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HUMAN ERROR PROBABILITY COMPUTATION FOR MANUFACTURING SYSTEM SIMULATION USING CREAM

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ABSTRACT: *Uncertainties in production and assembly processes have a significant influence on performance. In most cases the notion of uncertainty implies machine breakdowns, defective items or various uncertainties in procurement. However, especially in manual production, each realistic model should also take into account and treat human related uncertainties. Unfortunately, in contrast to "standard" uncertainties, there are no statistical data credible enough to use in order to model them. In the present paper we demonstrate the application of Cognitive Reliability and Error Analysis Method (CREAM) in manual assembly. Through the knowledge of experts Cream permit to highlight the main cognitive errors, their impacts and to elicit these errors quantitatively.*

KEYWORDS: *Cream, manual assembly, human errors, cognitive reliability*

1 INTRODUCTION

This work was motivated by the necessity to create a simulation model capable to reproduce a real manual automobile assembly line with a high degree of details. Under *degree of details* we understand not only the total correspondence with real assembly operation sequence and physical size of production line, but also all unpredictable events that can occur during assembling. Under unpredictable phenomena we understand uncertainties linked to manual assembly process: availability of resources, delivery delays, inaccuracies in the technical information, breakdowns of working tools, etc. There exist a vast number of papers proposing methods to treat these types of uncertainties. In the present work we focus our attention on human related uncertainties. Among them can be cited operator's errors, misunderstandings, oversight mistakes, etc.

Assembly process we should model is specific because products have different degrees of complexity, maturity, different routing and processing times. It means, for example, that we cannot use the standard average processing time to model the duration of an assembly operation. We should take into account the difficulty and novelty of operations (products), the experience of the operator and other cognitive factors that can have an influence on performance. But the main difficulty is the absence of adequate historical data and models of the human factors impact.

In this paper we propose the application of the CREAM method for an assembly line but beyond this particular case we want to show that it is possible to use this approach to model the cognitive aspect in manufacturing systems in general. The rest of the paper is organized as follows. Section 2 contains a few examples of papers where authors made an attempt to model human factors. In the second part on this section we speak about specific methods (of Human Reliability Analysis) that characterize the human behaviour in terms of cognition processes. In Section 3 we demonstrate the application of CREAM via an example of a generic assembly task and discuss obtained results.

2 LITERATURE REVIEW

Among all papers discussing uncertainties related to humans we can distinguish two principal groups. The first group tries to adopt the standard mathematical approaches, like probability theory, fuzzy logic or models created due to the existence of a large amount of historical data. The second group of papers covers methods of Human Reliability Analysis (HRA) that studies human reliability and performance and the influence of different human factors on them. Note that the ergonomics of working place and methods of it optimising are not considered in this paper.

The problem of the influence of some factors on human performance in automotive industry was studied by (Baines et al. 2004). The aim of their paper was to find how to decrease the difference between reality and simulated human performance, consequently improving the quality of the simulation's prediction. However, authors were looking for a mathematically well explained and argued models, easy to implement. As a result, two models/performance related theories were chosen: *daily biological rhythm* and *age*. To model changes in the operator's performance due to biorhythms, Spenser's (1987 cited Baines *et al*. 2004) model was used. In this case, human's performance can be calculated by mathematical equation and depends on the time of the day and time since sleep. As for second model, authors used those of Warr (1995 cited Baines *et al*. 2004), which assumes that performance decrements linearly starting from 30 years until 65, where the impact is maximal. Simulation of the manufacturing process showed that model is sensitive to the ageing model: cycle time can increase up to 35%; by cons biorhythms are not capable to change the performance significantly.

The objective of the paper of (Mason et al. 2005) was to find a valid method to model *human performance variation* (HPV) within simulation tools. Authors have chosen a statistical representation of HPV; they tested four types of probability distributions (Pearson IV, Normal, Weibull and Gamma) across 10 operations and concluded that in terms of the r^2, Pearson type IV distribution gives the most reliable fit.

(Song *et al*., 2006) pointed out that labor processing time depends on a number of factors, as size of product, its material, specifications, equipment efficiency, labor skill level, and shift arrangement. So the classical method of its estimation doesn't give satisfactory results. Authors proposed to integrate simulation and Artificial Neural Networks (ANN) to model manual processing times. Factors influencing productivity can be divided into two groups: related either to *product complexity* or *working environment*. The main drawback of the method is the necessity of possessing the historical data to train the ANN models, which is often not the case.

Labor related uncertainty was also considered in (Ali and Seifoddini 2006). Inter alia the focus was pointed out on worker's experience, age and working environment factors. Fuzzy numbers were used to represent different factor levels. Once more, the final objective was to create an adequate simulation model (within ARENA). Authors demonstrated that taking into account aforementioned human factors can considerably improve the accuracy of simulation model.

Uncertainty modeling approaches proposed in the papers cited above can be used to take into account *some* of the human factors, but give no answer on *how we can model failures and errors committed by operators*. This is the reason we decided to use one of the HRA techniques.

