A POSTERIORI HUMAN RELIABILITY ANALYSIS OF A TRAIN CRASH SCENARIO BY THE FUZZY 'CREAM'

Marseguerra M., Zio E., Librizzi M.
Department of Nuclear Engineering , Polytechnic of Milan , Via Ponzio 34/3, Milano 20133, Italy

In this paper a fuzzy quantification procedure for computing probabilities of operator action failure within the Cognitive Reliability and Error Analysis Method (CREAM) is applied to an actually occurred train crash scenario. The fuzzy version of the CREAM paradigm is shown capable of accounting for: i) the ambiguity in the qualification of the conditions under which the action is performed (Common Performance Conditions, CPCs) and ii) the fact that the effects of such conditions on the human performance reliability may not all be equal. This research work has been carried out within the project Vs (*Virthualis, web site: http://www.virthualis.org*), FIS5-1999-00250, funded by the European Union

1. INTRODUCTION

Recent studies of human performance in accidents have shown that the influence of the contextual conditions in which the task is performed is actually greater than the characteristics of the task itself. This has led to focusing human failure analysis on the modeling of the relationship between the context and the probability of human failure. This viewpoint has led to the development of the so-called 'second generation' methods of HRA, like the Cognitive Reliability and Error Analysis Method (CREAM) [1] and A Technique for Human Error Analysis (ATHEANA) [2].

In this work, we embrace the human cognition model of CREAM which assumes that the human failure probability depends directly on the level of control that the human operator has over the contextual scenario in which is requested to perform. The level of control is discretized into four modes in ascending order of control and performance reliability, and thus in descending order of human failure probability: scrambled, opportunistic, tactical, strategic. To each control mode is associated a typical failure probability interval. For the given contextual scenario in which the task is performed, the control mode is determined by nine Common Performance Conditions (CPCs) which qualify the context in terms of linguistic descriptors. The linguistic descriptor of each CPC is associated to a particular contextual effect on the performance reliability, in terms of whether it is improved, reduced or not significantly modified. The number of CPCs improving and reducing performance reliability are mapped to the context-specific control mode and corresponding failure probability interval.

Recently, some research efforts have been performed to derive point values of human error probability both by means of probabilistic techniques [3] and fuzzy approaches [4], for use in reliability analyses and probabilistic risk assessments.

With respect to the latter, two quantitative issues are here addressed. First of all, specifying the action context by qualifying the CPCs levels is not an easy task even in the case of retrospective analysis and even more in risk prediction, due to the lack of accurate, unambiguous data and information about the context. Hence, ambiguity inevitably enters in the specification of the action contextual scenarios [5]. In this respect, an extension of the approach presented in [4] is here proposed to capture quantitatively such ambiguities. Secondly, the assumption that the CPCs are all equally important for performance reliability may not always hold ([1], [4]). In this respect, the Analytic Hierarchy Process (AHP) [6] is here employed to structure the CPCs weight assignment by expert judgment.

The paper is structured as follows. In Section 2, the fuzzy logic framework of the CREAM cognitive model is summarized [4] and its generalization for allowing an ambiguous definition of the CPCs levels in terms of fuzzy sets is presented. Section 3 sketches the basics of the AHP and Section 4 illustrates the logic behind a possible hierarchy for the CREAM CPCs. An application is then illustrated in Section 5 with regards to the analysis of an actually occurred train crash. Some conclusions are drawn in the last Section.

2. FUZZY CREAM

Uncertainty and ambiguity are inherent in human reliability analysis and thus must be incorporated explicitly, in a transparent way. In this respect, a fuzzy extension of CREAM has been proposed in [4]. In the following, the steps of such approach are briefly sketched.

The 9 CPCs underpinning CREAM (Table 1) are treated as linguistic variables x_k, $k=1,2,\ldots,9$, whose characterizing terms (the linguistic descriptors of the CPCs levels) are mathematically expressed in terms of fuzzy sets (FSs) X_k^v, $v=1,2,\ldots$ disposed on a (0,100) rating range called Universe of Discourse (UOD) in fuzzy terminology (Fig. 1). The generic fuzzy set X_k^v is defined in terms of the membership function (MF) $\mu_{X_k^v}(x_k)$. Following the original CREAM methodology, to each linguistic term of each CPC is associated a linguistic descriptor of the effect on the performance reliability, in terms of whether it is improved (positive effect), reduced (negative effect) or not significantly modified (no effect) (Table 1).

Table 1: CPCs and linguistic terms. In italic are the improving CPCs levels, in bold the reducing ones.

