological) effect and thus causes desired functional changes in the human body, but it can also cause side effects. Therapeutic psychotropic drugs belong to a group of medicines that work on the central nervous system but may affect other systems. Each drug has a specific action on one or more neurotransmitters or neuroreceptors in the brain. They act by temporarily modifying a person's neurochemistry, which causes changes in a person's perception, cognition, mood, and behavior [66]–[68]. Of the 22 adverse reactions to antidepressants at therapeutic doses listed in the most current reference [16], 13 affect psychocognitive and psychomotor functions, directly or indirectly, causing from 2% to over 30% of patients one or more of the following reactions: (1) Seizures, (2) Drowsiness/sedation, (3) Excitement/hypomania, (4) Disorientation/confusion, (5) Tremor, (6) Headache, (7) Asthenia/fatigue, (8) Gastrointestinal distress, (9) Blurred vision, (10) Orthostatic hypotension/dizziness, (11) Tachycardia/palpitations, (12) ECG changes and (13) Cardiac arrhythmia.

The mechanisms that determine the process of absorption, distribution, biotransformation and elimination are the same as other drugs [66]. The effect of the drug depends on the dosage and in general, the higher the dosage, the greater the effect. However, people react differently to each drug. In general, at the beginning of treatment, medications can directly affect important functions for task performance [67], [69]. Instead, continued use tends to affect less [15]. The conditions that justify the use of psychotropic medication may also compromise functions, in particular coordination, psychomotor coordination, cognition and attention when the individual is not using the medication. Physicians' decisions should balance all these processes to get the best outcome for the patient, but, in any case, it is a factor of influence on the person's performance, whether with or without drug use.

Authors did not find any publication in the Human Reliability Assessment (HRA) field reporting practical experience of considering the psychotropic drugs effects when assessing the risk of human failure in O&M of industrial systems, nor describing appropriate methods for this purpose.

### III. MODELS AND METHODS

The methodology was applied to hydroelectric plants, systems composed of water reservoirs, dams, spillways, sluice (often), hydro-turbines, electric generators and associated equipment, such as transformers, circuit breakers, cooling systems, water and oil motors and valves, auxiliary power generators, fire extinguishing systems, among other components.

A total of eight power plants had their layout inspected, and operational and maintenance personnel were interviewed about their work. At these interviews, employers are conducted to express any kind of stressful condition and can send a private message to the team if they want to. Some staff members reported using psychotropic drugs occasionally, primarily to treat stress and anxiety, all over 40 years old. Some operators used antiepileptics regularly.

As commented in section II-A, HRA methods consider several PSFs that need to be quantified to be used in estimating HEP. To include the impact of psychotropic drug use when quantifying PSFs, it was necessary to construct a conceptual model and functional structure that combines the results of the three areas of knowledge that participate in the construction of the solution to the problem addressed: (1) ergonomics - E, (2) psychiatry - P and (3) human reliability engineering - R.

Figure 2 depicts the built model that consists of a four-layer interaction network that links the use of psychotropic drugs in the first layer to the fourth layer that returns a Contributing Factor to be used to account for the impact of psychotropic drug use through a suitable PSF, according to the HRA method used. Each node represents a drug, a human function, a task activity, and an O&M task in the first, second, third, and fourth layers, respectively. We include a data conversion unit that matches the output of our network to the input type of the chosen HRA method. This is done considering that the methods do not use the same scale for input PSFs.

Connections between nodes are established through weights, as in neural networks, but these weights are estimated by humans. Three multidisciplinary teams, one for each dimension of the problem, interacted with the IT team. All three teams followed a systematic approach consisting of a consensus building methodology created by consultants, which will be the subject of a future article. In summary, each expert assigns two values (quantitative or qualifier) for each weight. These values were used to calculate two weighted averages (upper and lower) by the expert ranking. Experts were ranked according to a "guide" generated by external experts, but their rankings were never reported. The resulting highest and lowest weighted averages, as well as the unweighted maximum and minimum values, were reviewed

by all experts independently and later in a meeting to define consensus. Prior to the meeting, the expert could change his assessment, but this was taken into consideration to penalize his ranking without his knowledge. At this meeting, consensus values were assigned to all factors that were not rejected by any exclusion criteria. Among the exclusion criteria, it was defined that weights assessed by less than 60% of consultants should be reevaluated in a next step by the Experts team. This procedure was followed for all layers and the corresponding weights were stored in PDIHR database. It took between two and four evaluations, depending on the layers.

The description of the node definition of each layer as well as the weights between nodes will be covered in the next sections.

### A. MODELING THE ERGONOMIC DIMENSION

In this section, we describe how the third and fourth layer nodes in Figure 2 were defined and the weights between them estimated. Six ergonomists and four reliability engineers from six hydropower plants worked together for approximately two years to build the ergonomic part of our model, following the consensus-building methodology.

#### 1) STRUCTURE OF THE FOURTH FLOATLAYER (TASK LAYER)

In total, considering the eight hydropower plants, a total of distinct 451 operational and maintenance tasks were identified in the Operation and Maintenance Manuals and confirmed in interviews with plant operators and managers. Of these, 212 were considered frequent and were performed at least once a week.

Based on the results of a reliability study conducted by AES Tietê's Department of Reliability and Operational Excellence, we selected 29 of the most relevant tasks identified in the study, shown in Table 2, considering the impact of a human failure and the frequency of these failures on the considered plants.

In Table 2 is the list of selected tasks. After evaluating the results of the methodology on the selected small set of tasks, the remaining tasks are being gradually analyzed and added to the database.

#### 2) STRUCTURE OF THE THIRD LAYER (ACTIVITY LAYER)

Task analysis can be performed in two steps: (1) descriptive step: consists of defining what leads to what, the parts that make up the task and the order in which they need to be performed, ie, what the job executor should do and (2) Analytical step: Find out what can go wrong and why [27]. In the descriptive step we use the usual approach in ergonomics to consider that all tasks can be broken down into a finite number of standard cataloged actions, we called activities, and each activity can even be performed more than once at different stages of the task script. These activities specify physical and mental processes, like the removal of a component or a simple test of an electronic element.

