32^{nd} European Modeling & Simulation Symposium
17^{th} International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 ISBN 978-88-85741-44-7 © 2020 The Authors.
DOI: 10.46354/i3m.2020.emss.014

A Shannon Entropy graph-based model to evaluate the operator mental workload involved in procedure-guided tasks

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Abstract

Recent studies showed that an increasing number of procedures are available in industrial processes, in fields such as maintenance and safety. In many cases, the complexity of a procedure requires a decision-making process to evaluate the correct choice to be adopted in a specific situation. To this concern, the operator is subject to the mental workload to identify the proper strategy to be applied for each case. In the scientific literature, a model that allows evaluating the task complexity of a procedure, through the 'Shannon Entropy' applied to graphs, was proposed by J. Park. Similarly, the mental workload of an operator in performing cognitive-oriented tasks was studied by G. Salvendy. Consistently to these topics, the authors propose a new model to estimate the mental workload of an operator during the execution of cognitive-oriented tasks of safety or maintenance procedures. The model has been applied to a numerical simulation; results obtained showed how the complexity of cognitive-oriented tasks of safety or maintenance procedures allows affecting the mental workload. The model can be usefully adopted to design emergency (safety) or maintenance procedures by considering the expected mental workload of operators in performing cognitive-oriented tasks.

Keywords: Task complexity; procedure-guided task; mental workload; Shannon entropy; cognitive-oriented task

1. Introduction

Despite increasing automation in modern manufacturing industry, human labour still represents an irreplaceable element in many operations and procedure (Boenzi et al., 2016). The employee performance and productivity are affected by many factors related on one hand to the line efficiency and, on the other hand, to the well-being of the workers (Digiesi et al., 2018). The recent methods adopted to evaluate the complexity in the application of a procedure, in maintenance and safety fields, are based on an analytic approach. In most cases, these methods do not consider the mental workload of the operator. In the safety sector this factor, if not properly evaluated, can bring to significantly reduction of the performance measure (Ante et al., 2018) or to fatal accidents. According to the Safety Report, most of the aeroplane accidents (approximately 80%) depend on human error and only 20% on machine failures (International-Air-Transport-Association, 2018). In the case of Nuclear Power Plants, from statistics studies conducted by INPO (Institute of Nuclear Power Operation), 48% of failure events (2010-2011) were caused by human error (Seong et al., 2013). Many fatal errors are due to wrong behaviours of the operators in procedures adoption. In these cases, when the procedure does not allow to avoid or to minimize the consequences of an accident, the proper question is "the procedure wrong" or "the person is wrong"? (Knight & Aucar, 2010). Many factors can lead to wrong behaviour of the operator (e.g. stress, incompetence, inexperience, etc.) in the adoption of the procedure. The Human Failure Event (HFE) is the result of human actions performed incorrectly and characterized by errors of omission or errors of commission. In the first case, three different ways can occur: the operator forgets to execute an action, the operator acts with a delay (the operator forgets to execute it or is unable to perform it at the right time) or the operator performs an action in advance (omitting to execute it at the right time) (Hollnagel, 1998). The errors of commissions occur when the operator acts incorrectly. The probability of an error, omission as well as of a bad decision of the operator in performing a procedure, increase with increasing the complexity (Wischgoll et al., 2019).

The TAsk COMplexity (TACOM) measure allows evaluating the complexity of a task in the application of procedures with an analytical approach based on graph entropy (Park et al., 2001). Based on the TACOM measure and considering the parameters task uncertainty and task arrival rate introduced by Salvendy. The purpose of the paper consists to develop, starting from the methodology introduced by Salvendy (Bi & Salvendy, 1994), a model based on the information's theory concepts allows identifying the variability and changes of the complexity of procedure-guided tasks and the corresponding perceived mental workload.