	CPC	UOD	Number of FS	CPC levels	Effect
1	Adequacy of Organization	[0,100]	4	**Deficient**	**Reduced**
				Inefficient	**Reduced**
				Efficient	Not Signif.
				Very Efficient	*Improved*
2	Working Conditions	[0,100]	3	**Incompatible**	**Reduced**
				Compatible	Not Signif.
				Advantageous	*Improved*
3	Adequacy of MMI and operational support	[0,100]	4	**Inappropriate**	**Reduced**
				Tolerable	Not Signif.
				Adequate	Not Signif.
				Supportive	*Improved*
4	Availability of procedures/plans	[0,100]	3	**Inappropriate**	**Reduced**
				Acceptable	Not Signif.
				Appropriate	*Improved*
5	Number of simultaneous goals	[0,100]	3	**More than actual capacity**	**Reduced**
				Matching current capacity	Not Signif.
				Fewer than actual capacity	Not Signif.
6	Available Time	[0,100]	3	**Continuously inadequate**	**Reduced**
				Temporarily inadequate	Not Signif.
				Adequate	*Improved*
7	Time of the day (circadian rhythm)	[0,24]	3	**Night (Unadjusted)**	**Reduced**
				Day (Adjusted)	Not Signif.
				Night (Unadjusted)	**Reduced**
8	Adequacy of training and exper.	[0,100]	3	**Inadequate**	**Reduced**
				Adequate with limited exper.	Not Signif.
				Adequate with high exper.	*Improved*
9	Crew collaboration quality	[0,100]	4	**Deficient**	**Reduced**
				Inefficient	Not Signif.
				Efficient	Not Signif.
				Very Efficient	*Improved*

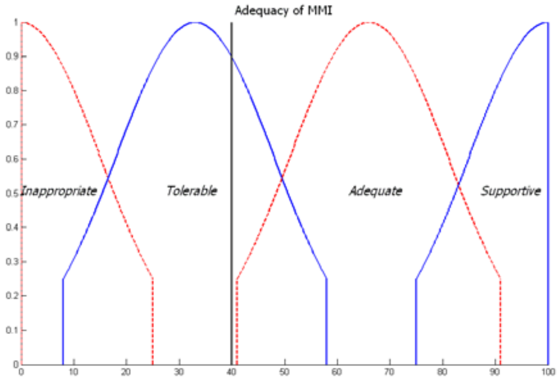

Figure 1: Bell-shaped FSs of CPCs "Adequacy of MMI and operational support" with a singleton fact.

Fuzzy rules are then constructed by combining the 9 CPCs levels in the antecedent part by an *and* operator, which is a t-norm here chosen as the *min*. Combining all possible levels (3 or 4) of all nine CPCs, the total number of rules is $N_r = 4^3 \cdot 3^6 = 46{,}656$.

As in the basic CREAM method, the linguistic label of the consequent control mode of a rule is obtained from the diagram of Fig. 2 where the *x* and *y* axis represent the sum of the linguistic labels of the antecedents which have negative and positive effects on the human reliability, respectively. For a given rule, the linguistic variables in its antecedents with negative and positive effects are separately summed to give the *x* and *y* values in the diagram, respectively: the location of the resulting (*x*,*y*) point identifies the linguistic label of the consequent in the rule, i.e. the control mode. Note that this procedure implies that all antecedents bear the same importance in defining the control mode.

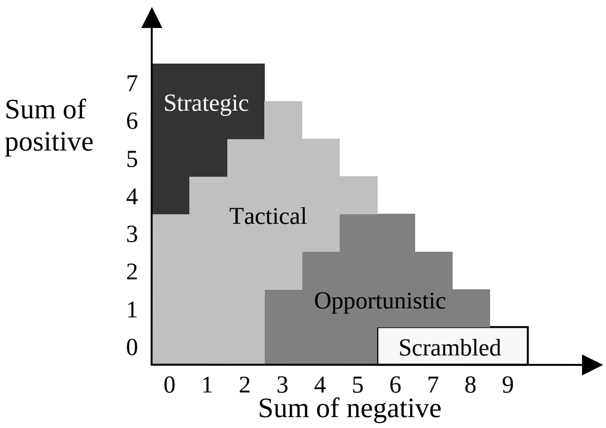

Figure 2: CREAM diagram for the definition of the control modes

To the consequent control mode Z_j of the generic j-th rule is associated a fuzzy set of MF $\mu_{Z_j}(z)$ describing the uncertainty in the value of human failure probability (Table 2 and Fig. 3).

Table 2: Control Modes and Human Failure Probabilities

MODE	**Reliability interval (probability of action failure)**
Strategic	0.5E-5< p <1.0E-2
Tactical	1.0E-3< p <1.0E-1
Opportunistic	1.0E-2< p <0.5E-0
Scrambled	1.0E-1< p <1.0E-0

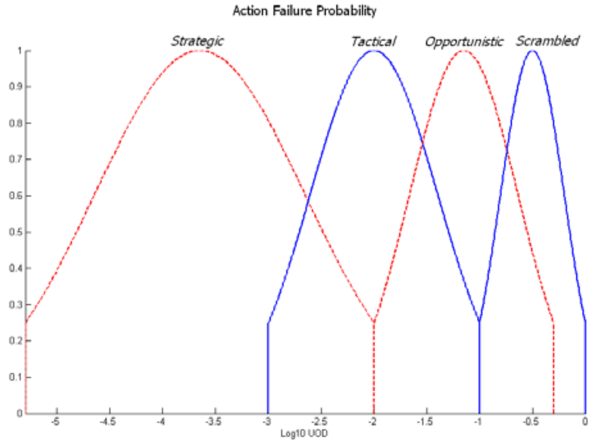

Figure 3: Bell-shaped FSs of consequent “Action Failure Probability”

In summary, the j-th Rule (j=1,2,…,46656) reads

$$\text{if } x_1 \text{ is } X_{1j} \text{ and } x_2 \text{ is } X_{2j} \ldots \text{ and } x_9 \text{ is } X_{9j} \text{ then } z \text{ is } Z_j \tag{1}$$

where the X_{k_j} and Z_j are the FSs pertaining to the j-th rule and the consequent is connected to the antecedent part of the rule by the implication operator *then*, here also implemented as the *min t*-norm.