A review of human reliability assessment methods was made in (Bell, J., Holroyd, J. 2009). Authors found 35 potentially relevant methods, but detailed analysis was only made for 17 of them, the most interrelates for *Health and Safety Laboratory*. Among them, 8 were consumed and might be used only in nuclear domain; 5 characterized as methods for use in "nuclear with wider application"; only 4 of them were *generic*.

From 9 HRA approaches that can be used for manufacturing problems, 5 belong to the so-called "1st generation" of methods. Their objective is to find the *Human error probability* (HEP). Prediction is mainly based on the skill and rule base level of human action and does not take into account context, errors of commission, etc. The list of shortcomings of first generation methods can be found in (Hollnagel E., 1998). Second generation methods complete the methods of the first generation by including the lacking elements. Cognitive Reliability and Error Analysis Method (CREAM) is one of the most known approaches of the second generation. For the first time it was proposed in (Hollnagel E., 1998).

Cream was chosen for the further utilization because it satisfies ours principal criterions:

- It provides qualitative results, expressed in an easy to use and interpret form;
- It can be applied by a person having a good knowledge of the production process and production line specificity;
- It doesn't require historical and statistical data;
- It takes into account the influence of working environment (including complexity and diversity of final products) on operator's performance;
- It stays comprehensive and handy.

The majority of papers discussing method CREAM found in the literature propose different mathematical methods to improve the quantification of HEPs. So, (Konstandinidou *et al*. 2006) proposed the use of fuzzy logic to model the parameters of method CREAM. Work was extended in (Marseguerra *et al*. 2006) to quantitatively capture the uncertainties caused by lack of data and information. Another example is the paper of (Kim *et al*. 2006), this time a probabilistic approach (Bayesian networks) was proposed.

(He et al., 2008) proposed a simplified method to realize the quantifying process of CREAM. Authors supposed that changes in human reliability could be represented by a logarithmic function. Application of simplified version of CREAM is demonstrated via two *type C* human actions (isolation of ruptured steam generator, and the cooling and depressurizing of the primary loop,) after Steam generator tube rupture (SGRT) initial event.

In the following section we demonstrate that method CREAM can really be used to estimate the HEP in manufacturing industry.

3 APPLYING CREAM IN MANUAL ASSEMBLY

There exist two modes of CREAM – *retrospective* and *predictive*. As the objective is an estimation of human related risks, we are interested in the predictive mode of CREAM. Two versions of predictive CREAM were proposed: *basic* and *extended*. The basic version consists in an examination of *Common Performance Conditions* (CPCs) for analysed task and determining a control mode, which characterize the comportment of a person. In other words, it can provide the general action's probability of performing the task incorrectly. In this case the analysis is not focused on what exactly should be done in terms of cognitive human activities. The extended version of the method uses the results of the basic and further develops it in order to distinguish the most probable failures for each segment of analysed task and estimate the error's probability for each of them.

Remember, the objective of our work is to obtain quantified data for each probable human error, thus the basic version of cream is not relevant for us. Therefore, the choice of the extended version of CREAM becomes evident. In the present paper, presentation of the method includes five following steps:

1. Construction of event sequence for a task chosen to analysis;
2. Examination and assessment of CPCs levels;
3. Developing of a cognitive demand profile;
4. Identifying of likely cognitive function failures;
5. Determining the specific action failure probability.

Each step of the approach is explained in a separate sub-section. In parallel we propose the complete analysis of an assembly task to have an illustration of the method. As we'll see, it is enough to have a good knowledge of the considered manufacturing system to use Cream.

3.1 Construct the event sequence

The purpose of this step is to provide a detailed analysis of a task (create an event sequence), that shall be a basis for all other steps. We'll use the Hierarchical task analysis (HTA) to do it. The idea is in following: we make a list of main task's steps that constitute the task and decompose them until the sub-steps represent the elementary actions (or the desired level of details is reached).

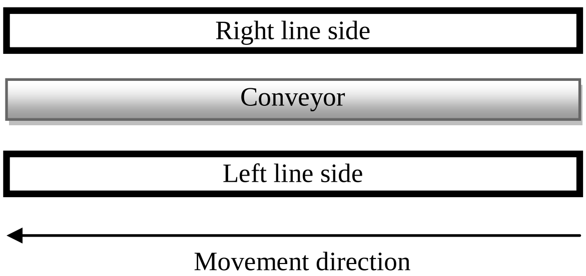

Figure 1: Simplified schema of assembly line

A simplified schema of the assembly line is presented in Figure 1. It consists of a *conveyor* which moves continuously at low speed, *products* to be assembled laid down on the conveyor, and two *line sides* – right and left. Line sides are used as mini part stocks, i.e. all part necessary for product assembling should be delivered and placed in corresponding location before assembling is launched. Note that assembly process is completely manual. In contrast to a great part of already existing literature's papers, we consider that human performance cannot be simulated and modelled similarly to those of machines. It depends on working conditions, operator's qualification, adequate organisation of production processes, etc.

