DEVELOPMENT OF HUMAN MACHINE INTERFACE (HMI) FOR DIGITAL CONTROL ROOMS IN NUCLEAR POWER PLANTS

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ABSTRACT

The analog control systems of traditional Nuclear Power Plants (NPPs) are being replaced by digital systems due to the fact that analog Instrumentation and Control (I&C) systems are becoming obsolete and such technology is no longer supported by manufacturers. The purpose of this study is to jointly evaluate the performance of an operator with a Human Machine Interface (HMI) in a NPP digital control room ensuring the efficiency and the safety of the NPP. The validity and the accuracy of the operators' actions are the primary goals that have to be preserved through the emergence of the HMI based in digital systems. The transition from analog to digital control systems leads to a more advanced support of the NPP; Video Display Units (VDUs) are used for monitoring the state of the NPP while alarm systems help for directing attention. The operators, in order to monitor information from the different VDUs, have to switch attention between different screens (alarms systems and control systems). Therefore, a well-established HMI is a significant challenge to the overall operation of the NPP, that actually helps the operators to learn from the available information in detecting possible anomalies and making the right decisions, to ensure safety, and in parallel to diminish the human error.

Key Words: Digital Control Room, Nuclear Power Plant, HMI, Fuzzy Logic

1 INTRODUCTION

The transition from analog to digital systems changes the way that the human operator interacts with those systems. The operation of many of Nuclear Power Plants (NPPs) in the United States is changing over to the era of digitalization. The shift from conventional-analog to digital control room for NPPs provides different ways of interacting between the human and the system, mainly via four aspects: environment, task, machine and human [1]. Moreover, it provides more ways for advanced support; individual alarm screens, computer-based processes, and large displays to help increase situational awareness. In digital main control rooms (MCRs), the operator's workload is reduced and the accuracy of their actions is improved. Generally, there are various characteristics that make the difference between analog and digital control rooms as aforementioned, but these characteristics can add further workload on operators. More specifically, in an analog MCR the operator can have the full scope of the NPP status visible on the panels, while in a digital MCR the operator utilizes computer based procedures which may mask risks [2]. So, human errors, either in analog or digital systems, may not be completely wiped out. However, the error can be managed using effective methods. The purpose of this study is to develop an HMI evaluator using Fuzzy Logic that may be contributed to enhance safety reduction of human errors in control rooms. The HMI evaluator combines features from both the machine and the human factors introducing the opportunity to integrate information about humans and machines at the same time. Generally, the HMI in a digital control room is the "vehicle", where information about the state of the power plant is translated into required operator actions in order to help them make decisions.

Much attention has been paid to Human Machine Interfaces and to the evaluation of the human performance in digital MCRs of NPPs the last decades. The authors in reference [2] made an extended comparison between the conventional and the digital control room using as a comparison measure the task complexity. Also, higher attention has been paid to performance of the operators and more specifically to the human factors that affect their performance, than to the machines [3]. The authors in reference [4] have developed and designed an evaluation system of operator performance in NPP MCRs considering only human performance aspects such as personnel task performance, physiological factors, and situation awareness. To cover the deficiencies that the HUPESS (Human Performance Evaluation Support System) has, the authors in reference [5] have developed a methodology of HMI. They try to improve the monitoring and detection tasks through DEMIS (Difficulty Evaluation Method in Information Searching) which is an HMI evaluation method which integrates poor human performance and design improvement. In reference [6] human performance measures, including plant performance, situational awareness, and workload are considered in order to validate, measure, and evaluate the performance of the operator in the digital MCR of the APR-1400. Moreover, the OECD Halden Reactor Project has focused on studying human factors in the nuclear area [7]. Additionally, the authors in reference [8] make an effort to evaluate the human factors in advanced control rooms of a nuclear power plant *a priori* to any of the operations of the NPP. Two stages of interviews follow the alarm operation procedure and the emergency operation procedure. The interviews are conducted in order to identify and eliminate the human errors associated with the procedures of the first step. The tasks that the operator has to cope with in an NPP are too complex and time consuming. The authors in reference [9] propose a balancing principle for the optimization of the HMI design. The proposed integrates into a single formula the HMI elements, the design, and the importance attributes. In reference [10], the LABIHS simulator is utilized in order for the proposed methodology to be applied focusing on the validation of the solutions performed during the design process. The authors in reference [11] propose a set of response procedures which the operators can follow when severe and unforeseen accidents occur. According to the authors, the proposed procedures provide an additional level of protection which the experience of the operator and other metrics cannot provide