In the application phase of the fuzzy model, the specific context in which the human operator action is performed is characterized by assigning a set of 9 crisp values $x_k^0 \in (0,100)$, $k = 1,2,...,9$ to the 9 CPCs antecedents. These values are fuzzified as singleton FSs $X_k^{'}$ and constitute the so called Fact, with MFs $\mu_{X_k^{'}}(x_k) = \delta(x_k, x_k^0)$, $k = 1,2,\cdots 9$ (Fig. 1). The Conclusion regarding the specific Fact is that the consequent linguistic variable *z* is described by the FS *Z’* inferred from the combination of the 46,656 fuzzy rules constructed as above explained. For the j-th rule, the inference stands from the application of the *and* and *implication min* operators to the rule antecedent and consequent parts

$$\mu_{X_{1j}}(x_1) \wedge ... \wedge \mu_{X_{9j}}(x_9) \wedge \mu_{Z_j}(z) \tag{2}$$

and the composition with the Fact implemented by the *max-min* operator. Thus, the contribution of the j-th rule to the Conclusion is

$$\left[\mu_{Z'}(z)\right]^{(j)} = \mu_{Z_j}(z) \wedge r_j \tag{3}$$

where

$$r_j = r_{1j} \wedge r_{2j} \wedge ... \wedge r_{9j} \text{ and } r_{kj} = \vee_{x_k} \mu_{X_k^{'}}(x_k) \wedge \mu_{X_{kj}}(x_k) = \mu_{X_{kj}}(x_k^0) \tag{4}$$

By combining all the rules, the final inferred Conclusion is then

$$\mu_{Z'}(z) = \vee_{j=1}^{j=N_r} \left[\mu_{Z'}(z)\right]^{(j)} \tag{5}$$

where N_r is the number of rules (here 46,656).

3. FUZZY CONTEXT CHARACTERIZATION

In the application of the fuzzy formulation of the CREAM method presented above, the specific context in which the human operator action takes place is defined by assigning crisp values in the rating scale (0,100). In practice, however, uncertainty and ambiguity are encountered in this characterization. To explicitly represent this, the previous fuzzy formulation is extended to allow the assignment of fuzzy sets for characterizing the context in which the task takes place.

Each CPC level $x'_k, k = 1, 2, \cdots 9$ constituting the Fact *x'* is no longer represented by a set of 9 singletons but rather by a set of 9 proper FSs X'_k, each one characterized by a corresponding MF $\mu_{X'_k}(x_k), k = 1, 2, \cdots 9$, on the UOD (0,100) (Fig. 4).

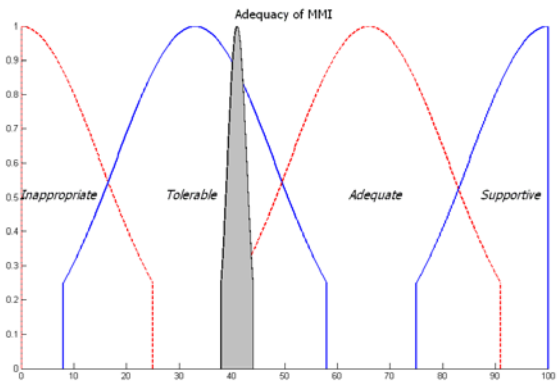

Figure 4: Bell-shaped FSs of CPC "Adequacy of MMI and operational support" with a FS fact (shaded).

The increased modeling flexibility provided does not introduce any additional mathematical complexity as the inference formulas (3)-(5) remain valid. From the computational point of view, the effect is the activation of more rules than those activated by singletons, due to the increased number of CPCs FSs involved. As it will be shown in the application of Section 5, the final fuzzy set inferred from the combination of these rules may include more than one control mode (Fig. 5).

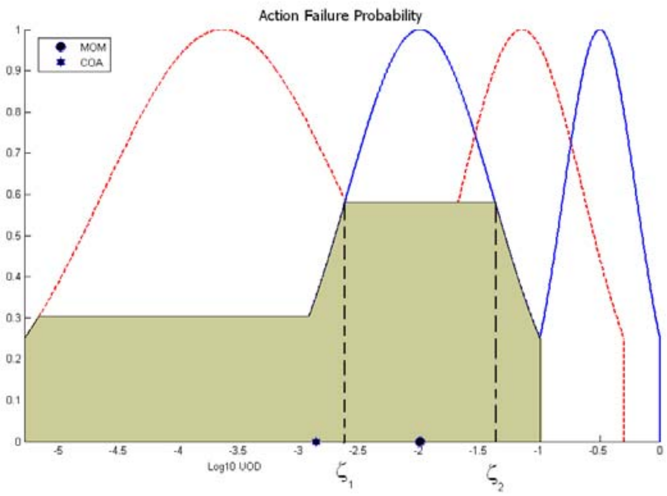

Figure 5: Inferred consequent FS (shaded area) and representative failure probability point value obtained by defuzzification by Mean of Maximum (MOM) and Center of Area (COA)(see Section 5.3) [7].

4. A METHOD FOR ASSIGNING WEIGHTS TO THE CPCS

As mentioned in the Introduction, the assumption that CPCs all equally affect the action performance reliability may not always hold [1]. In certain cases, one may need to assign weights to measure the relative influence that the different CPCs have (Fujita and Hollnagel, 2004).