As a demonstration example we'll use a Manual Kit Assembly Operation (MKAO). Considered assembly line imposes some specific conditions explained below. Before each operation, an operator should consult the *instruction sheet*. Information about each operation includes its *type*, the type and *reference* of part involved, its *location* at the line side, type and name of necessary *assembly tool*, the exact location of action (screwing in our case), etc. Next, the operator should go towards corresponding line side (right or left, see Figure 1), and find necessary part (or *kit*) using the *part reference*. Here kit is a set of pre-assembled parts. Then part should be positioned to the *corresponding place* on the product to assemble. Afterwards, the operator takes (if necessary) corresponding *assembly tool*, for example a drill or a screwdriver, and realize the operation. After that he should *drop* the tool on its place and accomplish the *visual inspection* of the operation performed to ensure its correctness. The last step is to *make a note* about performed operation in the vehicle log book

The result of Hierarchical Task Analysis for considered assembly task MKAO is presented in following list:

- **a.1.** *Read* the instruction
- **a.2.** *Move* to the line-side
- **a.3.** *Find* the part
- **a.4.** *Move* to assembled object
- **a.5.** Establishment of the kit (on their place)
- **a.6.** Assembly
    - **a.6.1** Find and Take a screwdriver
    - **a.6.2** Screwing
    - **a.6.3** Drop the screwdriver
- **a.7.** Visual inspection
- **a.8.** Fill a log book

As stated above, the list represents all main steps that an operator realise to accomplish an assembly task.

3.2 Examination and assessment of the work conditions

Context information has a very important role in defining possible error modes. It represents the *work conditions* under which the task is performed, i.e. results can be different for a given task performed under different conditions. (Hollnagel 1998) pointed out that working conditions can be characterized using 9 factors, called *Common Performance Conditions* (CPCs). They are, *Adequacy of organization*; *Working conditions* (physical aspect like lightening, noise, interruptions, etc.); *Adequacy of MMI (Man-Machine Interface) and operational support* (plant interface, indications or available information); *Availability of procedures/plans* (availability and quality of procedural guidance);

Number of simultaneous goals (task complexity); *Available time* (or availability of time); *Time of day* (day/night); *Adequacy of training and preparation*; *Crew collaboration quality*.

These nine CPCs represent a minimal set of disjoint factors influencing on human performance. The general principle here is that advantageous CPCs can improve human performance (operator will be more productive and will make less errors), while disadvantageous can reduce it.

3.2.1 CPC levels assessment

First part of the Step 2 is the *assessment* of CPCs *levels* for the considered task. All possible levels for each CPCs are presented in the second column (named CPC level) of Table 1. This operation should be performed by a person (*analyst*) with a good general knowledge and visibility of the considered system. For the assembly task MKAO, assessed CPC levels are presented in Table 1 and highlighted in bold.

As it was mentioned earlier, MKAO is an assembly task taken from automotive industry. Below we explain our choices of CPC levels.

- Generally, production line is operated by a quite experienced staff, so it is assumed that the *adequacy of the organization* level is *efficient*.
- Considered assembly line is located in a separate close placement with a good lightening and heating, which permit to conclude that we have an *advantageous* level of *working conditions*.
- Operators of the line have detailed assembly plans, light indicators and informatics support so the Adequacy of MMI and operational support CPC is of *supportive* level.
- Because of the presence of product of low maturity and high complexity, assembly documentation can have some inaccuracies or even be incomplete. Which is the reason the level of *availability of procedures/ plans* CPC is only *acceptable*.
- The *number of simultaneous goals* is the amount and difficulty of tasks a person is supposed to carry on at the same time. Its CPC level is assumed to be *matching current capacity* because at that moment operators are not really time limited but they have to perform multiple tasks at the same time (each operator should acquire new information, perform the action and control the effect of his action).
- *Available time* was determined *temporarily inadequate* for the same reason (see previous point).
- One of particularities of the line is the necessity to perform operator's training. The fact that there are few experienced operators permits us to determine the *adequacy of training and preparation* level as *adequate with low experience*.
- Operators work in small teams, so the Collaboration quality is supposed to be *very efficient*.

CPC Name	CPC Level	Expected effect on performance reliability
Adequacy of organization	Very efficient	Improved
	Efficient	**Not significant**
	Inefficient	Reduced
	Deficient	Reduced
Working conditions	**Advantageous**	**Improved**
	Compatible	Not significant
	Incompatible	Reduced
Adequacy of MMI and operational support	**Supportive**	**Improved**
	Adequate	Not significant
	Tolerable	Not significant
	Inappropriate	Reduced
Availability of procedures/ plans	Appropriate	Improved
	Acceptable	**Not significant**
	Inappropriate	Reduced
Number of simultaneous goals	Fewer than capacity	Not significant
	Current capacity	**Not significant**
	More than capacity	Reduced
Available time	Adequate	Improved
	Temporarily inadequate	**Not significant**
	Continuously inadequate	Reduced
Time of day	**Day-time (adjusted)**	**Not significant**
	Night-time (unadjusted)	Reduced
Adequacy of training and preparation	Adequate high experience	Improved
	Adequate low experience	**Not significant**
	Inadequate	Reduced
Crew collaboration quality	**Very efficient**	**Improved**
	Efficient	Not significant
	Inefficient	Not significant
	Deficient	Reduced