A well-established HMI is an enormous challenge to the operation of an NPP, that can actually help the operators learn from the available information by detecting possible anomalies and making the right decisions, to ensure safe operation and in parallel to diminish human error. More specifically, the HMI has to provide the operator with a means in order to assist the operators to restore the NPP to operating normal status when they are coping with unforeseen events. The primary design goal of such an HMI evaluator is to compute the performance of the operator under specific circumstances (normal, and abnormal operation of the NPP) in order that the most appropriate operator may be selected in a case of hiring or evaluation. Moreover, elimination of human errors, more efficient control functions, and improved reliability in the control room are secondary design goals of the HMI evaluator. Thus, an HMI evaluator is necessary in order to ensure the performance of the operator under digital MCRs and to enhance in that way the safety of NPPs. The OAKFLAT[1] simulation engine is used as a data generation system, creating values related to the machine factor. It is worth mentioning that the OAKFLAT simulator is analog based but it is used only for generating some values of the variables for the proposed HMI evaluator for digital control rooms. The remainder of this paper is organized as follows: in section 2 and 3 the proposed methodology and the evaluation results are presented respectively. In the last section some concluding remarks are denoted.

2 PROPOSED HMI EVALUATOR

The HMI evaluator is designed as a joint system associated with the human and the machine influence for the operation of the NPPs. The proposed evaluator is an extension of the evaluator described

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[1] http://www.gamtech.com/oakflat.aspx

in reference [12]. More specifically, a two layer fuzzy-based evaluator (see Fig 1.) which combines the characteristics concerning both human and machine factors is developed. On one hand, the first layer is associated with the machine and, more specifically, its output yields how higher the operational risk of the NPP is due to the various values. The higher the value of the output, the higher the risk. On the other hand, the second layer corresponds to the human factor and it provides the reliability (physical and mental) of the operator to cope with unforeseen events and the normal operation of the NPP. The final output of the joint system gives the overall performance of the operator under a specific operational state of the NPP.

The fuzzy logic system (FLS) that is associated with the human factor consists of four sub-fuzzy logic systems. More precisely, the first one is associated with the fatigue of the operator which is the result of the integration of the number of sleeping hours and the consecutive days that the operator has worked. The second fuzzy logic system combines the physical with the mental fatigue as measured through the stress of the operator. The third one integrates the simulation score of the operator and the operator's average training hours in digital MCRs. The output of the last fuzzy logic system and the output of the second one are combined into a forth fuzzy logic system with the experience of the operator to be the third input of the forth fuzzy logic system. The output of the forth fuzzy logic system is the final output regarding of the triangular shape is utilized to represent the membership functions of the fuzzy variables. The number of the IF-THEN rules for each sub-fuzzy logic system is different. The number of rules for the FLS called *Machine* is 54. The number of Rules for the FLSs called *OperEfficiency, Fatigue, Psychology* and *HumanOutput* is 9, 12, 6, and 27, respectively. Furthermore, the number of rules of the *Joint* FLS is 20.