The remainder of the paper is organized as follows: A review of scientific contributions on the TACOM measure and mental workload techniques is reported in Section 2; in Section 3, the materials and method of the introduced model are detailed; the discussion of the numerical simulation results are in Section 4; finally, conclusions are in Section 5.

2. State of the Art

2.1. *TACOM* measure

The TACOM measure allows to estimate the task complexity of Emergency Operating Procedures in Nuclear Power Plants (Park & Jung, 2007). The TACOM measure is composed of five sub-measures each of which considers different aspects of the task complexity (Table 1). The contribution of each sub-measure is related to the 'Shannon Entropy' (Shannon, 1948). It is a general concept of the information theory applied to multiple fields (Mowshowitz, 1968). Each sub-measure is identified by a specific graph (Park & Jung, 2007) and the value of each sub-measure is calculated through the 'Shannon Entropy' applied to a graph (Mowshowitz, 1968), still evaluated in bit unit (Rashevsky, 1955). Two out of five sub-measures express the sequence (SLC) and the number (SSC) of actions (nodes in a graph) that a subject has to cope with to accomplish a given task. The SLC and SSC sub-measures are represented by the same graph (ASG, Action Structure Graph) (Table 1). Figure 1 depicts an example of ASG.

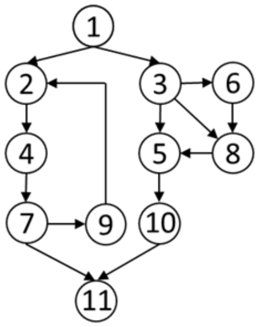

Figure 1. Example of ASG

The evaluation of the entropy of a graph is depicted in eq. 1 (Park & Jung, 2007).

$$Entropy = H = -\sum_{i=1}^{h} p(A_i) * \log_2 p(A_i) \ [bit] \qquad (1)$$

Where A_i is the ith distinctive class in a graph, h is the total number of distinctive classes and $p(A_i)$ is given by the rate between the number of identical nodes in A_i and the total number of nodes in a graph. The definition of class depending on the concepts of first and second-order 'Shannon Entropy' (Davis & Leblanc, 1988; Park et al., 2001). The class of the nodes, in the first-order entropy, depends on their in- and out-degree branches. The nodes which have the same in- and out-degree branches belong to the same class (in Figure 1 nodes 4, 6, 9, 10). For the second-order entropy, nodes which have the same number and type of neighbor nodes within one branch distance, belong to the same class (in Figure 1 nodes 4 and 9). The same graph (ASG, Action Structure Graph) represents the SSC and the SLC sub-measures. A different contribution to the entropy by SLC (expressed through the first-order entropy) and the SSC (expressed through the second-order entropy) sub-measure, is given. Depending on the specific sub-measure, the first or second-order entropy is evaluated.

Table 1. The TACOM sub-measures

Sub-measures	Definition	Entropy	Graph representation
SIC (Step Information Complexity)	Complexity due to the amount of information to be processed by human operators	First order	ISG (Information Structure Graph)
SLC (Step Logic Complexity)	Logical complexity originated from the sequences of actions to be followed by human operators	First order	ASG (Action Structure Graph)
SSC (Step Size Complexity)	Complexity caused by the number of actions to be conducted by human operators	Second order	ASG (Action Structure Graph)
AHC (Abstraction Hierarchy Complexity)	Complexity resulted from the amount of domain knowledge to be considered and/or required by human operators	Second order	AHG (Abstraction Hierarchy Graph)
EDC (Engineering Decision Complexity)	Complexity varied with respect to the amount of cognitive resources to be used and/or required by human operators, which is needed to establish an appropriate decision criterion	Second order	EDC (Engineering Decision Graph)

The evaluation of the TACOM measure is described in eq. 2

$$TACOM = \sqrt{\begin{matrix} 0{,}621 * (0{,}716 * SIC + 0{,}284 * SSC)^2 + \\ 0{,}239 * (0{,}891 * SLC + 0{,}109 * AHC)^2 + \\ 0{,}14 * EDC\hat{}2 \end{matrix}} \quad [bit] \tag{2}$$