Generally, most O&M procedures are available in the Operation and Maintenance Manuals and can be used as the

**TABLE 2. O&M task selected at the first stage of the project.**

n	Task	System/Equipment
1	Routine Operator Inspection	Hydroelectric Power Plant
2	Release to Start	Generating Unit
3	Post-Maintenance Regulation	Generating Unit
4	Visual Inspection	Electric Generator Radiator
5	Leak Inspection	Electric Generator Radiator
6	Visual Inspection	Speed Regulator
7	Visual Inspection	Suction Tube (Inspection Hatch)
8	Visual Inspection	General Water Feed Manual Valve
9	General Inspection	Compressed Air Valve of the Emergency Auxiliary Group
10	Functional Testing	Pneumatic Starter of the Emergency Auxiliary Group
11	Leak Inspection	Hydraulic Safety Valve
12	Operation Check	Inlet Pipe Manual Valve Opening
13	External Mechanical Cleaning	Inlet Pipe Manual Valve Opening
14	General Inspection	Generator Braking System Valve
15	General Inspection	Hydraulic System Safety Valve
16	External Mechanical Cleaning	Hydraulic Actuator Servo Motor
17	Mechanical Reconditioning	Drain Pump
18	Mechanical Review	Drain Pump
19	Mechanical Inspection	Electric Generator Regulating Ring
20	Internal Mechanical Cleaning	Electric Generator Regulating Ring
21	Mechanical Inspection	Turbine Head
22	External Mechanical Cleaning	Turbine Head
23	Leak Inspection	Turbine Head
24	Alignment	Exhaust Oil Box Pump
25	Mechanical Reconditioning	Exhaust Oil Box Pump
26	Operational Check	Exhaust Oil Box Pump
27	Mechanical Inspection	Exhaust Oil Box Pump
28	Leak Inspection	Turbine Cap Fixing Screw
29	Mechanical Inspection	Turbine Cap Fixing Screw

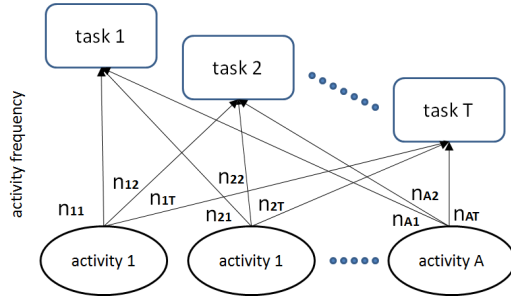
basic source document for preliminary task analysis. The task description is completed by interviews and in situ observations. Even when procedures are written, it is necessary to talk to O&M staff to identify the differences between writing and what is actually done to better understand the relevant PSFs.

Figure 3 represents the decomposition of  $T$  tasks into  $A$  activities, where  $n_{a,t} \geq 0$ , defined for all activities  $a = 1, 2, \dots, A$  and all tasks  $t = 1, 2, \dots, T$ , is the times an activity  $a$  is performed on task  $t$ .

After decomposing the 29 O&M tasks described in the section above into 102 primary activities, a consolidation step was made, merging highly similar primary activities into one. This led to a set of 33 activities common to all tasks. From this set, 18 activities were then chosen that depend significantly on psychic functions, which are listed in Table 3.

#### 3) RELATIONSHIP BETWEEN THE THIRD (ACTIVITY) AND FOURTH (TASK) LAYERS

The first relationship between tasks and activities was described in the previous section and is given by the times



**FIGURE 3.** Decomposition of industrial tasks into activities. Here  $n_{a,t} \geq 0$  denotes the times an activity  $a$  is executed in task  $t$ .

**TABLE 3.** Activities highly dependent on psychic functions.

n	Activity
1	Monitoring
2	Diagnosis
3	Adjustment
4	Inspection/Check
5	Repair
6	Test
7	Sampling
8	Maneuvers
9	Communication
10	Planning
11	Removal
12	Installation
13	Assembly
14	Counting
15	Measuring
16	Handling and Transportation
17	Administrative Services
18	Services

an activity is performed within a task, denoted as  $n_{a,t}$ . Nevertheless it is common sense to believe that an error in one activity may have a greater or lesser impact on the failure of the task as a whole than another activity. For this reason, following the principle governing reliability and risk analysis, according to which risk is the product of the frequency of the failure / accident event multiplied by the expected damage / loss caused by each failure / accident, we have established that the relationship between the fourth (task) layer and the third (activity) layer is given by the times an activity is performed during the execution of a task multiplied by the relevance of a single error in an activity in inducing the failure of the entire task. To represent the impact of a failure in an activity  $a$  to the failure of a task  $t$  we used the variable  $r_{a,t} \geq 0$ , interpreted as relevance, for all tasks  $t = 1, 2, \dots, T$  and all activities  $a = 1, 2, \dots, A$ . Thus the weight between node  $a$  in the third layer and node  $t$  in the fourth layer is calculated as:

$$w_{a,t} = r_{a,t} n_{a,t}. \quad (1)$$

Note that instead of using the frequency of the activity we choose the times the activity is performed so that the probability of failure of larger tasks is greater than that of smaller tasks with the same type of activity. The difference

**TABLE 4.** Times each activity listed in Table 3 is executed in the task *Routine Operator Inspection*.

Activity	$n_{a,t}$ (times)	$f_{a,t}(\%)$ (frequency)
Monitoring	6	7.9
Diagnosis	22	29.0
Adjustment	0	0.0
Inspection/Check	28	36.8
Repair	0	0.0
Test	2	2.6
Sampling	0	0.0
Maneuvers	2	2.6
Communication	6	7.9
Planning	2	2.6
Removal	0	0.0
Installation	0	0.0
Assembly	0	0.0
Counting	2	2.6
Measuring	4	5.4
Handling and Transportation	0	0.0
Administrative Services	0	0.0
General Services	2	2.6
TOTAL	76	100

between times and frequency is shown in Table 4 for an example task *Routine Operator Inspection* listed in Table 2.

Adding the frequencies of the *inspection* and *diagnostic* activities, we see that they account for 65.8% of all activities in that task. Both activities require several physical and mental functions, which will be commented on in the next section. To perceive some subtle peculiarities of the activities, the activity *diagnostic* occurs to solve new problems, ie, without previous experience, or in situations where the human mind is making a decision on a comparative basis and requires different areas of mind to solve the problem. In the same context, *Monitoring* is an activity that has several characteristics similar to those of *Inspection/Check*, but requires a time-dependent function to track the oscillation of a specific parameter in a system and its is expected the operator to not only observe but also act.

The result of the team's work can be condensed into two  $A \times T = 18 \times 29$  size consensus matrices:  $r_{A \times T}$  and  $n_{A \times T}$ , as follows:

$$r_{A \times T} = \begin{bmatrix} r_{1,1} & r_{1,2} & \dots & r_{1,T} \\ r_{2,1} & r_{2,2} & \dots & r_{2,T} \\ \vdots & \vdots & \dots & \vdots \\ r_{A,1} & r_{A,2} & \dots & r_{A,T} \end{bmatrix} \quad (2)$$

and

$$n_{A \times T} = \begin{bmatrix} n_{1,1} & n_{1,2} & \dots & n_{1,T} \\ n_{2,1} & n_{2,2} & \dots & n_{2,T} \\ \vdots & \vdots & \dots & \vdots \\ n_{A,1} & n_{A,2} & \dots & n_{A,T} \end{bmatrix} \quad (3)$$

containing the relevance and frequency of the activities in the tasks, respectively. Generating the "r" relevance matrix required four iterations of the consensus building process, and



yet it was rejected in the final assessment because it did not reflect consistent consensus. For this reason, all relevance was set equal to 1 while a new study for its reevaluation is not performed.