The tool here chosen for this task is the Analytic Hierarchy Process which is composed of three major steps [6]: the building of a hierarchy to decompose the problem at hand, the input of pairwise comparison judgments regarding the relevance of the considered parameters and the computation of priority vectors to obtain their ranking. The method is intended, in our case, to provide a transparent and reproducible way to assign importance weights to the different CPCs affecting performance reliability.

4.1 The Hierarchy for the CPCs

A possible three-levels hierarchy for rating the CPCs importance obtained following the lines of reasoning in [1] is plotted in Fig. 6. The intermediate level introduced is characterized by three elements that indicate the main attributes which are believed to influence the reliability of performance of an action by a human operator: action load, working environment and operator preparedness. Each CPC influences directly these attributes of human action performance, with different intensity. A reasonable judgment in this respect may be the one represented qualitatively in Fig. 6 in terms of thick connecting lines for the more influencing CPCs and light lines for the less or negligibly influencing CPCs.

For example, it seems reasonable to state that the “number of simultaneous goals” (CPC 5) and “available time” (CPC 6) strongly influence the action load; the working environment is affected by the “adequacy of organization”, “working conditions”, “adequacy of MMI”, “time of the day” and “crew collaboration quality”, CPCs number 1,2,3,7 and 9, respectively; the operator preparedness is affected by CPC 4, “availability of procedures and plans” and CPC 8, “adequacy of training”.

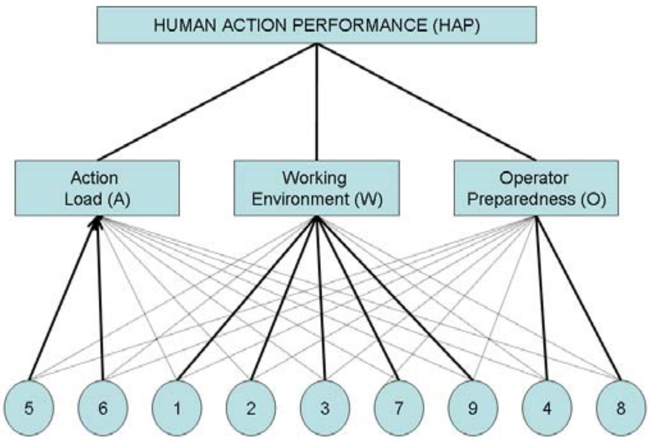

Figure 6: Hierarchy for CPCs. Thick lines represent direct influence on the attribute above; light lines indicate negligible or no influence.

A first pairwise comparison matrix (indicated as HAP) needs to be provided by the expert for pondering the relative importance of the intermediate-level attributes with respect to the hierarchy goal of Human Action Performance. For example, in Table 3 the action load (A) is regarded very strongly more important (a value of 7) than working environment (W) and strongly more important (a value of 5) than operator preparedness (O); the operator preparedness (O) is in turn considered slightly more important (a value of 3) than working environment (W) (note that for absolute consistency, the operator preparedness (O) should be assigned a value of 7/5 when compared to working environment (W), giving a consistency ratio of 0).

Table 3: Pairwise comparisons for the intermediate-level attributes.

HAP	**A**	**W**	**O**
A	1	7	5
W	1/7	1	1/3
O	1/5	3	1

Consistency Ratio CR=5.59E-2.

Then, one 9x9 pairwise comparison matrix needs to be assessed for each one of the three attributes A,W and O to quantify the relative importance of the CPCs. This entails providing the judgment on the relative importance of the CPCs by comparing them two at the time in regards of their influence on each of the intermediate attributes, A,W and O. This should reflect the previous judgments on the intensity of direct influence of the CPCs on the attributes, as qualitatively visualized in Fig. 6 by thick and light lines. These judgments could be automatically translated in quantitative terms, for example by assigning a value of 9 to all CPCs with intense direct influence on an attribute (thick lines in Fig. 6) when compared to those with negligible influence on that same attribute (light lines in Fig. 6) which are in turn assigned a 1. Thus, for example, in the comparison with respect to attribute A (action load) CPC 5 (“number of simultaneous goals”) would be assigned a 9 and CPC 2 (“working conditions”) a 1. Then, the only pairwise comparison judgments to be actually provided would be those relative to the comparisons between pairs of CPCs both with intense influence on the attribute considered in the comparison (thick lines in Fig. 6), e.g. CPCs 5 and 6 with respect to attribute A (action load). Tables 4-6 synthetize the above procedure: the shaded boxes are those to be assigned by the expert in the pairwise comparison.