The TACOM measure to quantify the complexity of procedure-guided tasks (Park, 2014) has applied. However, the method does not consider some factors that affect the complexity of procedure-guided tasks, such as the task arrival rate and the quality of the information provided that allows identifying the variability in the complexity of procedure-guided tasks. Currently, the operator who performs a task, included in a procedure, receives data and information from multiple sources, in many cases affected by uncertainty and imprecision. The execution of a task causes a significant mental effort on the operator. Therefore, the evaluation of the procedure complexity, considering the variability and uncertainty of the task (i.e. task arrival rate and quality of the information provided), represents the basic-information to evaluate the operator's mental workload involved in procedure-guided.

The TACOM measure depends on the evaluation of data collected in 112 simulations of Nuclear Power Plants accidents (e.g. LOCA, SGTR, etc.) through the use of a full-scope simulator adopted in a Main Control Room (MCR) (Park et al., 2005). Each accident referred to a specific procedure to be followed, each of which composed of multiple tasks. The effort required by the operators in performing the emergency task was mainly a mental effort since the tasks were characterized by cognitive more than motor workload. Consistently to the approach adopted, the TACOM measure represents a good indicator for cognitive-oriented tasks.

2.2. Mental workload techniques

In scientific literature, the mental workload is defined as the mental demand required to perform a generic task, it is mainly related to the complexity of the task. With increasing of the procedure-guided complexity, increase the mental effort to be required to the operator. In most cases, the increase of the mental effort led to the increase of the Human Error Probability (Digiesi et al,. 2019). According to Miller (1956), the information-processing demand shall not exceed the information-processing capacity of the operator to perform the same task (Miller, 1956). Consistently to this perspective, Rasmussen (1974) claimed that each person has a limited processing resources (Rasmussen, 1974).

Are available many techniques aim to evaluate the mental workload, a different methodology for each of them is adopted (Xie & Salvendy, 2000). The empirical methods depend on subjective opinions and physiological-assessment measures like heart rate, oxygen consumption and EEG (Neville Moray, 1988). The analytical methods consist of two different sub-categories, the first sub-category includes the assessment through the "experts' opinion" (Vidulich et al., 1991). The second sub-category includes simulation and mathematical models as well as task-analysis methods. The simulation models depend on the statistical nature of the task (Card et al., 1986; Harris et al., 1986) are based on the control theory, on the queuing and the information theory. In the case of work environments that required continuous controlling tasks and specific system parameters, the control theory is generally adopted (Levison, 1979). The queuing theory considers the operator as a single-channel processor who performs multiple tasks, the execution of the tasks simultaneously is neglected by this approach (Moray et al., 1991). The information theory considers the limited capacity of the operator, according to Senders et al. the limit of this method is related to the framework, generally too structured for adopting in real tasks (Senders, 1964). In the phase of the design process, the task-analysis methods to evaluate the workload, are used. According to experts they are generally adopted for specific and complex scenarios (Linton et al., 1989; Wickens, 1991). Figure 2 summarizes the techniques described.