Looking at Eq. 1 it can be seen that the weights are obtained as the convolution of matrices  $r_{A \times T}$  and  $n_{A \times T}$ , that is, the weights matrix relating Activities and Tasks is given by:

$$w_{A \times T} = r_{A \times T} * n_{A \times T}. \quad (4)$$

Denoting the output at a task-node  $t$  by  $y_t$  and by  $x_a$  the input at an activity-node  $a$  it holds

$$y_t = \sum_{a=1}^A w_{a,t} x_a, \quad \forall t = 1, 2, \dots, T. \quad (5)$$

Here  $y_t$  is a variable that quantifies the increase in the contributing factor to failure of task  $t$  due to the increased probability of human failure performing the task's activities, represented here by the input variables  $x_a$ ,  $a = 1, 2, \dots, A$ .

According to the network architecture, the  $x_a$  inputs are the activity node (third) layer outputs that depend on the inputs generated by the psychic function (second) layer. Calculating the outputs of the second layer is one of the subjects of the psychiatric dimension of the model, dealt with in the next section.

## B. MODELING THE PSYCHIATRIC DIMENSION

In this section, we describe how the first, second and third layers in Figure 1 were defined and the weights between them estimated. The estimates were done by a multidisciplinary team consisting of five psychiatrists, three ergonomists and three reliability engineers, following the consensus-building methodology. At all, building the psychiatric dimension of our model took over three years.

After the compilation of drugs registered to deal with stress, depression and other psychic disorders, many drugs were analyzed. However, only those that can cause significant side effects affecting human performance were considered, according to the opinion of psychiatrists based on extensive literature review [14]–[17], [67], [70]–[73].

### 1) STRUCTURE OF THE FIRST LAYER (DRUGS)

It is well known that the use of sedative drugs such as benzodiazepines, antiepileptics, some antipsychotics and some antidepressants are described in the drug recommendation (labeling) as a risk condition for occupational accidents. These medications have many side effects that can directly or indirectly interfere with tasks. For this reason, an exhaustive search on the two largest online drug databases [74], [75] was conducted to select the psychotropic drugs to be considered. The selection criterion was the nature and frequency of side effects that could undermine the work performance of plant operators as well as the frequency of prescription by Brazilian psychiatrists. Table 5 shows the 16 psychotropics drug

TABLE 5. Selected psychotropic drugs categories.

id	Drug Category
1	Anti depressives
2	Tricycle
3	Selective serotonin reuptake inhibitor
4	Serotonin and noradrenaline reuptake inhibitors
5	Noradrenaline and dopamine reuptake inhibitors
6	Selective noradrenaline reuptake inhibitors
7	Antagonist 2 (serotonin and noradrenaline disinhibitor)
8	Antagonist/Inhibitor to serotonin reuptake
9	Inhibitor of monoamine oxidase
10	Agonist of the receptors de melatonin
11	Benzodiazepines of small action
12	Benzodiazepines of intermediate action
13	Benzodiazepines long action, Anticonvulsant
14	Antipsychotics typical
15	Antipsychotics no typical
16	Others — group of drugs frequently used in medical practice

TABLE 6. List of selected psychic functions.

id	Psychic Functions
1	Surveillance
2	Attention/Concentration
3	Memory
4	Psychomotor/Equilibrium
5	Thinking
6	Orientation/Guidance
7	Conation
8	Intelligence
9	Pragmatism
10	Imagination
11	Language
12	Affectivity
13	Perception

categories selected according to the severity of the collateral effects, which represent the first layer nodes.

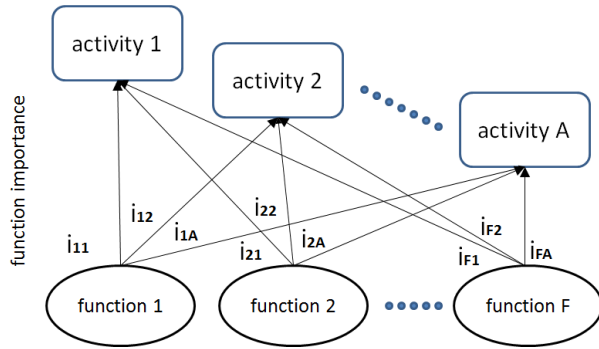
### 2) STRUCTURE OF THE SECOND LAYER (FUNCTIONS)

To set the second layer nodes it was done a criterious compilation of applied neuroscience works. In particular, [76] reviews the functions and mental processes occurring in different cerebral zones. After analysis by the expert's team 13 psychic functions, listed in Table 6, were identified as the most relevant and frequent in O&M activities, as described earlier in [77].

It is interesting to note that two functions above: Conation and Orientation/Guidance, are not found in the literature of human factors, so it deserves to be better studied by the human reliability community, in particular, to see if the impact of deficiencies in these two functions has already been considered to be somehow integrated into a broader concept/factor, or if they were simply neglected in all previous studies and models.

### 3) RELATIONSHIP BETWEEN THE SECOND (PSYCHIC FUNCTION) AND THIRD (ACTIVITY) LAYERS

Once the relevant psychic functions have been listed as well as the activities that make up the range of O&M tasks in the hydropower plants studied, it was time to establish the



**FIGURE 4.** Importance of Psychic Functions and Industrial Activities.  $i_{fa}$  = importance of psychic function  $f$  to activity  $a$ .

**TABLE 7.** Psychic functions related to some activities.

Activity	Psychic Functions
Monitoring	surveillance, attention/concentration, perception, memory, thinking, conation, pragmatism.
Inspection/Check	surveillance, attention/concentration, perception, memory, thinking, conation, pragmatism, language, psychomotor.
Sampling	surveillance, attention/concentration, perception, memory, conation, pragmatism, psychomotor, orientation/guidance.
Communication	attention/concentration, intelligence, language, memory, affectionateness.

relationships between functions (second layer) and activities (third layer), as shown in Figure 4. The weights that bind the nodes of the second and third layers were denoted as  $i_{f,a}$  and represent the *importance*, but based on the negative influence, of deficiencies in the completion of a given psychic function  $f$  during the execution of an activity  $a$ .

This way the output  $x_a$  (introduced in Eq. 5) of the third (activity) layer is given by

$$x_a = \sum_{f=1}^F i_{f,a} z_f, \quad \forall a = 1, 2, \dots, A, \quad (6)$$

where  $F$  is the number of psychic functions considered in the model, which in our case is 13, and  $z_f$  is the input at the second (function) layer, generated at the first (drug) layer. The way the  $z_f$  values were generated is addressed in the next section.