Table 1: Common performance conditions for the task MKAO

The possible relations between CPCs levels and influence of CPCs on performance reliability (PR) were also proposed in (Hollnagel 1998). They are bimodal and based on general human factor knowledge. There are three types of effects of CPC on PR: *improved*, *not significant* and *reduced*. *Not significant* effect means that it is relatively small and in general it is not possible to determine whether the effect on performance reliability will be positive or negative. In our case (highlighted in grey in Table 1), there are three CPCs that have positive effect on PR, six with no significant effect and no one with a reduced. The kind of relations explained here called ***direct***. However, there exist dependencies between CPCs and in the case of "*not significan*t" direct effect, *indirect* or *mediated* relation may take place. Next subsection covers this aspect.

3.2.2 Auto dependency of Performance Conditions

The second part of the Step 2 is about verifying whether any *CPC should be adjusted* or not. It is assumed in Cream that all CPCs except "time of a day" and "adequacy of organization" depend on each other. Table 2 shows the dependency (correspondent cells are in gray) between the CPCs. Each grey cell means that the CPC in the *left hand column* (the same line) is affected by the CPC from the *upper cell* of the same row).

CPCs Name	Adequacy of organization	Working conditions	Adequacy of MMI and op. supp.	Availability of procedures/ plans	Number of simultaneous goals	Available time	Time of day	Adequacy of training and prepar.	Crew collaboration quality
Adequacy of organization	■								
Working conditions	+	■	+			+	+	+	
Adequacy of MMI and operational support	+		■						
Availability of procedures/ plans	+			■					
Number of simultaneous goals		-	-	-	■				
Available time		+	+	+	-	■	+		+
Time of day							■		
Adequacy of training and preparation	+							■	
Crew collaboration quality	+							+	■

Table 2: Dependence between CPCs (Hollnagel 1998)

Thus, *available time* CPC depends on the 6 following CPCs: working conditions, adequacy of MMI, availability of procedures, number of simultaneous goals, time of day and crew of collaboration quality. In this table "+" represents direct CPC dependency (increase-increase and decrease-decrease) and "-" denotes inverse dependency (decrease-increase and increase-decrease). For example, *available time* inter alia depends from *time of day* and *number of simultaneous goals*. Time of day CPC has a direct influence (+) on available time, so if it is improved, then *available time* is assumed to improve also (and vice versa). Dependency of available time on the number of simultaneous goals is indirect (-), so when *number of simultaneous goals* is improved *available time* is assumed to be reduced (and vice versa). It was assumed that an ***indirect effect*** can be produced (expected effect on performance can be changed) on a given CPC **only if** all the following conditions are satisfied:

a) It depends on **more than one** other CPC (Table 2)
b) Primary effect of this CPC is "**Not Significant**" (Table 1)
c) Majority of CPCs that have an influence on it are **synergistic** (i.e. point in the same direction).

First requirement is satisfied for four CPCs (in all cases): *working conditions* (depends on 5 CPCs), *number of simultaneous goals* (depends on 3 CPCs), *available time* (depends on 6 CPCs) and *crew collaboration quality* (depends on 2 CPCs). For the two subsequent requirements we consider only these four CPCs.

Primary effects for each CPCs should be taken from Table 1 (column 3). For task MKAO the primary effects are following:

Working conditions — improved
Number of simultaneous goals — *not significant*
Available time — *not significant*
Crew collaboration quality — improved

So, **second requirement** is true only for *Number of simultaneous goals* and *Available time* CPCs.

Third condition is to verify whether the majority of CPCs which have an influence on the considered one are synergistic or not. All CPCs satisfying both criterions have to be verified in order. This "majority" was defined in the following way: 4 of 5 for working conditions; 2 of 3 for number of simultaneous goals; 4 for available time; 2 of 2 for crew collaboration quality. For the task MKAO, the primary effects of *number of simultaneous goals* and *available time* can be changed. In Table 3 we show the three CPCs that have an influence on number of simultaneous goals and *available time* (first column), their primary effects on performance (column 2), and character of dependency ("+" or "-", column 3).

Influencing CPCs	**Primary effect**	**+/-**
Number of simultaneous goals		
Working conditions	Improved	—
Adequacy of MMI and op. supp.	Improved	—
Availability of procedures/plans	Not significant	—
Available time		
Working conditions	Improved	+
Adequacy of MMI and op. supp.	Improved	+
Availability of procedures/plans	Not significant	+
Time of day	Not significant	+
Crew collaboration quality	Improved	+

Table 3: Indirect dependency for *number of goals* CPC

To have an effect on *number on simultaneous goals*, a minimum of two of three CPCs should be synergistic. As an example: *working conditions* and *adequacy of MMI and operational support* have "*improved*" primary effect. In the third column we see a sign "—", which means that the dependency is inverse – *increase-decrease*, because the primary effect of two CPCs is "improved". That way we should change the CPC level of *number of simultaneous goals* to *fewer than capacity*, which also corresponds to "*not significant*" effect on PR. For the second CPC (*available time*) only three CPCs which have an influence on it are synergistic, so the third condition is not satisfied.