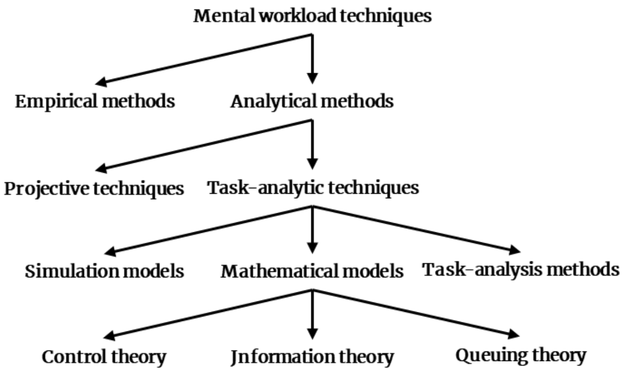

Figure 2: Theoretical framework of modelling and estimating the mental workload

Each of the described techniques for mental workload assessment has pros and cons, so it is necessary a joint adoption of more techniques for the same case, to obtain an exhaustive evaluation. The proposed methodology of Salvendy is based on the joint adoption of mathematical models and task analysis methods (Bi & Salvendy, 1994). The human mental workload predicted, in this case, depends on different task parameters. It can be applied to multiple scenarios and does not require detailed information. The model proposed by Salvendy, appropriately modified, allows evaluating the mental workload of the operator involved in procedure-guided tasks applying the graph entropy concepts.

3. Material and Methods

The operator who executes procedure-guided tasks is subject to a mental effort in performing the activities. With increasing of the task complexity increase the mental demand required by the system. The techniques described previously for the mental workload are domain and subject dependent: these lacks underlined the necessity to evaluate the mental workload objectively, starting from the measurement of the complexity of cognitive-oriented tasks.
Mathematical models for estimating the mental workload consider the operator as a 'server' with limited memory capacity and limited information-processing resources (Miller, 1956). Consistently to this approach, the operator manages his limited resources to face the multiple activities related to decision-making (i.e. planning, monitoring and information processing). A significantly cognitive load is required by this kind of decision-making process, according to Rasmussen (1974) the working memory and long-term memory attitudes are needed to manage these phases (Rasmussen, 1974). The working memory can process only a limited number of elements, so to satisfy the cognitive requirements, the long-term memory of the operator is needed (Paas et al., 2003). In other words, the information received is elaborated by the operator in the working memory and together with the information stored in the long-term memory, the decision-making process is led. The operator has a limited cognitive capacity, so it is necessary to minimize his mental demand which depends on the complexity in performing the cognitive-oriented tasks of a procedure. Therefore, the evaluation of the complexity of procedure-guided tasks allows identifying the mental demand of the operator.

The parameters that describe the changes in the system configurations represent the main sources of the task load. They are related to the factors that reflect the perceived mental workload of the operator (i.e. mental demand, task temporal demand, performance, effort level, frustration level) (Bi & Salvendy, 1994). In the present model, the TACOM measure, the task arrival rate and the task uncertainty are the system parameters that change the system configurations (i.e. complexity of procedure-guided tasks) and reflect the variation of the perceived mental workload (Figure 3).

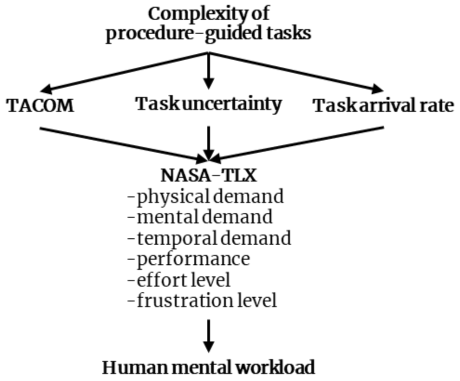

Figure 3. Relation between the complexity of procedure-guided tasks and the human mental workload

The task arrival rate represents the number of tasks that an operator performs at the same time. In an industrial context, an operator can face more than one task at the same time. Therefore, the multiple tasks will contribute to increasing the perceiving mental workload (Moray et al., 1991). Increasing the task arrival rate, increase the complexity required by activities as well as grow the mental workload perceived (Hwang et al., 1984; Sheridan, 1988).

The task uncertainty identifies the quality of the information provided to the operator who bases his decision criterion on them. Therefore, reducing the quality of the information provided, increase the complexity of the execution of the task. As a consequence, increases the time required to perform the task. In this case, indeed, the operator will pursue his decision based on incomplete information. This means that reducing the quality of the information provided causes an increase in the complexity of the activities and contribute to the increase of the perceived mental workload (Tulga & Sheridan, 1980).
Five sub-measure, summarized in Table 1, are considered for the TACOM measure evaluation. In

particular, the SLC and SSC refer to the task structure as they express the sequence and number of actions to be performed through the Action Structure Graph (ASG). On the base of the graph entropy concepts, the structure of the task (ASG), allows to affect the task complexity (Park et al., 2001).