Table 7 shows the list of important psychic functions for performing four of the 18 activities considered in our model.

According to the choice of the experts involved, it was decided to use a qualitative scale to define the importance of psychic functions in activities. This scale, shown in Table 8, has 4 levels.

As an example, Table 9 shows the consensus for the activity Monitoring.

In our approach, once the importance of psychic functions is established for a given activity, they will be the same for all tasks in which that activity is performed, ie they do not change

**TABLE 8.** Qualitative Scale to Assign Importances of the Psychic Functions for the Activities.

Importance	Symbol
Strong	S
Moderate	M
Moderate on some cases or Rare	R
Weak	W

**TABLE 9.** Ordered assigned importances to the 13 psychic functions in the Monitoring activity.

Psychic Function	Importance to the activity
Surveillance	S
Attention/Concentration	S
Memory	S
Perception	S
Thinking	M
Conation	M
Pragmatism	M
Psychomotor/Equilibrium	R
Intelligence	R
Imagination	R
Language	R
Affectivity	W
Orientation/Guidance	W

from one task to another. In all cases in which there was doubt between two importances, the largest one was selected by consensus, aiming to build a conservative model.

As can be seen, Eq. 6 is not able to operate with qualitative variables. To solve this inconsistency, a quantitative (numeric) scale was associated with the qualitative scale established for the importance of psychic functions. This is discussed in the section III-C.

#### 4) RELATIONSHIP BETWEEN THE FIRST (DRUG) AND SECOND (PSYCHIC FUNCTION) LAYERS

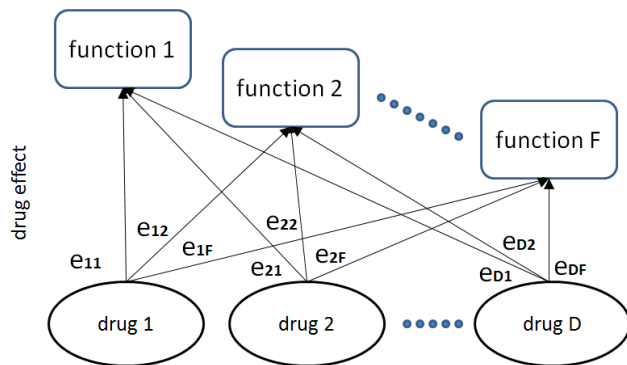
The links between the first and second layers is due to the negative effect of psychotropic drugs on psychic functions. The general interaction is shown on Figure 5. The strength of the known negative effect<sup>3</sup> of a drug  $d$  on a psychic function  $f$  is represented by the variable  $e_{d,f}$ , which is the weight that relates node  $d$  in the first layer to node  $f$  in the second layer.

This way the output  $z_f$  (introduced in Eq. 6) of the second (psychic function) layer is given by

$$z_f = \sum_{d=1}^D e_{d,f} u_d, \quad \forall f = 1, 2, \dots, F, \quad (7)$$

where  $D$  is the number of psychotropic drug types considered in the model, which in our case is 16, and  $u_d$  is the output generated at the first (drug) layer. In the current approach,  $u_d$  is a binary indicating whether an operator took drug  $d$  within the corresponding drug period of effect. This is recorded at the moment the operator fills in the job start sheet (in the

<sup>3</sup>Note that the positive (desired) effects of psychotropic medications are not considered in our approach. The positive effect is not supposed to increase the individual's psychocognitive abilities, but only to leave it in the normal condition of any operator with the same experience.



**FIGURE 5.** Effect of psychotropic drugs on psychic functions.  $e_{df}$  = effect of psychotropic drug  $d$  to psychic function  $f$ .

**TABLE 10.** Qualitative scale to evaluate drugs effects on psychic functions.

Symbol	Description
(++)	Relatively common or Strong
(+)	Can occur or Moderately strong
(-)	Absence or rare/Weak
(X)	Low

SARO system). If drug  $d$  was not used,  $u_d = 0$  and  $u_d = 1$  if it was used. If more than one drug is used, more than one  $u_d$  is equal to 1, which means that its effects will be added up.

However, since the first layer is the input layer, it can be modified by creating functions at its nodes to take into account other variables, such as the time since ingestion and the dose of the drug. This will be a subject that will be studied in the future.

A team of seven psychiatrists proposed a four-level qualitative scale, shown in Table 10, for the negative side effects of psychotropic drugs considered to degrade the relevant psychic functions shown in Table 6 over the psychic functions listed on Table 6. In the current approach, neither drug interactions nor drug dosing were taken into account, so the assigned effect was based on the use of single drug and at the nominal dose for the patient's gender and age.

In cases where the operator has taken more than one of the drugs considered to be dangerous, for example if he takes a medicine that combines several drugs, the simultaneous effect of all drugs is considered. In fact, drug interactions may reduce or increase the effect of single drugs on different psychic functions [14], [66]. However, complete and reliable data for these complex processes have not been found in the literature or experts consulted. Thus, it was decided not to include any terms of drug interaction in the model that could not even be qualitatively estimated in practice.

To illustrate the results of the experts, Table 11 shows the consensus of the psychiatric team's assessment of the degrading impact (in frequency and magnitude) of tricyclic antidepressant side effects on psychic functions. Four drugs were considered: Amitriptyline (A), Clomipramine (C), Imipramine (I) and Nortriptyline (N).

**TABLE 11.** Example of effects over psychic functions of antidepressant psychotropic drugs (Amitriptyline (A), Clomipramine (C), Imipramine (I), Nortriptyline (N)). Functions are ordered as in Table 9.

Psychic Function	Tricyclic Antidepressant			
	A	C	I	N
Surveillance	++	++	+	+
Attention/Concentration	++	++	+	+
Memory	+	++	++	+
Perception	++	++	++	+
Thinking	X	X	X	X
Conation	++	++	+	-
Pragmatism	++	++	+	-
Psychomotor/Equilibrium	++	++	++	+
Intelligence	-	-	-	-
Imagination	-	-	-	-
Language	X	X	X	X
Affectivity	-	-	-	-
Orientation/Guidance	-	-	-	-

Combining the data from Tables 9 and 11, it is clear that Clomipramine (C, second column above) is the worst drug for Monitoring activity. To guide the reader through the reasoning that leads to this conclusion, let us start by noting that the first 4 functions are the most important, i.e. the only ones rated as Strong (S) for the Monitoring activity in Table 9. Then, Looking now at the first four rows of Table 11, it can be noted that the sum of the effects of the first four rows is the largest (++) in the second column, corresponding to Clomipramine. The second worst drug is amitriptyline (first column of Table 11), which affects little less (+) memory function (third row) than Clomipramine, having the same effect as Clomipramine on the remaining 12 psychic functions.