3.3 Build a Cognitive demand profile

The following step of CREAM is to build a *cognitive demand profile* in order to understand which specific cognitive activities are involved to accomplish the task and which kind of failures (errors) are the most susceptible to happen.

We distinguish following fifteen critical cognitive activities: *co-ordinate, communicate, compare, diagnose, evaluate, execute, identify, maintain, monitor, observe, plan, record, regulate, scan*, and *verify*. Each of these activities corresponds to an elementary action of a person. This list of activities was taken from (Rouse 1981, cited Hollnagel 1998) and (Barriere et al. 1994, cited Hollnagel 1998).

The construction of a cognitive demand profile begins with the allocation of a single cognitive activity to each task's step of MKAO. If it appears that it is not possible to choose a *predominant* cognitive activity for a given task's step, the first step of CREAM should be resumed because of an insufficient level of detail, i.e. the task's step should be divided further. The procedure should be repeated until getting rid of the ambiguity in cognitive activity assessment.

Cognitive activities retained for our example are listed in Table 4. So task's step **a.1** corresponds to *observation* activity (read specific measurement values or system indications); task's steps **a.2**, **a.4** and **a.6.3** are considered as not cognitive; task's steps **a.3** and **a.6.1** correspond to *identify* activity (specific operation retrieve information and investigate details); task's steps **a.5** and **a.6.2** represent *execution* activity (perform a previous specified action); **a.7** is an *evaluation* (related terms are "inspect" and check); finally, task's step **a.8** corresponds to *record* cognitive activity (write down or log system events).

Step #	**Task's step or activity**			**Cognitive activity**
a.1	*Read* the instruction			Observe
a.2	*Move* to the line-side			*Not cognitive*
a.3	*Find* the part			Identify
a.4	*Move* to assembled object			*Not cognitive*
a.5	Establishment of the kit			Execute
a.6	Assembly	***a.6.1***	Find and Take a screwdriver	Identify
		a.6.2	Screwing	Execute
		a.6.3	Drop the screwdriver	*Not cognitive*
a.7	Visual inspection			Evaluate
a.8	Fill a log book			Record

Table 4 : Cognitive activities for the example task

Hereinafter we'll take into account only cognitive activities, so steps **a.2**, **a.4**, and **a.6.3** appear outside of analysis.

The current version of CREAM includes four cognitive functions: *observation, planning, interpretation* and *execution*. Each cognitive activity is associated with one or several cognitive functions and can be described by a corresponding combination. Table 5 provides the cognitive demand matrix. Lines corresponding to the cognitive activities involved to the analysis of the task MKAO are highlighted in gray. This way *evaluate* is the combination of *planning* and *interpretation*; *record* is the *combination* of *planning* and *execution*; *execute*, *identify* and *observe* activities correspond to *execution*, *planning* and *observation* function correspondingly.

Activity type	**Cognitive function**			
	Observation	Interpretation	Planning	Execution
Co-ordinate			X	X
Communicate				X
Compare		X		
Diagnose		X	X	
Evaluate		X	X	
Execute				X
Identify		X		
Maintain			X	X
Monitor	X	X		
Observe	X			
Plan			X	
Record		X		X
Regulate	X			X
Scan	X			
Verify	X	X		

Table 5: A generic cognitive-activity-by-cognitive-demand matrix (Hollnagel 1998)

Sometimes it is relevant to represent the cognitive demand profile of a task in a bar-chat diagram (for MKAO task see Figure 2). This diagram was deftly obtained by counting the number of occurrences of each cognitive function in MKAO. According to the figure, the dominant cognitive function of the task MKAO is *interpretation*, important part intended for *observation* and *execution*.

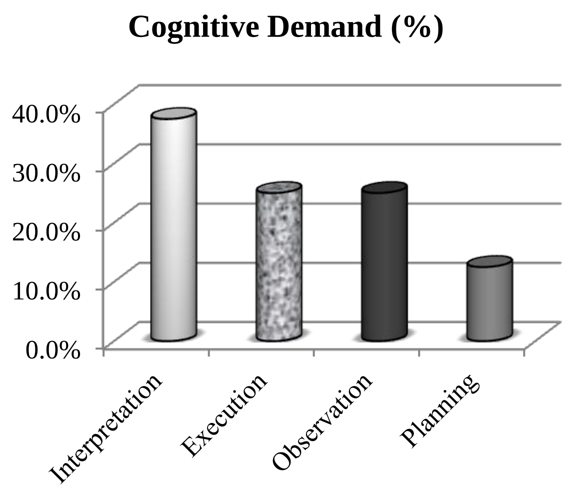

Figure 2: Cognitive Demands profile for MKAO

3.4 Identify likely cognitive function failures

The purpose of this step is to determine the *predominant types* of expected failures for a whole task. The complete list of *Cognitive Function Failures* (CFF) with short descriptions is presented in Table 6. This list includes the main failure modes for four cognitive functions (see the precedent subsection).