According to the structure of the graph, the mental workload can be lower if compared to another graph with the same number of nodes linked in a more complex and structured way.

The evaluation of the TACOM measure (SLC and SSC sub-measures), by varying of the task arrival rate, task uncertainty on the complexity of the procedure-guided tasks as well as on the mental workload of operators are summarized in the numerical simulation, introduced in next section. In Figure 4, an example of three different cognitive-oriented tasks required to the same operator is showed.

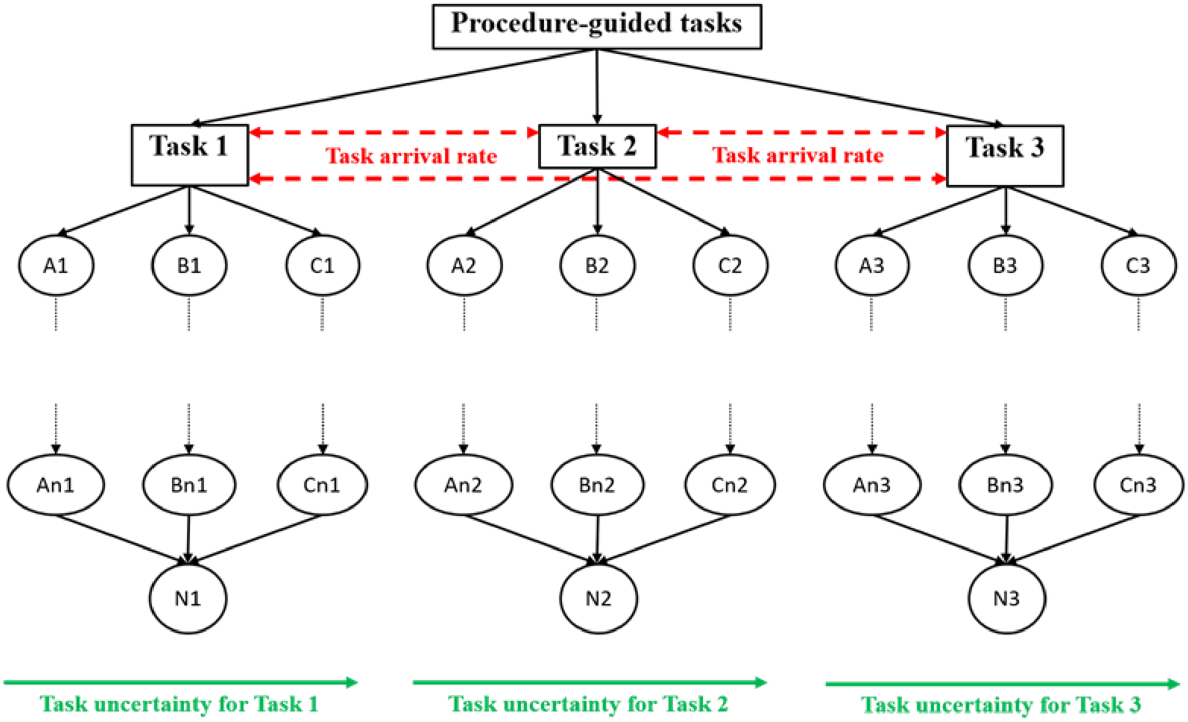

Figure 4. Example of a framework of procedure-guided tasks

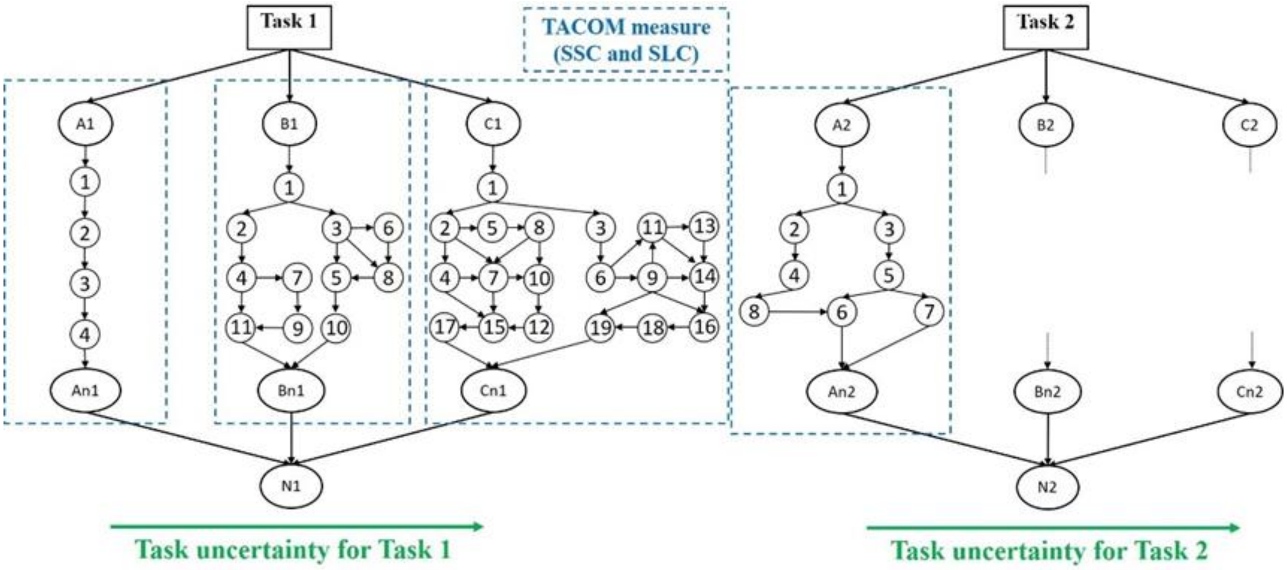

Figure 5. ASGs for 'Task 1' (A1, B1, C1) and 'Task 2' (only A2 for simplicity)

The three cognitive-oriented tasks required to the operator can show up one at a time (e.g. task 1), two at a time (e.g. tasks 1 & 2 or tasks 1 & 3 or tasks 2 & 3) or all at the same time (tasks 1, 2 & 3). Consistently to the different cases highlighted will change the value of the task arrival rate (Figure 4). The task uncertainty parameters and the TACOM measure (SLC and SSC sub-measures) showed in fig. 5, affect the operator's effort in carrying out the cognitive-oriented tasks. For 'Task 1', the node 'N1' represents the task accomplished, the operator can choose between multiple alternatives each of them is strong dependently on the characteristics of the information provided. In case the information provided to the operator is complete and it is of high quality (A1), a minimum number of actions is required to complete the task. On the contrary, if the information provided is incomplete and it is of a lower quality (B1, C1), the difficulty to complete the task increase. In figure 5, the ASGs of 'Task 1' (A1, B1, C1 ASGs) and' Task 2' (A2 ASG) are shown.

4. Results and Discussion

The quality of the information provided to the operator for performing the cognitive-oriented task affects on its complexity (fig. 5). Consistently with increasing of the number of possible actions to be performed, increase the complexity of the task (TACOM measure). By Comparing the 'Task 1' with the 'Task 2', considering the same level of task uncertainty (i.e. level A), it is possible to observe that the corresponding graphs have different task structure (SSC and SLC sub-measures). In this case, the values of SLC and SSC (for A1, B1, C1, A2) identified adopting the equation 1., showed that for 'Task 1' increases the SLC and SSC from A1 to C1 (Table 2). Two parameters (SLC and SSC) and three sub-measures allow evaluating the TACOM measure to identify the complexity of the procedure-guided tasks.