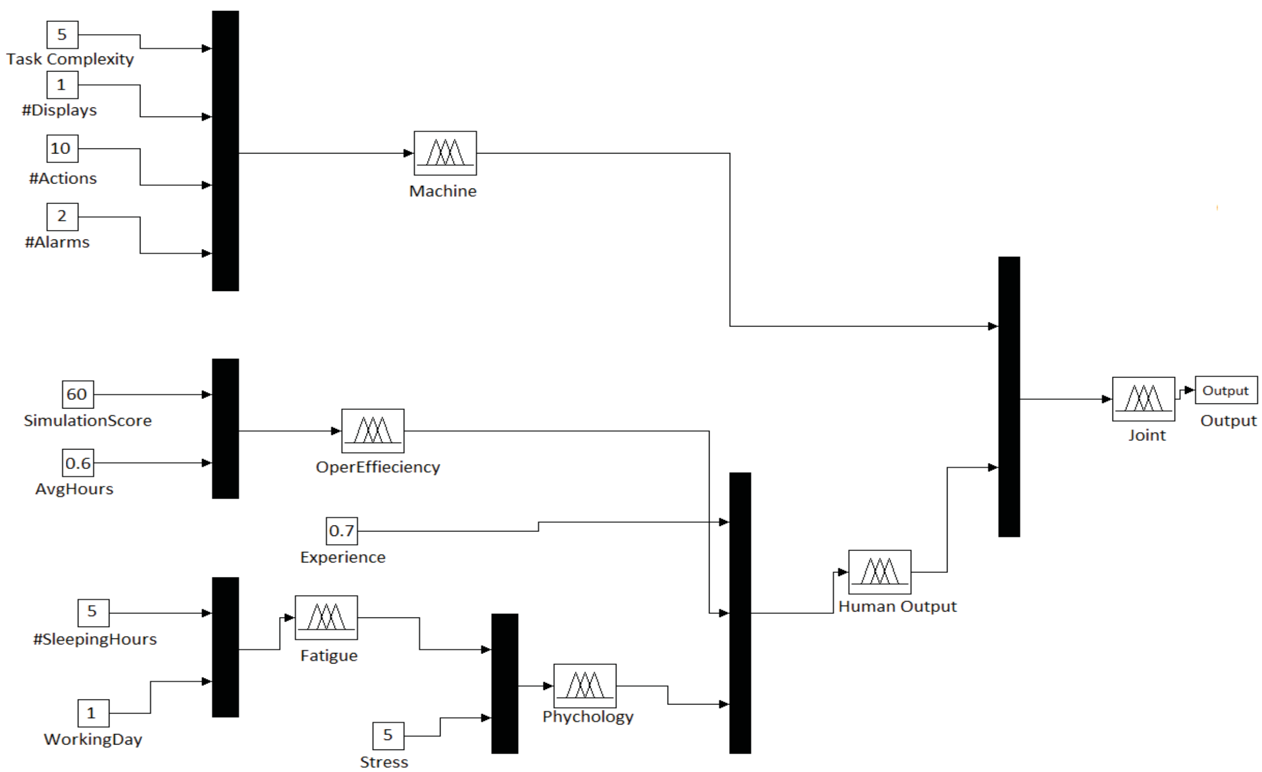

Figure 1. The architecture of the proposed HMI evaluator.

2.1 Human Factors

In complex and large systems like NPPs, the human reliability is the most significant factor. Human errors can lead to irreversible system failures. Therefore, a well-established HMI evaluator can prevent human errors leading in that way to the safe and reliable operation of NPPs. Human reliability is expressed both in qualitative and quantitative terms [13]. Regarding the qualitative term, it is considered as the humans' activities needed in order the operation of the NPP to be safe and reliable. The quantitative term is associated with probabilities regarding their errors. In the next segments the features regarding the human factor are described in more detail. Before getting into more details about human reliability features it is worth mentioning that we combine the features into different fuzzy logic systems in order to generate the output associated with the human factor. More specifically, the simulation score and the average training hours of the operator give the efficiency of the operator at a simulated NPP. Regarding the fatigue of the operator, it is affected by the hours that the operator slept the previous day, the number of days that he has been working, and the time of the day. So, the fatigue is the output of another fuzzy logic system which takes as input the aforementioned features (see Fig. 1). The operator's physical health (the fatigue) is combined with the psychology of the operator, using his stress, in order to take his physical and mental fatigue. The experience of the operator, the physical and mental fatigue, and the efficiency of the operator are utilized as three inputs of the fuzzy logic system which gives the reliability of the operator.

2.1.1 Simulation Score

Over the last few decades, a full-scope simulator has become a major tool that is used more and more for NPP operator training. So, it is meaningful to use the simulation score of the operator to measure how efficiently he reacts under emergency conditions or normal ones. In this study and especially in the proposed evaluator the value range of the variable *SimulationScore* is 0 to 100.