Table 4. Matrix for attribute A

A	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	1	1	1	1/9	1/9	1	1	1
2	1	1	1	1	1/9	1/9	1	1	1
3	1	1	1	1	1/9	1/9	1	1	1
4	1	1	1	1	1/9	1/9	1	1	1
5	9	9	9	9	1		9	9	9
6	9	9	9	9		1	9	9	9
7	1	1	1	1	1/9	1/9	1	1	1
8	1	1	1	1	1/9	1/9	1	1	1
9	1	1	1	1	1/9	1/9	1	1	1

Table 5. Matrix for attribute W

W	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1			9	9	9		9	
2		1		9	9	9		9	
3			1	9	9	9		9	
4	1/9	1/9	1/9	1	1	1	1/9	1	1/9
5	1/9	1/9	1/9	1	1	1	1/9	1	1/9
6	1/9	1/9	1/9	1	1	1	1/9	1	1/9
7				9	9	9	1	9	
8	1/9	1/9	1/9	1	1	1	1/9	1	1/9
9				9	9	9		9	1

Table 6. Matrix for attribute O

O	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	1	1	1/9	1	1	1	*1/9*	1
2	1	1	1	1/9	1	1	1	1/9	1
3	1	1	1	1/9	1	1	1	1/9	1
4	9	9	9	1	9	9	9		9
5	1	1	1	1/9	1	1	1	1/9	1
6	1	1	1	1/9	1	1	1	1/9	1
7	1	1	1	1/9	1	1	1	1/9	1
8	9	*9*	9		9	9	9	1	9
9	1	1	1	1/9	1	1	1	1/9	1

For achieving higher consistency one could assign a value equal to $9/k$ to the CPCs with intense influence on the attribute when compared to those with negligible influence. The value k is the value judgment assigned to the CPC when compared to the CPC judged to have strongest influence (see the example in the Application of Section 5), i.e. receiving the highest comparison value (obviously, $k=1$ for the strongest CPC).

5. APPLICATION

5.1 Problem Description

The proposed method has been applied to an a posteriori evaluation of a contextual scenario of a train crash actually occurred (Fujita and Hollnagel, 2004). The accident refers to a collision between a commuter train and a train at rest while waiting to pull into a station. The collision speed was estimated to be about 30 km/h. This is anomalously high considering that the commuter train was equipped with an Automatic Train Stop system (ATS) which gives an alarm when the train goes through a stop signal and automatically stops the train if the driver fails to acknowledge the alarm. The driver was killed in the accident, so that it has not been possible to verify the correct functioning of the ATS system. However, from the post-accident investigation it is believed that the ATS system had worked properly in sending the alarm signal and that the driver has turned off the alarm by automatic reflex, thus continuing without the automatic breaking system.

5.2 Basic CREAM

The CPCs evaluations reported in Table 7 qualify the description of the accident context given in (Fujita and Hollnagel, 2004). The adequacy of organization has been considered deficient because the station management was unable to remediate at the incorrect use of the ATS. The working conditions have been judged incompatible because the station is placed after a descending and blind curve and there were many trains due to the rush-hour surge: this made it difficult for the driver to detect the obstacles ahead in time. The number of simultaneous goals is expected to be matching the current capacity of the driver. The adequacy of training and the availability of procedures have been assumed inadequate and inappropriate, respectively: the driver habitually resets the alarm signal and this work habit defeats both the ATS system and the overall safety procedure associated to it. Note that such procedure leaves the final decision to the driver on whether to stop or continue. For similar reasons, the adequacy of Man Machine Interface is considered inappropriate. The available time has been assessed continuously inadequate due to the rush implied by a delay of the train with respect to its schedule. Finally, both time of the day and crew collaboration are not considerable for this context and thus have been assessed of no influence (‘day time’ and ‘efficient’ with zero score, respectively).

With regards to the effect on the performance reliability, the above linguistic description of the context amounts to 6 reducing CPCs and 3 with no influence. Application of the basic CREAM leads to the identification of the Scrambled control mode and a HEP in the interval [1.00E-1,1.00], with a central value of 5.50E-1.

Table 7. Context description in terms of CPCs. An improved effect on human reliability is indicated with a + label and a reduced effect with a – label.

CPC	LEVEL	EFFECT
Adequacy of Organization	Deficient	-
Working Conditions	Incompatible	-
Adequacy of MMI	Inappropriate	-
Availability of procedures	Inappropriate	-
Number of simultaneous goals	Matching current capacity	0
Available Time	Continuously inadequate	-
Time of the day	Day-time	0
Adequacy of training	Inadequate	-
Crew Collaboration	Efficient	0

5.3 Fuzzy CREAM

The fuzzification procedure amounts to performing the following steps: set the universe of discourses (UODs) of the antecedents and the corresponding partitioning fuzzy sets; develop the fuzzy knowledge base, i.e. the set of rules, as explained in Section 2; select the defuzzification method.

The UODs for the rating of the CPCs are chosen equal to [0,100] except for the CPC “Time of the day” which is [0,24]. The supports of the fuzzy sets of the relative linguistic descriptors are given in Table 8. On these supports, the individual membership functions for all the 9 antecedents linguistic descriptions are arbitrarily chosen of Gaussian shape, truncated below a membership value of 0.25 (Fig. 7).

Table 8. Fuzzy sets supports. In italic are the improving CPCs levels; in bold the reducing ones.