The procedure-guided was simulated to identify the corresponding TACOM measure. It has been observed that increasing of the number of actions required to the operator (SSC sub-measure), increase the amount of the information to be processed (SIC), the amount of the knowledge (AHC) as well as the cognitive resources required (EDC). The analytical relationship between the three sub-measures and SSC can be evaluated through a regression analysis based on the data of 91 distinctive simulations referred to emergency tasks (Park, 2009). The results showed that increasing the number of actions to be executed (SSC), increase the values of SIC, AHC and EDC sub-measures (Figure 6).

Table 2. Evaluation of SLC and SSC

	SLC [bit]	SSC [bit]
A1	$-\left\{2*\left(\frac{1}{6}*\log_2\frac{1}{6}\right)+\frac{4}{6}*\log_2\frac{4}{6}\right\}=1{,}252$	$-\left\{6*\left(\frac{1}{6}*\log_2\frac{1}{6}\right)\right\}=2{,}585$
B1	$-\left\{3*\left(\frac{1}{13}*\log_2\frac{1}{13}\right)+\frac{5}{13}*\log_2\frac{5}{13}+\frac{2}{13}*\log_2\frac{2}{13}+\frac{3}{13}*\log_2\frac{3}{13}\right\}=2{,}287$	$-\left\{13*\left(\frac{1}{13}*\log_2\frac{1}{13}\right)\right\}=3{,}7$
C1	$-\left\{6*\left(\frac{1}{21}*\log_2\frac{1}{21}\right)+\frac{2}{21}*\log_2\frac{2}{21}+\frac{3}{21}*\log_2\frac{3}{21}+\frac{4}{21}*\log_2\frac{4}{21}+\frac{6}{21}*\log_2\frac{6}{21}\right\}=2{,}951$	$-\left\{21*\left(\frac{1}{21}*\log_2\frac{1}{21}\right)\right\}=4{,}392$
A2	$-\left\{3*\left(\frac{1}{10}*\log_2\frac{1}{10}\right)+\frac{2}{10}*\log_2\frac{2}{10}+\frac{5}{10}*\log_2\frac{5}{10}\right\}=1{,}961$	$-\left\{10*\left(\frac{1}{10}*\log_2\frac{1}{10}\right)\right\}=3{,}322$

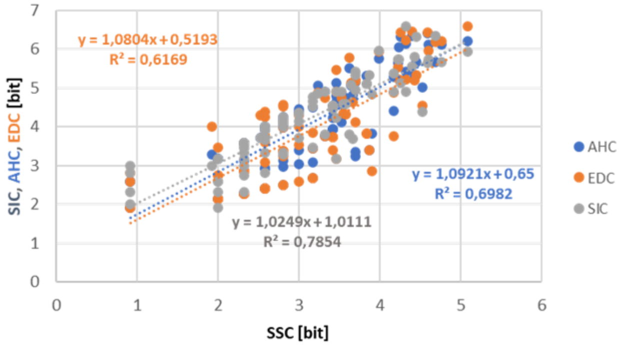

Figure 6. Linear regression analysis

The TACOM measure for each task (Eq. 2), starting from values of SLC and SSC (Table 2) as well as the results of the regression analysis (Figure 6) previously identified was calculated. In Table 3 are summarized the results.