Cognitive function	**Potential cognitive function failures**	
Observation errors	*O1*	Observation of wrong object
	O2	Wrong identification made
	O3	Observation not made
Interpretation errors	*I1*	Faulty (wrong or incomplete) diagnosis
	I2	Decision error (not making or wrong decision)
	I3	Delayed interpretation (not in time)
Planning errors	*P1*	Priority error
	P2	Inadequate plan formulated
Execution errors	*E1*	Execution of wrong type (force, distance, speed or direction)
	E2	Action at wrong time
	E3	Action at wrong object
	E4	Action out of sequence
	E5	Action missed (not performed)

Table 6: Generic cognitive function failures (Hollnagel 1998)

Having this list and taking into account CPCs, the analyst with a good knowledge of both a system and the task is capable of deciding which cognitive function failure is most likely for each task's step.

Step #	**Task's step or activity**			**Potential failures**
a.1	*Read* the instruction			O1, O2, O3
a.3	*Find* the part			I1, I2, I3
a.5	Establishment of the kit			E1, E2, E3, E4,E5
a.6	Assembly	a.6.1	Find a screwdriver	I1, I2,I3
		a.6.2	Screwing	E1, E2, E3, E4,E5
a.7	Visual inspection			I1, I2,I3, P1, P2
a.8	Fill a log book			I1, I2,I3, E1, E2, E3, E4, E5

Table 7: Possible failure modes for MKAO task

In Table 7 we give the set of potential CFFs for each task's step of MKAO (obtained by the combination of Tables 4, 5 and 6). The objective of the expert in this step is to choose one (the most probable) CFF for each task's step. The choices for MKAO are explained in the list below:

- Reading instruction (**a.1**) implies consulting the corresponding instruction sheet. Errors of types (O1) (O3) are less probable, because of the specificity of the assembly process (see subsection 3.1), by cons *Wrong identification* (**O2**) can be made because of the novelty and diversity of the assembled product.
- Task's step **a.3** consists on finding the necessary part, having its location and reference. This way *faulty diagnosis* (I1) and *delayed interpretation* (I3) are not suitable for the case. *Decision* error (**I2**) is therefore chosen as the most probable CFF.
- The following task's step (**a.5**) consists on putting the part to the right location on the product. *Sequence* (E4) and *time* (E2) failures types are not relevant. We consider that having the part in its hands, the operator cannot *forget* to place it (E5), as well as he cannot put it with *wrong speed* or *direction* (E1). Whereas *mix-up* and *location* errors (**E3**) are probable for this step.
- The looking up of the necessary tool (**a.6.1**) process is analogical to the step **a.3**. So the predominant CFF for this task's step is *decision error* (**I2**).
- Screwing operation (**a.6.2**) is the assembling of early posed parts. Logically we can exclude the errors of *wrong timing* (E2), *object* (E3), *sequence* (E4), and *missed action* (E5). While *insufficiently screwed* part problem (**E1**) can appear.
- Visual inspection of performed operation (**a.7**) consists in checking if there is any visible problem to the naked eye. We can eliminate *planning failures* (P1 and P2), because of their irrationality for this task. The most probable error that an operator can commit is the *non-detection* of an anomaly, which corresponds to a *faulty* (wrong or incomplete) *diagnosis* (**I1**).
- Finally, the most relevant fault for the recording task (a.8) is *action missed* (**E5**) (forgetfulness of operator).

In Table 8 we present the recapitulative of possible failures analysis. CFFs that correspond to each task's step are highlighted in gray. The last row of the table demonstrates the total quantity of each CFF encountered in task MKAO.

Step #	**Task's step or activity**			Observation			Interpretation			Planning		Execution				
				O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5
a.1	*Read* the instruction				■											
a.3	*Find* the part							■								
a.5	Establishment of the kit													■		
a.6	Assembly	***a.6.1***	Find a screwdriver					■								
		a.6.2	Screwing									■				
a.7	Visual inspection						■									
a.8	Fill a log book															■
			Totals		**1**		**1**	**2**				**1**		**1**		**1**

Table 8: Likely failure modes for MKAO

Analogically to cognitive demand profile analysis, data from Table 8 can be represented by a bar-chat diagram (see Figure 3) of the "predominant error tendencies in the task". Note for task MKAO the *cognitive demand* and *cognitive function failure* profiles are different. It can be explained by the fact that for each task's step we have to choose the most probable failure type. In such a way, the most probable failure types for MKAO are *interpretation* and *execution* (42%). For the more complicated tasks, a bar-chat diagram can be built for each segment of task separately. In this case we can detect that different types of preventive actions are needed for each task segment.