2.1.2 Average Training Hours

Besides the Simulation Score, the average training hours of the operator in digital MCRs is also included as input in the evaluator. The daily education and training of the operator is necessary to ensure safe and efficient operation of an NPP by giving the opportunity to the operator to develop their skills for controlling the functions of the NPP under normal and emergency conditions. To calculate the value range regarding the average training hours, we made the assumption that the days that the operator can be trained is 270, hence 2160 hours for 8 hours of training per day. More specifically, the value of the feature average training hours is the ratio of the operator's training hours to 2,160 hours. Therefore, the range of the variable *AvgHours* has to be from 0 to 1. The higher the value of the *AvgHours* variable the more hours, the operator has been trained.

2.1.3 Number of sleeping Hours

Regarding the sleeping hours, it is a feature that mostly affects the operator's fatigue. The range of the variable *#SleepingHours* is 0 to 8 in the proposed evaluator.

2.1.4 Working day

The operators have to be on alert continously during their shifts. In this study we assume that the operator works on a three 8-hour shift. In order to include the time of the day we assume that the first shift is a morning shift, the second one an afternoon shift, and the third in the row is a night shift. It is worth mentioning at this point that the specific feature is developed as a crisp set. Moreover, choosing the three-day based shifts, we declare that the third day the probability of the operator making mistakes is higher due to the fact that it is on his last day of his shift. Moreover, the shift during the night is the most dangerous and risky period for human errors [14].

2.1.5 Fatigue

As mentioned previously, the fatigue (variable *Fatigue* in the FLS) is the output of a fuzzy logic system which combines the sleeping hours and the working day. Its range is from 0 to 10 with the 0 and 10 to correspond to low and high fatigue respectively.

2.1.6 Stress

Stress has been identified to have the most significant effect on human performance, especially in complex systems like the NPPs. The operator's stress is affected mostly [15] by environmental factors, time pressure, complexity of a task, high overload, and loss of critical information. In this study, we model the stress to take values in the range from 0 to 10. It is worth mentioning that the stress and the complexity of the task which are inputs of the proposed evaluator are related. More specifically, the higher the task complexity is, the higher the stress of the operator to cope with the task is.

2.1.7 Experience

The performance of an operator is affected on digital MCRs by his experience on both traditional analog and digital MCRs. The operator can react quickly in the digital MCRs if he has more years of experience in digital control rooms rather than in the conventional ones. This is due to the fact that the operator has the knowledge and the experience to automatically take some actions without any required thoughts about his next move. The value of *Experience* variable is from 0 to 1, which denotes that the higher the value is the more qualified the operator in digital MCRs is.

2.2 Machine Factors

2.2.1 Complexity of the task

Each task for the safe and reliable operation of the NPP has a different degree of difficulty. The operator in an NPP has to cope with different tasks during his shift. The difficulty of the task may affect the overall performance of the operator, leading to errors that are important with respect to the safe operation of the NPP. The value of the *TaskComplexity* variable ranges from 0 to 10.

2.2.2 Number of displays

The operator workstation consists of four main screens [16]; Dynamic Alarm Console (DAC), System Information Console (SIC), Safety Related Information Console (SRIC), and Computerized Operating Console (COC). Besides the screens that the operator has to control at the workstation, there is the Large Display Panel (LDP) placed on the front of the operator's workstation. The operator has to control during his shift the LDP, the SIC, and the SRIC and the other workstation screens regarding the state of the NPP. More specifically, DAC is associated with abnormal events in the NPP, while the COC provides all the necessary information about the strategies that the operator has to follow after a scram of the reactor. The value of *#Displays* variable can be either 0 or 1; low number of screens or high number of screens, respectively.

2.2.3 Number of actions

Each operator may follow different strategies in order to face each unforeseen or normal task of the NPP. The most experienced and qualified operator propably can select the easiest and quickest way to solve a problem. This is an aftereffect of his experience of how he has to react at abnormal or normal conditions. Because of that the number of actions (*#Actions*) in our evaluator ranges from 0 to 15.