	CPC	**Membership Level Intervals**			
1	Adequacy of Organization	**Deficient**	**Inefficient**	Efficient	*Very Efficient*
		0-25	10-60	40-90	70-100
2	Working Conditions	**Incompatible**	Compatible	*Advantageous*	
		0-30	20-80	70-100	
3	Adequacy of MMI	**Inappropriate**	Tolerable	Adequate	*Supportive*
		0-25	10-60	40-90	70-100
4	Availability of procedures	**Inappropriate**	Acceptable	*Appropriate*	
		0-30	20-80	70-100	
5	Number of simultaneous goals	**More than …**	Matching…	Fewer than…	
		0-30	20-80	70-100	
6	Available Time	**Continuously …**	Temporarily …	*Adequate*	
		0-30	20-80	70-100	
7	Time of the day	**Night**	Day	**Night**	
		0-11	8-20	16-24	
8	Adequacy of training	**Inadequate**	Adequate limited	*Adequate High*	
		0-30	20-80	70-100	
9	Crew collaboration	**Deficient**	Inefficient	Efficient	*Very Efficient*
		0-25	10-60	40-90	70-100

Two ways for performing the defuzzification procedure are considered [7]:

- Mean of Maximum (MOM) method: the HEP is taken as the central value of the support $\left[\zeta_1, \zeta_2\right]$ of the part with maximum membership in the inferred consequent fuzzy set (Fig. 5). Recall that, by construction the part of the consequent fuzzy set with maximum membership value comes from the consequent control mode of the rules which are most strongly activated by the Fact (Section 2).

- Center of Area (COA) method: the HEP value is given by the "center of mass" of the area under the consequent fuzzy set (Fig. 5). By construction, then, it accounts for all control modes consequents of activated rules, appropriately weighted by their activation strength.

In the implementation of the extended fuzzy CREAM (Section 3) to the present application, the qualitative, linguistic characterization of the context reported in Table 8 is fuzzily quantified by assigning the arbitrary crisp scores in Table 9 and translating them into a fuzzy Fact by introducing an arbitrary uncertainty spread of 4 units around the assigned scores. The intervals of score values thereby obtained constitute the supports for the bell-shaped fuzzy sets constituting the contextual Fact, centered at the score values originally assigned (Fig. 7). Notice that, in this example, in spite of the uncertainty in the assignment all the fuzzy sets of the Fact intersect with only one fuzzy set of the respective CPC.

The resulting Fuzzy Fact is input to the fuzzy knowledge base and in this case it activates rules characterized by Opportunistic and Scrambled consequent control modes. Then, the MOM defuzzified HEP is equal to 3.16E-1 and coincides with the central value of the support to the fuzzy set of the most fired control mode, in this case the Scrambled one (Fig. 8). The COA-HEP takes account of the other activated control mode (Opportunistic) and it is equal to 1.35E-1.

Table 9. Crisp scores of the CPCs (base case).

CPC	SCORE
Adequacy of Organization	12
Working Conditions	15
Adequacy of MMI	12
Availability of procedures	15
Number of simultaneous goals	50
Available Time	15
Time of the day	12
Adequacy of training	15
Crew Collaboration	70

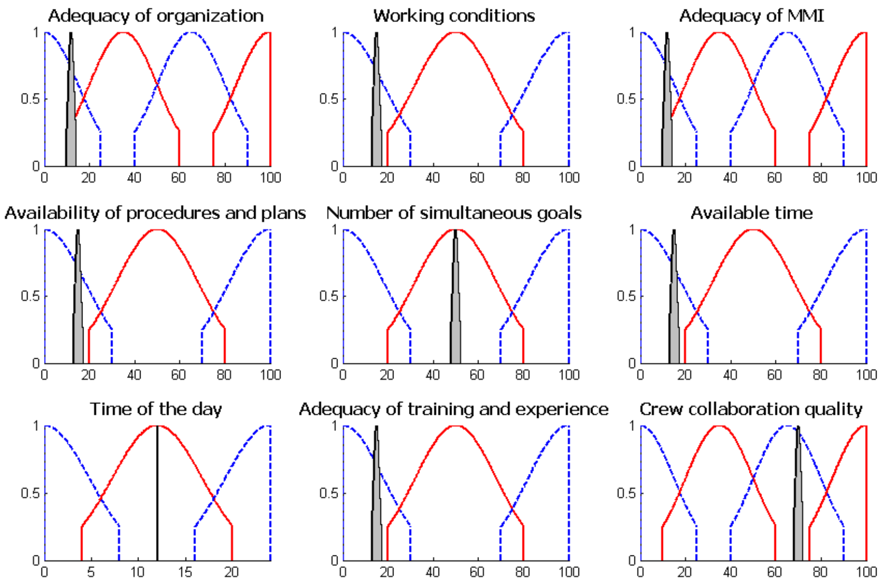

Figure 7: CPCs and Fact (shaded) fuzzy sets.

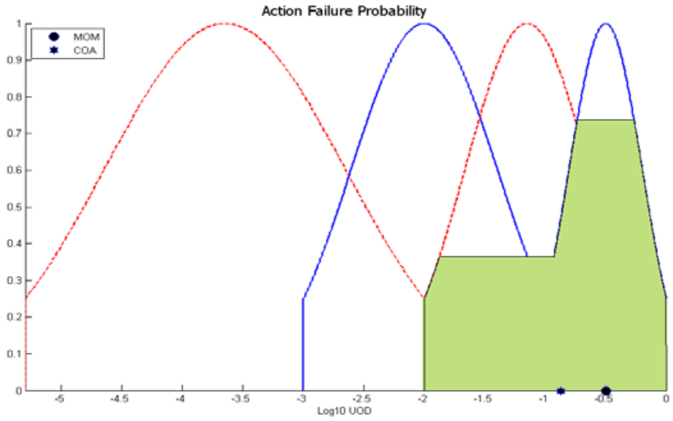

Figure 8: Inferred consequent fuzzy set (shaded).