The side effects of all subcategories of all categories of psychotropic drugs presented in Table 5 were evaluated following the described methodology.

### C. MODELING THE HUMAN RELIABILITY DIMENSION

In this section, we describe how all the layers in Figure 1 are connected, allowing us to calculate the negative effect of a given drug on a given task. The integration was made by a team of one psychiatrist, one ergonomist, one reliability engineer and two software engineers, following the consensus building methodology. The integration of our model took over a year and a half. This team was also responsible for overall project coordination.

Our definition of error is given by [78], [79], according to which an error is something that, although not intended by the actor or undesirable by a set of rules or an internal-external controller, led the task or system outside acceptable limits. In our case, the unscheduled shutdown of a safety/protection system or turbine, or the unintentional discharge of reservoir water or the increase of the reservoir water level above the safety level, for example, is outside the acceptable operating limits.

To quantitatively assess the impact of drug use on human reliability, the qualitative scales of Table 8 and 10 were transformed into quantitative ones, which implies attributing a numerical weight proportional to the expected contribution to human failures. Tables 12 and 13 show the attributed values

**TABLE 12.** Qualitative values of the psychic function relevance to the activity and their attributed value.

Function importance to the activity ( $i_{f,a}$ )	Attributed Value
S	1.000
M	0.500 (= 1/2)
R	0.250 (= 1/4)
W	0.125 (= 1/8)

**TABLE 13.** Qualitative values of effect of drug on psychic function and their attributed value.

Effect of drug on psychic function ( $e_{d,f}$ )	Attributed Value
++	1.000
+	0.666 (= 2/3)
-	0.333 (= 1/3)
X	0.000

for psychic function importance on activity ( $i_{f,a}$  used at Eq. 6) and the effect of drug on psychic function ( $e_{d,f}$  used at Eq. 7).

The maximum of both scales is the unit, but the minimum value is not the same. In the effect scale the smallest value is zero which indicates null side effect, but in the importance scale the smallest value is 1/8. This is due to the greater reliance on psychiatrists' estimates of the impact on psychic functions of drug side effects ( $e_{d,f}$ ) than on the estimates of ergonomists and reliability engineers on the importance of each function in O&M task activities ( $i_{f,a}$ ). Therefore, it was agreed that no psychic function would be considered totally irrelevant to any human activity, but that a drug could not affect certain psychic functions at all.

The vast majority of published studies on human reliability focus on high-risk areas such as the chemical and nuclear industry and rail and air transport. Studies can be classified according to their objectives into four categories: (1) to investigate whether accidents / incidents were caused by human or technical failure to settle legal responsibilities; (2) in case of human failure, identify the internal and external factors and the scenario in which they were caused, ie, identify the causes of accidents / incidents that induced human error to contextualize attenuating conditions, (3) evaluate the factors that lead to increased likelihood of human error under certain critical operating conditions that precede high-risk accidents (identified by experience or Probabilistic Risk Analysis) to improve: (i) working conditions; (ii) risk prevention management mechanisms and (iii) operator training programs (using simulators or not); (4) assess operational risk across different industrial sectors to establish insurance policy, loss coverage and premium.

It is worth noting that the first two goals are post-accident and the last two pre-accidents, but both have in common the extration of knowledge to be used to prevent further accidents.

The purpose of this paper is to present a methodology developed for pre-accident assessments, but which differs from objectives 3 and 4 above in several respects: (a) focuses on hydroelectric generation that is not classified as a high

risk industry; (b) endeavors to prevent incidents that cause interruptions in power generation or alteration of the voltage and frequency parameters of the energy produced, which are penalized by the ANEEL regulatory agency, (c) considers operating and maintenance personnel and tasks and (d) the result is the assessment of the contribution of psychotropic drugs to human error in routine O&M tasks in order to optimize the allocation of human resources to the tasks defined for each work session. It is done according to the human reliability assessment based on matching the effects of drug-types used by different team members with the demands of the tasks to be performed.

To quantify the contribution of psychotropic drugs to human error in an O&M task  $t$ , we need to combine equations 5, 6 and 7, ie, substituting  $x_a$  from Eq. 6 into Eq. 5 we have

$$y_t = \sum_{a=1}^A w_{a,t} x_a = \sum_{a=1}^A w_{a,t} \left( \sum_{f=1}^F i_{f,a} z_f \right), \quad (8)$$

and then substituting  $z_f$  from Eq. 7 into Eq. 8 we obtain

$$y_t = \sum_{a=1}^A w_{a,t} \left( \sum_{f=1}^F i_{f,a} \left( \sum_{d=1}^D e_{d,f} u_d \right) \right), \quad (9)$$

Finally, recalling that  $w_{a,t} = r_{a,t} n_{a,t}$  (Eq. 1) we obtain the explicit formula for  $y_t$  which is the *Psychotropic Drug Use (PDU) Contribution to Human Failure for Task  $t$* ,

$$y_t = \sum_{a=1}^A r_{a,t} n_{a,t} \left( \sum_{f=1}^F i_{f,a} \left( \sum_{d=1}^D e_{d,f} u_d \right) \right). \quad (10)$$

All the coefficients in Eq. 10 are stored in the knowledge database (PDIHR) for the selected tasks. The database is being gradually updated by a permanent experts team.

In the case of a single drug  $d$  use Eq. 10 reduces to the form

$$y_{d,t} = \sum_{a=1}^A r_{a,t} n_{a,t} \left( \sum_{f=1}^F i_{f,a} e_{d,f} \right), \quad (11)$$

from which we can extract the term in parentheses corresponding to a single activity  $a$ , denoted as  $\delta_{d,a}$ , in the form

$$\delta_{d,a} = \sum_{f=1}^F i_{f,a} e_{d,f}, \quad (12)$$

Equation 12 is adequate to illustrate the calculation process as shown in Table 14 for drug  $d$  = Amitriptyline and activity  $a$  = Monitoring.

Notice that the columns function importance and drug effect have two subcolumns, one with the qualitative scale and the other with the quantitative scale. The last column is the product of the importance and effect values. The sum of the last column is the  $\delta_{d,a}$ , which in this case is 5.5.

Thus Amitriptyline will contribute with  $5.55 * r_{\text{Monitoring},t}$  points every time the activity Monitoring ( $n_{\text{Monitoring},t}$ ) be executed in any O&M task  $t$ , remembering that  $r_{\text{Monitoring},t}$  is the relative relevance of the Monitoring activity in the task  $t$ .