2.2.4 Number of alarms

In digital MCRs, the presentation of alarms is totally different in contrast to analog ones [17]. For example, the APR-1400 presents the alarms as an alarm list using alarm symbols on the Large Display Panel of the control room. The alarm list is text-based presenting the thresholds of the variables related to the alarms of the NPP operation functions. It is more convenient and efficient for the operator to look at a part of the LDP for the alarms of the system. For the processing of the alarms, there exist four main functions (a) sorting alarms according to priority, time, (b) suppressing alarms according to NPP state, (c) the multisetpoint relationship, and (d) filtering alarms. We chose arbitrarily the number of alarms (*#Alarms*) to have an upper limit of 15 due to the fact that there was not a specific number found of how many functions related to the alarm list. We made the assumption that this number of alarms is a good representative in order to measure the performance of the operator under specific kinds of alarms.

In Table 1 the range of each variable for both human and machine factors is presented in detail. The rows with the "down-right diagonal" pattern indicate the output of the sub-fuzzy logic systems, while the "up-right diagonal" pattern (Machine, HumanOutput) indicates the inputs for the final FLS for which its output is the row which is indicated with the "vertical" pattern (Joint). It is worth mentioning that there are more factors that may influence the alterness of the operator. These include the humidity, the ambient temperature, the lighting, and the design of the control room. Improper values of these factors may influence the fatigue, the attention, and the overall performance. In this study, we made the assumption that these factors are configured properly in order not to affect the behavior of the operator eliminating in that way errors due to those factors.

Table I. HMI variable ranges.

Fuzzy variable	Ranking	Linguistic terms
TaskComplexity	0-10	Low, Medium, High
#Displays	1-2	Low, High (crisp)
#Actions	0-15	Low, Medium, High
#Alarms	0-15	Low, Medium, High
Machine	0-10	Low, Medium, High
SimulationScore	1-100	Low, Medium, High
AvgHours	0-1	Low, Medium, High
OperEfficiency	0-10	Low, Medium, High
#SleepingHours	0-8	Low, Medium, High
WorkingDay	1-4	1^{st}, 2^{nd}, 3^{rd} (crisp)
Fatigue	0-10	Low, Medium, High
Stress	0-10	Low, Medium, High
Psychology	0-10	Low, Medium, High
Experience	0-1	Low, Medium, High
HumanOutput	0-10	Low, Low+, Medium, Medium+, High
Joint	0-10	Low-, Low,Medium, Medium+, High, High+

3 EVALUATION RESULTS

In this section, the evaluation results obtained from the proposed evaluator are presented. For the test cases the OAKFLAT[2] simulation platform was used as a data generation system, taking the values for (a) the number of actions, (b) the number of alarms the operator has to deal with, and (c) the number of displays-parameters he has to observe. The values taken from the simulation engine are related to the values of the variables associated with the machine factor. In Fig. 2, the interface of the OAKFLAT

[2] http://www.gamtech.com/oakflat.aspx

simulation engine is depicted. It consists of 6 main components: the warning lights, the status line, the reactor diagram, the command line, the help line, and the main control display.

For evaluating the performance of the operator three different cases are considered. More specifically, the simulation days parameter of the simulation engine is used as the main one to design the cases. The less the simulation days, the more complex the task becomes. In particular, the operator has less time to complete a task, so the risk of error is high. The time for completing a task is of uppermost importance for the safe and reliable operation of an NPP. So, in the first case the number of simulation days is 15, in the second one 20 and in the third case 25. In all the cases the task is the same; the simulation score has to be 20,000 or above and the core temperature not to be higher than 600°F. The three cases are conducted for three different operators considering their experience in the simulation engine; an operator who has high experience, one with medium and one with low experience is used.