Obviously, the results obtained depend on the input to the fuzzy model and in particular on the evaluation scores of the CPCs and associated uncertainty spread, within the variability of the respective supports of their linguistic descriptors.

5.4 Weight extension

To account for the different importances of the CPCs, the analytic hierarchy process is applied to the hierarchy of human action performance presented in Section 4.1. The pairwise comparison entries between the hierarchy intermediate attributes “Action Load (A)”, “Working Environment (W)” and “Operator Preparedness (O)” have been reported in the previous Table 4. In Tables 10,11 and 12, the pairwise comparison entries between CPCs are given for the attribute A, W and O respectively. The “automatic” entries for the CPCs with direct influence (thick lines in Fig. 6) are obtained with the procedure for maximum consistency explained at the end of Section 4. For the attribute Action Load (A), only one judgment is then necessary with regards to the relative importance of CPCs 5 and 6: the former is considered very strongly more important (a value of 7) than the latter. According to the maximum-consistency automatic procedure for the assignment of the pairwise comparison entries, a unitary value is assigned to all CPCs with negligible effect when compared among each others and a value of $9/k$ to the intense-effect ones, with k=1 for the strongest influencing CPC 5 and $k=7$ for the other CPC 6. For the Working Environment (W), the CPC 7 is considered of lower influence on human performance with respect to all other CPCs that affect this attribute. The other values introduced quantify the following two arbitrary judgments: the CPCs 2 and 3 are considered equally important, the CPC 1 is considered more influent than CPC 9 and both more relevant than the others. Finally, for the attribute O, the CPC 8 is considered of value 7 with respect to CPC 4.

Table 10. Pairwise comparison for the attribute A

A	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	1	1	1	1/9	7/9	1	1	1
2	1	1	1	1	1/9	7/9	1	1	1
3	1	1	1	1	1/9	7/9	1	1	1
4	1	1	1	1	1/9	7/9	1	1	1
5	9	9	9	9	1	7	9	9	9
6	9/7	9/7	9/7	9/7	1/7	1	9/7	9/7	9/7
7	1	1	1	1	1/9	7/9	1	1	1
8	1	1	1	1	1/9	7/9	1	1	1
9	1	1	1	1	1/9	7/9	1	1	1

Consistency Ratio, CR=0.

Table 11. Pairwise comparison for the attribute W

W	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	7	7	9	9	9	8	9	7/3
2	1/7	1	1	9/7	9/7	9/7	8/7	9/7	1/3
3	1/7	1	1	9/7	9/7	9/7	8/7	9/7	1/3
4	1/9	7/9	7/9	1	1	1	1	1	7/(3*9)
5	1/9	7/9	7/9	1	1	1	1	1	7/(3*9)
6	1/9	7/9	7/9	1	1	1	1	1	7/(3*9)
7	1/8	7/8	7/8	1	1	1	1	1	7/(3*8)
8	1/9	7/9	7/9	1	1	1	1	1	7/(3*9)
9	3/7	3	3	3*9/7	3*9/7	3*9/7	3*8/7	3*9/7	1

Consistency Ratio, CR=2.36E-4.

Table 12. Pairwise comparison for the attribute O

O	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	1	1	1/9	1	1	1	7/9	1
2	1	1	1	1/9	1	1	1	7/9	1
3	1	1	1	1/9	1	1	1	7/9	1
4	9/7	9/7	9/7	1	9/7	9/7	9/7	1/7	9/7
5	1	1	1	1/9	1	1	1	7/9	1
6	1	1	1	1/9	1	1	1	7/9	1
7	1	1	1	1/9	1	1	1	7/9	1
8	9	9	9	7	9	9	9	1	9
9	1	1	1	1/9	1	1	1	7/9	1

Consistency Ratio, CR=0.

The resulting priority vector of the CPCs is [6]:

[0.098,0.058,0.058,0.059,0.402,0.069,0.057,0.126,0.072] (6)

CPC 5, related to "Action Load", bears the largest importance, followed by CPC 8 influencing the attribute "Operator Preparedness". The remaining CPCs, in order of influence, are 1,9,6 followed by the group 4,2,3 and 7.

The weights thereby obtained are summed as negative and positive effects on the human performance reliability to determine the action control mode corresponding to the contextual scenario under evaluation. This requires a scaling of the total negative and positive weighted contributions in the ranges [0,9] and [0,7] so as to be able to still use the diagram of Fig. 2 for the definition of the control modes.

Fig. 9 compares the inferred consequent fuzzy sets for the scores in Table 9: for comparison, on the left is reported the case with "weighted CPCs" and on the right the case with "no weighted CPCs" (the same result reported in Fig. 8).