**TABLE 14.** Calculation of  $\delta_{d,a}$  for the drug Amitriptyline in activity Monitoring.

Functions	Function importance		Drug effect		$i_{f,a}$ $e_{d,f}$
	Level	$i_{f,a}$	Level	$e_{d,f}$	
Surveillance	S	1	X	0.33	0.33
Att./Conc.	S	1	++	1	1.00
Sens./Perc.	S	1	+	0.66	0.66
Memory	S	1	+	0.66	0.66
Language	W	0.125	+	0.66	0.08
Thinking	W	0.125	+	0.66	0.08
Intelligence	W	0.125	+	0.66	0.08
Imagination	M	0.5	+	0.66	0.33
Conation	M	0.5	+	0.66	0.33
Pragmatism	M	0.5	++	1	0.50
Psychomot./Eq.	F	0.25	++	1	0.25
Affectivity	F	0.25	++	1	0.25
Orient./Guid.	S	1	++	1	1.00
Drug effect to the activity ( $\delta_{d,a}$ )					5.55

We performed these calculations for all activities and all drugs and stored the results in the PDIHR database.

However, as our main practical objective was to provide a way to optimize O&M staffing for different tasks, given that human reliability depends on psychotropic drug intake and task demands, normalization of  $\delta$ s is recommended. Normalization transforms absolute values, context- and situation-dependent quantities, into relative values, which are often independent of such conditions.

In our case, there are two normalization alternatives: (1) Absolute Normalization, dividing all  $\delta$ s by the theoretically possible  $\delta$  maximum value ( $\delta_M$ ) and (2) Relative Normalization, dividing all  $\delta$ s by the maximum value found in the data ( $\delta_{max} = \max(\delta)$ ). In the first case, the maximum possible  $\delta_M$  theoretical value may be extremely higher than the values observed in practice and, therefore, the normalized  $\delta$  values may be very small. Ergonomists and neuroscientists know that humans don't like to deal with very small or very large numbers. In the second option, as the knowledge database will be continuously fed over time, whenever a higher  $\delta$  value arises in the practice of using the system, it will be necessary to recalculate all coefficients that depend on that value. But this is not the greatest difficulty, but it will be very difficult to compare the  $\delta$ s themselves or their dependent data, which have been normalized using different  $\delta$  maximum values, compromising this way the analysis of the temporal evolution of any  $\delta$ -related indicator.

To avoid recalculations, we use  $\delta_M$  to normalize the  $\delta$ 's primary values. The maximum theoretical  $\delta$  is obtained in a hypothetical case where all the  $i_{f,a}$  and  $e_{d,f}$  coefficients in Eq. 12 are equal to one, whereby  $\delta_M = F = 13$ , ie equal to the number of psychic functions considered. Thus, the normalized  $\delta$ s are defined and denoted as

$$\hat{\delta}_{d,a} = \frac{\delta_{d,a}}{\delta_M} \quad (13)$$

and should be used instead of non-normalized  $\delta$ s. Note that the normalized  $\delta$  for the example with Amitriptyline drug and Monitoring activity is 0.4269, which is not such a small

number. Reliability engineers can use this result to perform human performance assessment on any task. The value obtained can be used to weight the effect of each drug to adjust the nominal HEP of the Monitoring activity.

The greatest uncertainty in the estimation of the various coefficients was observed when establishing the relevance of activities to tasks ( $r_{a,t}$ ) in Eq. 10. A high dispersion of estimates did not allow the establishment of reliable consensus values. We believe that more experts can help to narrow the best estimates, but it takes more time and resources. Conversely, estimates of activity frequencies in tasks were very consistent, with relative dispersion below 30%. Therefore, at this stage of the project we chose to disregard the relevance estimates (assuming all the coefficients  $r_{a,t} = 1$ ).

#### D. SPECIFICITIES OF THE USED HUMAN RELIABILITY ASSESSMENT METHODS

Among the various HRA methods three of them: THERP, SLIM and HEART, were developed for NPPs, so they are best suited for non-nuclear power plant applications [13]. In most HRA methods there are four kind of HEP:

- 1) The *nominal* HEP, which is the probability of a given human error when the effects of plant-specific PSFs have not yet been considered.
- 2) The *basic* HEP, which is the probability of human error without considering the conditional influence of other tasks.
- 3) The *conditional* HEP which is a modification of the basic HEP to account for influences of other tasks or events.
- 4) The *joint* HEP, which is the probability of human error on all tasks that must be performed correctly to achieve some end result.

Our objective is to evaluate how the *conditional* HEP (3<sup>rd</sup> above) calculated with these methods reflects the inclusion of the new Contributing Factor, measured by the  $y_t$  variable described in this article (Eq. 10). More specifically, how does the basic HEP change when the operator uses some psychotropic medication before performing a task. To do this, you need to know the nominal HEP of the task, calculate its basic HEP considering the effects of plant-specific PSFs, and then calculate the conditional HEP due to psychotropic drug use. In our case, we choose the path that requires the smallest set of procedural modifications in the selected methods. However, as the modifications depend on the HRA method employed, this section is devoted to a brief description of them.

##### 1) HEART

HEART method consists of five steps:

- 1) Classify the task in terms of its generic human unreliability into one of the eight generic HEART task types. The nominal HEP ranges from 0.00002 (0.000006 – 0.00009) to 0.55 (0.35 – 0.97). Let  $C_t \in [1, 8]$  be the selected class of the studied task  $t$  and  $P_n(C_t)$  be its nominal HEP.

- 2) Identify relevant Error Producing Conditions (EPCs) to the scenario/task under analysis to obtain the corresponding multiplier. Let  $EPC_{i,t} = 1$  if the  $i$ th EPC is relevant for task  $t$  and  $EPC_{i,t} = 0$  otherwise. There are 38 EPCs and multipliers ranges from 1.02 to 17.00. Let  $M_i \in [1.02, 17]$  denote the multiplier of the  $i$ th EPC. From these EPCs only one (the 30<sup>th</sup>) refers to the operators physiological condition: "Evidence of ill-health amongst operatives, specially fever" with a multiplier  $M_{30} = 1.2$ .
- 3) Estimate the proportion of effect (between 0 and 1) of each relevant EPC on the task  $t$  based on expert's judgement. Let's  $r_{i,t} \in [0, 1]$  denote the proportion of effect of the  $i$ th EPC for task  $t$ . If an EPC  $i$  is not relevant for a task  $t$  (that is  $EPC_{i,t} = 0$ ) then it has a null effect on the task  $r_{i,t} = 0$ .
- 4) Calculate the "assessed impact" ( $I$ ) for each EPC  $i$  such that  $EPC_{i,t} = 1$ , according to the formula:

$$I_{i,t} = (M_i - 1)r_{i,t} + 1$$

- 5) Calculate the Human Error Probability for task  $t$  multiplying all the EPC's impacts and then multiplying the result by the nominal HEP, based on the formula:

$$HEP_t = P_n(C_t) \prod_{i|EPC_{i,t}=1} I_{i,t}$$

## 2) SLIM

SLIM method consists of seven steps:

- 1) Selection of the members of Subject Matter Expert (SME) groups.
- 2) Selection of Tasks for Assessment.
- 3) Task Analysis - full verbal description of the task from SME group members so that the *task elements* (called activities in this paper) and personnel required, and the PSFs influencing task performance are clear to everyone.