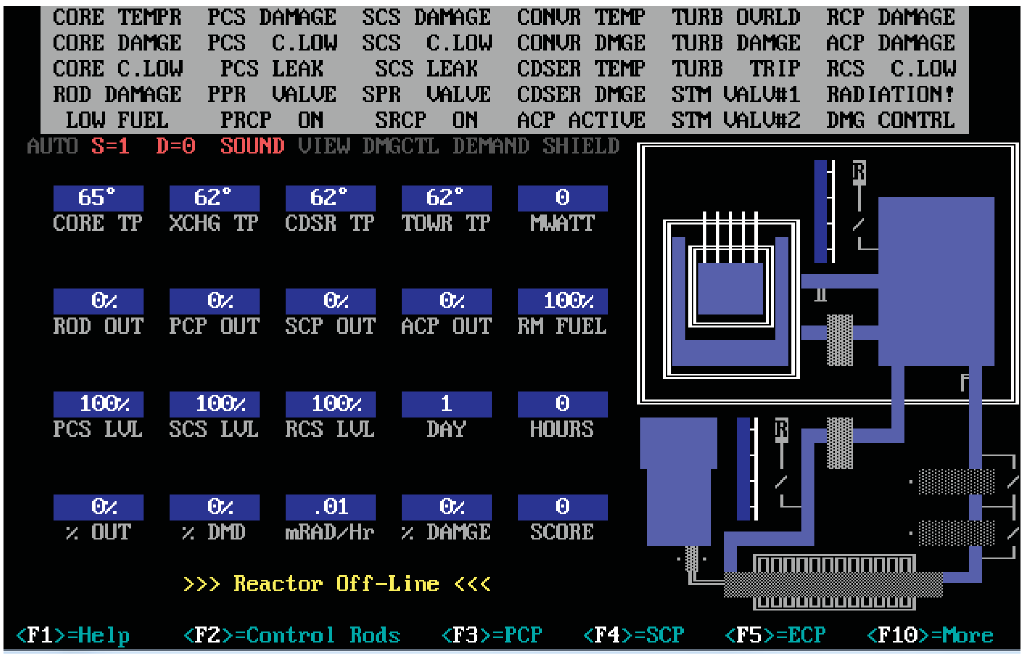

Figure 2. OAKFLAT Simulator's engine Interface[1].

More specifically, in Table II the configuration of the test cases, and more precisely the value of each fuzzy variable and the final output of the Joint system are presented in detail. It should be mentioned that the higher the value of the final output, the higher the performance of the operator. In particular, as aforementioned, the number of operators is three with different experiences in the simulation engine. The variables *SimulationScore* and *AvgHours* are strictly related to the experience of the operator. So, the lower the operator's experience, the lower the *SimualtionScore* and the *AvgHours* have to be. The value of the *TaskComplexity* variable is associated with the case which is considered. For instance, in the case where the simulation days is 15, the value of the *TaskComplexity* variable is 10 due to the fact that it is more difficult to complete a task when the time is limited. Therefore, the value of the *TaskComplexity* variable is 5 and 1 when the simulations days are 20 and 25, respectively. It should be mentioned again at that point that the operators' stress is also related to the complexity of the task and the experience, so the value of the *Stress* variable follows the value of the *TaskComplexity* variable. In order for all the cases to be covered, three different values for the *#SleepingHours* and *WorkingDay* variable are utilized. In particular, we can validate how the operators' performance is affected primarily by the task and second by the human factors such as how many hours he slept, and how stressed he is.

In the next lines, a brief description of the results of each case for each different operator is presented. Regarding the results associated with the operator with the low experience (**Operator 1** in

Table II), it is clear that in **Case 1** where the value of the simulation days is 15, the operator needs more actions and he has to cope with more alarms in order to complete the assigned task. Due to the fact that the operator has to change the rod output in order to increase the simulation score and keep the temperature balanced, a wrong value due to his low experience may lead to overheating of the reactor; more alarms that the operator has to resolve come up. The output of the HMI evaluator is **0.71** for **Case 1** and **2.5** for **Cases 2** and **3**. The output of **Cases 2** and **3** is the same due to the fact that both the number of actions and the number of alarms belong to the same fuzzy set for both cases; HIGH and LOW respectively; so the final output is not affected.

Table II. Evaluation results of the cases with the three different operators.