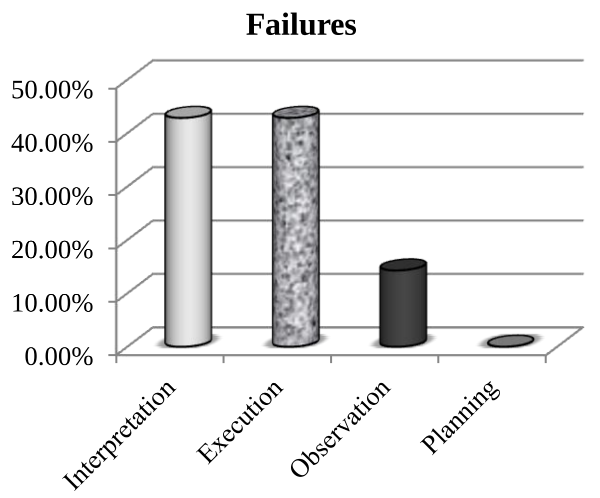

Figure 3: CFF profile of the MKAO

The result of this analysis provides important information to the company by revealing the priority areas for improvement and development in its action plans. If one realize only qualitative analyse of a task, information given by Figure 3 can be used for establishing necessary preventive procedures to decrease the chances of failures occurring.

3.5 Determine failure probability.

From this we proceed to quantitative analysis of human related uncertainties. Having the cognitive function failures for each step of task MKAO, we will determine the *Cognitive Failure Probability* (CFP) for each of them. This step consists of two stages: 1) assigning the nominal CFPs; 2) counting of CPCs effects on the nominal CFP values.

To make the article self-sufficient, we provide the Table 9 with the nominal cognitive probability values extracted from (Beare et al. 1984, Gertman and Blackman 1994, Swain and Guttman 1983, and Williams 1989 cited by Hollnagel 1998). For each failure type there are three values: *nominal* value and its *uncertainty bounds* (5^{th} and 95^{th} percentiles).

Failure type	**Nominal values of CFP**		
	Lower bound (.5)	*Basic value*	*Upper bound (.95)*
O1	3^{e-4}	1^{e-3}	3^{e-3}
O2	2^{e-2}	7^{e-2}	1.7^{e-2}
O3	2^{e-2}	7^{e-2}	1.7^{e-2}
I1	9^{e-2}	2^{e-1}	6^{e-1}
I2	1^{e-3}	1^{e-2}	1^{e-1}
I3	1^{e-3}	1^{e-2}	1^{e-1}
P1	1^{e-3}	1^{e-2}	1^{e-1}
P2	1^{e-3}	1^{e-2}	1^{e-1}
E1	1^{e-3}	3^{e-3}	9^{e-3}
E2	1^{e-3}	3^{e-3}	9^{e-3}
E3	5^{e-5}	5^{e-4}	5^{e-3}
E4	1^{e-3}	3^{e-3}	9^{e-3}
E5	2.5^{e-2}	3^{e-2}	4^{e-2}

Table 9: Nominal values and uncertainty bounds for CFF (Hollnagel 1998)

Nominal CFP value for each task's step is the *Basic value* from Table 9. For example, for the task's step **a.1** with probable CFF **O2** the nominal CFP is equal to 7^{e-2}, for the task's step **a.3** (CFF **I2**) the nominal CFP equals to 1^{e-2}, etc. Nominal CFPs for all task's steps of MKAO are presented in Table 11 (see columns 1-3).

CPC Name	**CPC Levels (for task MKAO)**	**Cognitive functions**		
		OBS	INT	EXE
Adequacy of organization	*Efficient*	1	1	1
Working conditions	*Advantageous*	0.8	0.8	0.8
Adequacy of MMI and operational support	*Supportive*	0.5	1	0.5
Availability of procedures/ plans	*Acceptable*	1	1	1
Number of simultaneous goals	*Fewer than capacity*	1	1	1
Available time	*Temporarily inadequate*	1	1	1
Time of day	*Day-time (adjusted)*	1	1	1
Adequacy of training and preparation	*Adequate, low experience*	1	1	1
Crew collaboration quality	*Very efficient*	0.5	0.5	0.5
	Total influence of CPCs	**0.2**	**0.4**	**0.2**

Table 10: Assessment of the effects of CPCs on CFF

The second part of this step is to account for the effects of CPCs on CFPs using the *weighted factors* of each CPC level on all cognitive function failures. The principle is as following: if the expected effect is "*not significant*" the weighted factor is equals to 1 (the nominal CFP value won't be changed); otherwise, the weighted factor is determined depending on the influence of a given level of each CPC (out of 9) to a given cognitive function (out of 4). Full version of the table reader can be consulted in (Hollnagel 1998).

Table 10 contains only values that will be used for further analysis of task MKAO (remember the expected effect of number of simultaneous goals was changed to *reduce*). The first column contains the list of all CPCs. The second shows the level of each CPCs for task MKAO (see subsection 3.2). We haven't CFFs of planning, so weighted factors for this cognitive function are not presented. In Table 10 the following abbreviations were used: OBS for observation, INT for interpretation and EXE for execution cognitive function. Note that weighted factor for all failure modes of the cognitive function is the same. The summary influence of CPCs on each cognitive function can be calculated by multiplying the weighted factors of nine CPCs. Results are reported in the last line of Table 10.