Tasks are described by: Task Goals, task Activities, task Location, time available, task Characteristics/event description, task initiators, job aids, etc.

Activities are grouped into four categories:

- a) Equipment/Machine Operation: Open/close, position, maintain, calibrate, fill/drain, use, repair, test, start/stop, adjust, select, check, etc.
  - b) Cognitive Processes: Monitor, detect, calculate, categorize, compute, encode, extrapolate, identify, interpolate, interpret, itemize, read, recall, learn, remember, tabulate, translate, analyze, choose, compare, decide, diagnose, estimate, plan, predict, schedule, design, recognize, etc.
  - c) Supervision: Advise, verify, manage, inspect, direct, instruct, supervise, etc.
  - d) Communication/Social Processes: Write, tell, discuss, transmit, read, ask, confer, communicate, etc.
- 4) Classification of tasks into small subsets of tasks affected by the same PSF set. The purpose of task

classification is to identify common general factors that influence performance. A PSF may have a different classification for two tasks but still be relevant to the performance of both. For example, experts can identify the "amount of time available" as a factor influencing the performance of two tasks. The success criteria for a "pseudo reactive" task can be 30 seconds; but for the second "longer - more complex" task, it may take 2 hours.

- 5) Selection of Calibration Task - two tasks must be included in each group of tasks which are similar to the tasks already in the group and for which HEPs are already available. This pair of tasks in each group will be referred to as "calibration reference tasks" because they will serve as reference tasks for calibrating or transforming the Success Likelihood Indexes (SLIs) into HEPs for other tasks in the group.
- 6) Use of the SLIM form by each SME group for each subset of tasks, followed by the *direct numerical assessment* of SLIs that are later transformed into the HEPs of all tasks in all subsets by each group member.
- 7) Analysis and Interpretation of Results from SLIM sessions. Correlational and nonmetric multidimensional scaling analyses conducted to assess the inter-judge reliability of SLIM methodology for estimating HEPs.

SLIM consider six PSF families:

- 1) Job and task instructions: Includes written procedures, written and oral instructions and communications, cautions and warnings, plant policies, work methods.
- 2) Task and equipment characteristics: Includes man-machine interface factors, instrumentation, team structure and communication patterns, availability of feedback, task criticality, frequency and repetitiveness of task, perceptual requirements of task, workload, information load, complexity of task, motor requirements of task.
- 3) Situational characteristics: Includes characteristics of the work environment (temperature, humidity, air quality, radiation, lighting, noise, vibration, cleanliness), architectural features, staffing/manning parameters, organizational structure (responsibility, authority, communication channels), actions by other personnel, work schedules (hours of work, work breaks, shift rotation), rewards, recognition, incentives, benefits, promotions.
- 4) Psychological Stressors: Includes stress-related factors such as suddenness of onset, task speed, task load, perceived risk, threats of failure and loss of job, monotonous, degrading, or meaningless work, long, uneventful vigilance periods, conflicting motives of job performance (e.g., accuracy vs. speed) distractions (noise, glare, movement, display flicker, display color).
- 5) Physiological Stressors: Includes duration of stress, fatigue, pain or discomfort, hunger or thirst, temperature extremes, movement constriction, disruption of circadian rhythm.

- 6) Organismic Factors: Includes previous training, experience level, state of current practice or skill, personality and intelligence variables, motivation and attitudes toward work, emotional state, mental or bodily tension or stress, knowledge of required performance standards, physical condition.

### 3) THERP

THERP estimates human reliability considering the dependences among human performance, equipment performance, other system events, and outside influences, but explicitly accounting for recovery factors ie, the probability of detecting and correcting incorrect task performance in time to avoid undesirable consequences. In any man-machine system, there are usually several recovery factors, e.g., inspections that increase the probability of detecting errors before they affect the system. This method considers six types of tasks in NPPs:

- 1) Routine control room monitoring tasks, e.g., periodic scanning of panels.
- 2) Preventive and corrective maintenance tasks, e.g., replacing a defective part in a system.
- 3) Calibration tasks, e.g., ensuring that readings from detectors are within the expected tolerance.
- 4) Postmaintenance or postcalibration tests, e.g., a test to see that a repaired component/subsystem works properly.
- 5) Change and restoration tasks, in which the normal state of a component is changed to permit maintenance, calibration, or tests and then is restored to their normal state after completion of the work.
- 6) Recovery tasks - those involving additional actions to detect deviant conditions. Among them, four are most common:
  - a) Checking someone's work (human redundancy),
  - b) Noticing out-of-tolerance signals,
  - c) Active inspections, with focus on specific items of equipment, usually via written procedures, and
  - d) Passive inspections, as the basic walk-around inspection.

THERP also considers six basic *Activities*, called "task behaviors", while coping with unusual conditions:

- 1) Perception - noting that some alarms are triggered
- 2) Discrimination - identifying the parameter (or set of parameters) that better reflects the nature of the problem.
- 3) Interpretation - assigning the probable primary causes to the problem that was discriminated.
- 4) Diagnosis - determining the most likely cause(s) of the abnormal event.
- 5) Decision-Making - choosing between alternative diagnoses and deciding which actions to carry out.
- 6) Action - carrying out the activities indicated by the diagnosis, operating rules, or written procedures.

Assessment of HEP in THERP has three steps:

- 1) Select interest tasks according to reliability or availability.
- 2) Task Analysis - it is done using a graphic method called the *HRA event tree* that considers correct and incorrect human actions. In the tree, members represent a binary decision process, ie, correct or incorrect performance are the only options. Thus, in every binary branch, the probabilities of events must add up to 1.0. Members of the HRA event tree show different human *Activities* as well as different conditions or influences (PSFs) on those activities. The values attributed to all human activities represented by tree branches (except those of the first branch) are conditional probabilities, ie, they are calculated assuming the success of the previous activity. First members can also be conditional probabilities if they represent a transfer from another tree. On systems without redundancy (series), the entire set of human activities must be performed correctly for system success to be achieved, but on redundant (parallel) systems, not necessarily homogeneous, failure will occur only if all human activities are performed incorrectly.
- 3) Estimate the relevant error probabilities. Once the HRA event tree is drawn correctly and the estimates of the conditional probabilities of success or failure of each tree member have been determined, the math is simple. The HEP of each path through the tree is calculated by multiplying the failure probabilities of all members in the path. Choosing the path with the highest probability of failure (or least probability of success) defines the HEP of the considered task.