	Operator 1			Operator 2			Operator 3		
Fuzzy Variable	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
TaskComplexity	10	5	1	10	5	1	10	5	1
#Displays	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
#Actions	15	10	9	14	11	7	12	9	4
#Alarms	13	2	4	8	6	5	7	4	5
Simulation Score	10	10	10	55	55	55	100	100	100
AvgHours	0.2	0.2	0.2	0.55	0.55	0.55	1	1	1
#Sleeping Hours	2 5 8	2 5 8	2 5 8	2 5 8	2 5 8	2 5 8	2 5 8	2 5 8	2 5 8
Working Day	2 1 0	2 1 0	2 1 0	2 1 0	2 1 0	2 1 0	2 1 0	2 1 0	2 1 0
Stress	9	9	9	5	5	5	1	1	1
Experience	0.2	0.2	0.2	0.4	0.4	0.4	1	1	1
Joint	0.71	2.5	2.5	4.5	7	7	7	9	9.11

Going through the results of the case in which the operator has medium experience (**Operator 2** in Table II), it can be observed that the operator takes less actions and he has to cope with less alarms only for **Case 1** and not for **Cases 2** and **3**. However, this affects positively the performance of **Operator 2** despite the fact that the values of both the number of actions and number of alarms belong to the same fuzzy set for both operators (**Operator 1** and **Operator 2**), due to the fact the **Operator 2** is more experienced and less stressed. At that point it has to be noticed that the experience of the operator has a significant role in his overall performance dealing with complex tasks. As regards the final case which is associated with the operator with the highest experience (**Operator 3** in Table II), it can be observed that the final output of the HMI evaluator is the highest one. In that case the operator's performance, due to his high experience; the low number of the actions, and the number of alarms, is the result of the joint FLS which integrates the highest output (**9.30** out of 10) of the human factor and the lowest one (**1.58** out of 10) of the machine factor which indicates low risk for the operation of the of the nuclear power plant.

Overall, it is strictly observable that the lower the experience of the operator the higher the risk is for the operator to make mistakes during the completion of a task. Besides the results that are associated with the data that are driven from the simulation engine in order to prove the validity of the proposed evaluator we ran some additional test cases (see Table III) with random values for all the fuzzy variables. In the test cases presented in Table III, some extreme cases and some simple ones are included. Concluding from all the results (Table II and III) it is clear that the influence of the *#SleepingHours* and the *WorkingDay* is not as important as the *Experience*, the *Stress*, the *SimulationScore* and the *AvgHours* when considering the human factor. On the other hand, considering the machine factor the *TaskComplexity*, the *#Actions*, and the *#Alarms* have the same influence on the final output.

Table III. Evaluation results of the cases with random values to the fuzzy variables.

Fuzzy Variable	Case A	Case B	Case C	Case D	Case E
TaskComplexity	0	10	10	0	5
#Displays	0	1	1	0	1
#Actions	0	15	15	0	10
#Alarms	0	15	15	0	2
Simulation Score	100	100	0	0	60
AvgHours	1	1	0	0	0.6
SleepingHours	8	8	2	2	5
WorkingDay	0	0	2	2	1
Stress	0	0	10	10	5
Experience	100	100	0	0	0.7
Joint	9.11	7	0.70	4.5	7.5

4 CONCLUSIONS

Concluding, a single evaluator gives the opportunity to calculate the performance of the operator under the different phases of a nuclear power plant operation; startup, normal operation, shutdown, and postulated accidents. Moreover, the different types of the digital control systems associated with the average hours that the operator has been trained in a simulator exhibits a direct relation and influence of the machine on the performance of the human.

In this study, an evaluator is proposed using fuzzy logic theory in order to jointly evaluate the performance of the operator and the HMI in a NPP. The evaluator platform consists of two main components; the human factor and the machine factor. By integrating both the human and the machine factor in a joint system, the more information from different sources is used in order to measure the performance of the operator under specific circumstances in the operation of the NPP. The results show that the performance of the operator is affected primarily by the experience of the operator either in a simulated-based or a real-based NPP, and the complexity of the task. The highest performance is 9.11 and the lowest one is 0.70 which is the output of the evaluator when we take for the human the highest values for the human factor and the lowest ones for the machine factor and the opposite, respectively.

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