Table 3. Simulation results of TACOM measure

	SIC [bit]	SLC [bit]	SSC [bit]	AHC [bit]	EDC [bit]	TACOM [bit]
A1	3,66	1,25	2,59	3,47	3,31	3,01
B1	4,80	2,29	3,70	4,69	4,52	4,11
C1	5,51	2,95	4,39	5,45	5,26	4,81
A2	4,42	1,96	3,32	4,28	4,11	3,74

The simulations carried out allowed to evaluate the

TACOM measure of various emergency tasks with different complexity. For each simulation, the required time needed to the operator to perform the task (TPT, Task Performance Time) and the corresponding Subjective Workload Score (SWS) was evaluated (Tab. 4). A correlation between TPS, SWS and TACOM has been estimated through a regression analysis showed below (Eqs. 3, 4).

$$TPT = 1{,}34 * e^{0{,}987 * TACOM} \ [s] \qquad (3)$$

$$SWS = 9{,}387 * TACOM + 2{,}7 \ [NASA - TLX\ score] \qquad (4)$$

Table 4. Simulation results of TPT and SWS

	TPT (s)	SWS (NASA-TLX)	TACOM [bit]
A1	26,13	30,95	3,01
B1	77,72	41,32	4,11
C1	154,12	47,83	4,81
A2	53,80	37,82	3,74

The estimated values of TPT and SWS are consistent with TACOM measure, indeed increasing the complexity, increase the evaluation in terms of TPT, SWS and TACOM.

Similarly, the complexity of the procedure-guided tasks (CP) can be evaluated considering the number of tasks, *k*, performed at the same time by the operator. In other words, $TACOM_i$ identify the TACOM measure of the i^{th} task, can be calculated as follows:

$$CP = \sum_{i=1}^{k} TACOM_i \ [bit] \qquad (5)$$

If an operator performs at the same time 'Task 1' with 'B1' complexity and 'Task 2' with 'A2' complexity, eq. 6 allows evaluating the corresponding CP value.

$$CP_{B1+A2} = TACOM_{B1} + TACOM_{A2} = 7{,}85 \ [bit] \qquad (6)$$

The results of the numerical simulation proved how the system parameters, strictly dependently on task arrival rate, task uncertainty and TACOM measure, are related to perceived human mental workload (i.e. mental demand, task temporal demand, performance, effort level, frustration level). In the simulations conducted, the model allows evaluating the perceived mental workload by varying the system parameter of the different procedure-guided with cognitive-oriented tasks.

It has been shown that the perceived mental effort of the operator is consistent with the change of the number of possible actions to be executed in a cognitive-oriented task. In other words, it was identified the analytical relationship between the complexity of the procedure-guided task (figures 4 and 5, Task 1), evaluated by TACOM measure, task uncertainty and task arrival rate, and the corresponding perceived mental workload.

5. Conclusions

The present model highlights how the task arrival rate, the task uncertainty and the TACOM measure affect the complexity of procedure-guided tasks (CP) and the perceived mental workload of the operator. The approach adopted in the conducted work is considered domain-independent since it is based on the general concept of the information theory by 'Shannon Entropy' graphs. The model proposed can be improved considering other factors that affect the mental workload of the operator, such as environmental and organizational.

In the industrial area, the model may be useful to evaluate the effectiveness of the procedure-guided considering both the structure of the cognitive-oriented task that the mental effort of the operator. Consistently to this approach, reducing the quality of the information provided, increase the workload that will affect the worker behaviour (i.e. increase the probability of errors or omissions, of the error of commissions as well as task failure). Further studies can be applied to support the design phase of procedure-guided tasks with the purpose to predict the subjective mental workload of the operator. The adoption of the model allows identifying the critical points of the procedure guided.

A promising improvement of the model proposed relies on the assessment of the task complexity adopting Industry 4.0 (I4.0) technologies. The strong connection between the 'smart' operator and I4.0 technologies (Facchini et al., 2020) allows simulating the procedure adopted to enhance the capacity of the operator to establish the proper choice during the execution of cognitive-oriented tasks. The improvements of the present model under I4.0 perspective, as well as the model validation in a real industrial work environment, will be investigated in future research.

Acknowledgements

This research work is part of the activities carried out in the context of the SO4SIMS project (Smart Operators 4.0 based on Simulation for Industry and Manufacturing Systems) funded by the Italian Ministry of Education, Universities and Research MIUR (Project PRIN – 2017FW8BB4).

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