In the following section, we describe an example task, how drug impact was included in the calculation procedure of each selected HRA method, and the HEPs calculated with (conditional) and without (basic) psychotropic drug use.

## IV. CASE STUDY

Of the 29 tasks considered most critical from a safety and availability standpoint, listed in Table 2, one (Operator Routine Inspection) was selected to illustrate the applicability of the method. A software developed called SARO - Sistema de Avaliação do Risco Operacional (*Operational Risk Assessment System*) based on the knowledge database and network structure was used.

Routine operator inspection is a common task considered of low complexity by most operators. The inspection has times to determine if a fault has occurred or is about to occur by identifying abnormal equipment states. The decision depends on the scenarios and perception created in the operator's mind. The task seems simple, however, there are many equipment that must be inspected. If the number of equipment increases, the number of activities increases and the task becomes increasingly complex.

Routine inspection at hydroelectric plants includes checking up to 35 different equipment on the inspection route with an average of 8 control points on each equipment;

**TABLE 15.** Comparative of the use of Amitriptyline and not use in the HEP for Operator Routine Inspection task.

HRA Method	basic HEP (No drug use)	conditional HEP (Drug use)	HEP Increase (%)
SLIM	0.40	0.54	35.0%
THERP	0.38	0.51	34.2%
HEART	0.60	0.69	15.0%

therefore, the task requires a total of 280 inspection points. Some ergonomic aspects, such as the design of equipment that makes it difficult to access inspection points increase the likelihood of human failure.

## V. RESULTS

The nominal HEP of the *Operator Routine Inspection* task in SLIM is 0.0002. We considered 8 PSFs: layout of workspace, the pressure of time, lighting, inspector experience, workplace interruptions, inspection points accessibility, task complexity and the organization support for decision making. The basic HEP of this task was 0.4.

In HEART the HEP of the visual inspection of one point is 0.03. However, the task is a multi-point inspection on various elements of equipment. We considered an scenario where 8 points of 35 different equipment are inspected within 4 hours of service. For this new condition, the basic HEP was 0.6.

The THERP method was tested using in each branch of the event tree a sequence of three activities for each Inspection point. The nominal HEP of inspection task has a probability of 0.0002. This value was used in all branches of the tree because is the same (inspection-diagnosed-action). The basic HEP was 0.38.

In the above assessments for the calculation of basic HEP the effect of psychotropic drugs was not included. Now, to calculate conditional HEP due to operator ingestion of a dose of Amitriptyline one hour before the start of work,  $y_{d,t}$  calculated according to Equation 11 was used as a multiplier of PSFs related to cognitive and sensory-motor functions. Table 15 shows the basic and conditional HEP calculated by three HRA methods when the new PDU-PSF was considered.

As can be seen on Table 15 the HEP values after the inclusion of the amitriptyline effect were greater than initials, varying from 15% for the HEART method to 35% for SLIM method. Applying the method described to include the Psychotropic Drugs Use (PDU) as an influencing factor in human reliability assessments significantly increased the likelihood of human failure in a moderately complex activity due to the operator's prior ingestion of a commonly used drug to reduce stress and anxiety.

## VI. DISCUSSION

The definition of all the relative relevance of the activities to all tasks  $r_{a,t} = 1$  was a tough decision, because including relevance was one of the key elements of the approach at the beginning of the project. However, it was very hard to reach a consensus on the impact of each activity, and a generalized solution would not be possible since a new assessment would be required for each specific task. The frequency of the

activity ( $n_{a,f}$ ) became the most important variable and it was verified that it is very simple to obtain this data when applying a systematic task analysis.

Another area in which our team of experts experienced a high degree of uncertainty was in establishing the strength of the influence of sensory-cognitive-motor functions on operational activities, facing a complete lack of previous results on the subject. The estimates obtained will be shared with the community of cognitive ergonomics and neurosciences as a starting point for a discussion leading to knowledge enhancement. These estimates are the connections between the second and third layers and can be adjusted by regression with operational error data.

Words mean different things to different people; consequently, there is uncertainty associated with any word used. There are three different universes of discourse in the proposed work, so the final results have a composition of the uncertainties of each one. The process of building the knowledge database that underpins the developed methodology depends on expert judgment, so the immeasurable subjective component of the judgment causes uncertainty. In addition, work in psychiatry is not an exact science and is based on experience with each specific drug and multivariate analysis of each patient's condition.

Uncertainties can have a significant impact on method results, but as the purpose of this paper is to present an instrument to begin measuring a neglected human performance influencing factor so far, quantifying the sensitivity of the result to uncertainties in the model parameters will be subject to future works. However, the authors are aware of this problem and the results obtained are considered grounded guidelines, but not determinant statements.

In spite of all the uncertainties, we believe, as mentioned in the introduction of this article, that our contribution to the improvement of human reliability analysis of operators of socio-technical systems in general is relevant for two reasons: (1) Considers for the first time the effects derived from the use of psychotropic drugs, an increasingly common event in our society, and (2) In matters related to risk control and / or reliability assessment, it is always advisable to use a method for evaluating influencing factors even if it depends on uncertain parameters, rather than not applying the method.

## VII. CONCLUSION

The use of psychotropic drugs is becoming increasingly common among operating and maintenance personnel in the industry and their effects should be considered in human reliability analysis. The presented method, based on a conceptual-mathematical model, is a way to include the use of psychotropic drugs as a factor of influence in human performance.

The method was designed to establish the impact of a specific drug on the execution of a task, broken down into a sequence of sensorimotor-cognitive activities, by an operator who is not mentally ill but who used the drug shortly before or during his workday, for some reason, justified or not.



The connection between a drug and a sensorimotor-cognitive activity is established through the product of drug effect on a given set of psychological functions and the relevance of those functions to the performance of said activity.

The applicability of the method was illustrated with a simple task carried out by a hydropower plant operator who took Amitriptyline. A PSF is calculated and used as input for three common HRA methods in power plants: SLIM, HEART, THERP. In this study case, the Human Error Probability (HEP) increased between 15% and 35% depending on the HRA method.

One of the expected contributions of this work is to establish the data needed to build a Knowledge Database (KDB) that supports the evaluation of the impact of the use of psychotropic drugs in human reliability. This KDB can be useful as a standard to collect human failure data. The experience of applying this instrument will support risk analysts and reliability engineers in their decision-making process.

Although there is a natural uncertainty in the model parameters associated with insufficient current knowledge the practical use of the developed system (SARO) will allow adjustment to the parameters over time.

So-far, the method is being used to optimize the allocation of human resources to the tasks defined for each workday in eight Brazilian hydroelectric plants. From a human reliability perspective, the method takes into account the type of drug taken by team members and the characteristics of scheduled tasks.

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