Step #	Failure type	Nominal CFP	Weighting factor	Adjusted CFP
a.1	O2 (OBS)	7^{e-2}	0.2	14^{e-3}
a.3	I2 (INT)	1^{e-2}	0.4	4^{e-3}
a.5	E3 (EXE)	5^{e-4}	0.2	1^{e-5}
a.6.1	I2 (INT)	1^{e-2}	0.4	4^{e-3}
a.6.2	E1 (EXE)	3^{e-3}	0.2	6^{e-4}
a.7	I1 (INT)	2^{e-1}	0.4	8^{e-2}
a.8	E5 (EXE)	3^{e-2}	0.2	6^{e-3}

Table 11: Adjusted CFPs for cognitive function failures

Thus, having the total weighted factor we can calculate the adjusted probability values for each task's step. For that it is necessary to multiply the nominal CFPs of each task's step (see column 3 of Table 11) by the corresponding CPCs weighted factor (column 4 of Table 11). In the result (Column 5 of Table 11) we have the adjusted CFPs for the most probable failure for each task's step. Obtained probability values can be used forthwith in the simulation model of the assembly line.

The final step of Hollnagel's CREAM is to incorporate the CFPs into Event Trees, i.e. getting a single probability value of a task failure. In our case all obtained probabilities will be incorporated into the simulation model, so this last stage can be omitted.

3.6 Discussion

The summary of the method is outlined in schematic form in Figure 4. Analysis direction is marked by horizontal grey arrow that crosses the figure. The upper half of the figure enumerates the data provided by CREAM, while the lower half summarizes the expert's contribution.

As we can see, the role of the expert's evaluation is an essential element of the analysis. In the beginning, the perfect understanding of the studied process is indispensible to perform correctly detailed *hierarchical task analysis*. Then, a global knowledge of the plant environment is necessary to estimate the levels of 9 *Common performance conditions*. The following step is to work out the *predominant cognitive activity*. This requires a good knowledge of the procedure to be followed for each task's step. Finally, expert should have enough data and make enough observation to choose the *most probable failure types*. Because of the necessity of the presence of an expert, method Cream cannot completely be automated.

4 CONCLUSIONS

In this paper we proposed to use the Cognitive Reliability and Error Analysis Method to qualifying and quantifying the operator's related uncertainties in manufacturing systems. The reasons of choosing this approach are: the analysis is essentially based on expert knowledge and evaluation; there is no necessity to have a big amount of historical and statistical data; method takes internal and external factors that can have an influence on human performance into account; the results expressed as probabilities of an operator's errors, can directly be used in the simulation model and for further study of the production line.

Apart from the obvious quantitative results (human error probabilities), there are two principal qualitative contributions: 1) creation of a cognitive demand profile of the tasks which represent the proportion of activities of each cognitive function; 2) development of a cognitive failure profile giving the proportions of probable failures types for the task (or task stages). The cognitive demand profile is a first approximation of "where the potential problem areas may be". Whereas the cognitive function failure profile shows the predominant error types in the task. Qualitative analysis results represent the essential information for decision makers; they reveal the priority areas for production process improvements.

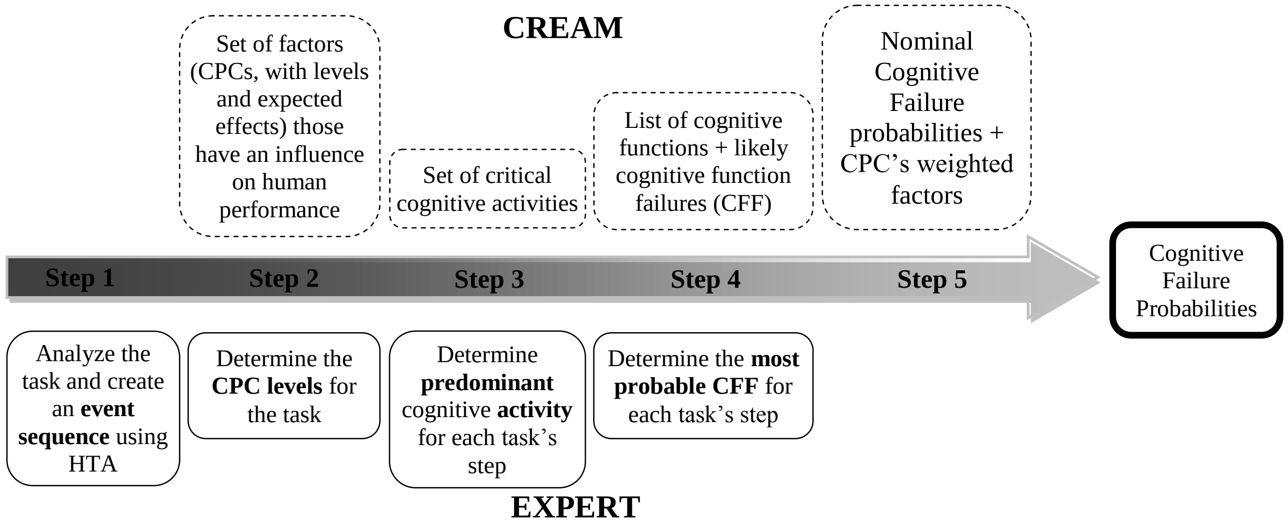

Figure 4: Synthesis of the CREAM and Expert contributions

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