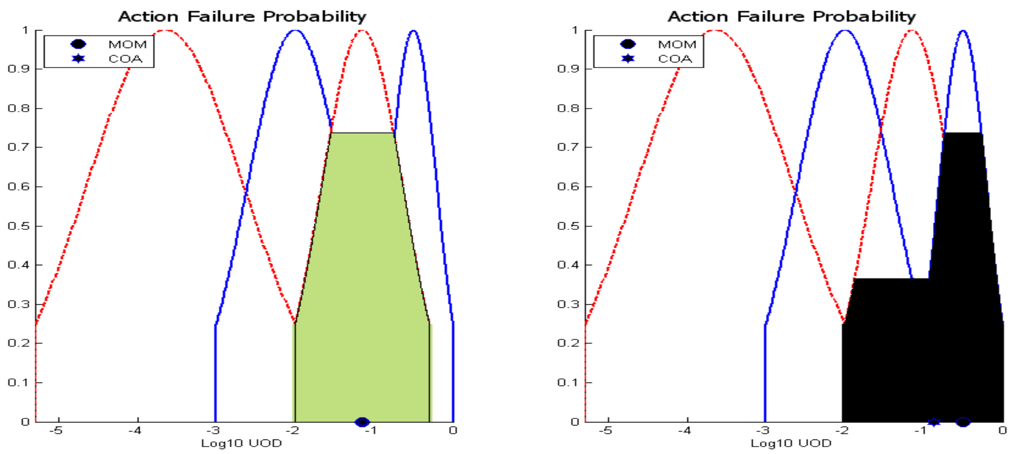

Figure 9: Inferred consequent fuzzy set (shaded). (Left: weighted CPCs, Right: no weighted CPCs)

The CPCs weighting modify the value of the inferred HEP to 7.08E-2 both for MOM and COA, due to the activation by the Fact of only rules with Opportunistic consequent control mode (Fig. 10).

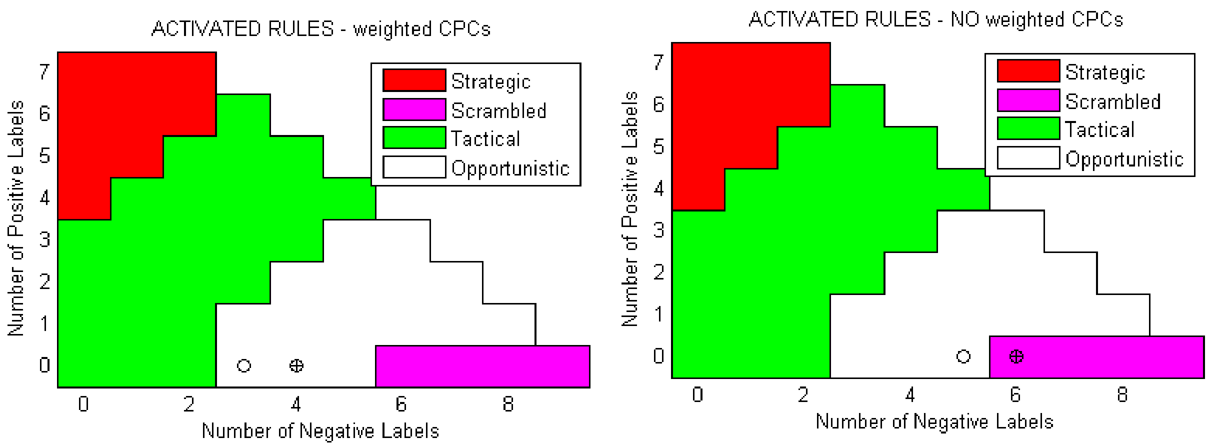

Figure 10: Activated rules. Left: weighted CPCs, Right: no weighted CPCs. The circle marks the location of the activated rule. The cross indicates the location of the rule with the largest strength.

6. CONCLUSIONS

In this paper, the procedure for the human error probability quantification by CREAM has been extended to take into account the inevitable ambiguity associated to the evaluation of the contextual scenario in which the human action takes place. This is achieved by performing the evaluation of the contextual scenario in terms of fuzzy sets (Fact). As shown by the train crash case study, this typically leads to the involvement of a number of control modes (Scrambled and Opportunistic in this case) in the definition of the HEP as a weighted combination of the effects of all the control modes activated by the introduced fuzzy judgment.

Furthermore, a systematic procedure for the CPCs rating by the AHP method has been propounded to account for their relative influence on human performance reliability. The application to the a posteriori analysis of a train crash scenario actually occurred has shown the added value gained. The approach presented allows a rational management of the ambiguities entering the quantification of the human failure probabilities to be fed into a quantitative safety assessment. The methodology is selfconsistent and lends itself for the application to the human error analysis methodology which will result from the Virthualis project.

REFERENCES

[1] Hollnagel E., Cognitive reliability and error analysis method (CREAM). Elsevier Science Ltd., 1998.

[2] Cooper S.E., Ramey-Smith A. M., Wreathall J., Parry G.W., Bley D.C., Luckas W.J., Taylor J.H., Barriere M.T., “A technique for Human Error Analysis (ATHEANA)”, NUREG/CR-6093, U.S. Nuclear Regulatory Commission, Washington DC,1994.

[3] Fujita Y., Hollnagel E., “Failure without errors: quantification of context in HRA”, Reliability Engineering and System Safety 2004; Vol 83, 145-151.

[4] Konstandinidou M., Nivolianitou Z., Kiranoudis C., Markatos N., “A fuzzy modeling application of CREAM methodology for human reliability analysis” , Reliability Engineering and System Safety, Vol.91-6, 2006, 706-716.

[5] Kim M.C., Seong P.H., Hollnagel E., “A probabilistic approach for determining the control mode in CREAM”, Reliability Engineering and System Safety 2006; Vol 91, 191-199.

[6] Saaty T.L., “The analytic hierarchy process”, McGraw-Hill International, NY, 1980.

[7] Klir G.J., Yuan B., “Fuzzy Sets and Fuzzy Logic: Theory and Applications”, Prentice Hall, 1995.