Quantitative analysis of ATM safety issues using retrospective accident data: the Dynamic Risk Modelling Project.

Maria Chiara Leva[1], Massimiliano De Ambroggi[1], Daniela Grippa[2], Randall De Garis[2], Paolo Trucco[1], Oliver Sträter[2]
[1] Politecnico di Milano, DIG Piazza Leonardo da Vinci 32, Milan Italy
[2] Eurocontrol, Bruxelles Safety and Security Management (DAS-SSM) Bruxelles Belgium
Contacts of the corresponding author:
Maria Chiara Leva[1]
Phone +39 0223994053
Fax: +39 0223994067
chiara.leva@polimi.it

Abstract

The Dinamic Risk Modelling was a research project aimed at developing a simulation approach able to provide a quantitative analysis of some critical activities of Air Traffic Control (ATC) operators considering the organizational context in which they take place, the main cognitive processes underneath, and the possibility to inform the analysis using retrospective accident data.

The pilot study was aimed at providing an overview of possible opportunities related to the use of a cognitive simulator within the Eurocontrol framework called CONOPS (which is a detailed description of future operational concept for Air Traffic in Europe).

The approach chosen within the field of HRA (Human Reliability Analysis) made use of a cognitive Simulator (named PROCOS), developed by Politecnico di Milano. The simulator in fact was built based on an Information Processing Level very much compatible with the one embedded in a method used by Eurcontrol for collecting accident data named HERA.

The pilot application was able to modify the calibration process of the simulator and make use of the retrospective accident data that was available.

The resulting approach can interact with standard risk assessment methodologies in order to analyze the criticalities arising from human performance in the ATC working contexts in the light of past experience.

Key words: cognitive simulation; human reliability analysis; Air Traffic Control; Dynamic Risk Modeling.

1. Introduction

Accidents are dramatic examples, amongst other less critical events, pointing out how prospective assessments methods often poorly represent human and organizational aspects and hence limit their value for accident prevention. In order to better anticipate those situations which may lead to accidents, the prospective and retrospective approaches have to be efficiently combined (Sträter, 2005).

Regarding the retrospective analysis of incidents, a research project has been set up at Eurocontrol that reviewed the theoretical and practical literature to determine the best conceptual framework upon which to base an ATM incident analysis tool. The conceptual framework chosen is that of human performance from the perspective of information processing (Isaac et al., 2002).

In order to exploit the data for prospective assessment, the approach of HERA-Predict (Isaac et al., 2004) was designed based on the experiences of using event data for safety assessment in nuclear power plants (Sträter, 2005). The lack of ad hoc data for the quantification process is in fact, one of the main issues affecting HRA applications in Air Traffic Management, the HERA-Predict approach is oriented towards tackling this issue. However the use of incident data for predictive purposes can be very difficult, especially if the prediction would like to refer to possible future scenario that differs from the one from which the data was collected.

Some data can be gathered in real time observations that can make use of virtual reality simulators for real operators to interact with, nevertheless there is a practical limit on the amount of human performance data that can be collected through virtual reality-based study; given that some human error probabilities are in the order of E-03 or even E-04, the amount of trials needed would be extremely high.

In this framework the development of a numerical simulator able to represent the performance of the controller or the team of controllers in a specified context can provide a useful mean for gathering data and analysis safety performance of a system. Such a simulator would be a cognitive one since it requires the capability to represent human performance. On the other side it should have the quantitative capability to produce a sufficient number of trials for gaining an estimation of Human Error Probabilities (HEP) that belong to the orders of magnitude mentioned above. One final requirement is that the tool should make use of retrospective accident data in calibrating its results.

Trucco and Leva (2007), developed a new cognitive simulator (PROCOS) for supporting human reliability analysis in complex operational context. The simulation model comprised two cognitive flow charts reproducing the behavior of a process industry operator. The flow charts were based on a model within an information processing perspective very similar to the one underpinning the HERA-PREDICT classification. Starting from this characteristics in the Dynamic Risk Modeling project it was then possible to modify the simulator in order to take into account a more detailed insight of the context of analysis (Air Traffic Management) and make use of the retrospective accident data suitable for the quantification process. The present paper introduces the main steps through which the project obtained its results.

2. The Use of Cognitive Simulation for HRA Prospective Analysis: PROCOS

A cognitive simulation consists of the reproduction of a model of cognition using a numerical application or computation. While the model of cognition is the theoretical representation of the mental processes and control actions developed by one or more operators during the execution of their tasks, given a physical system and a definite context (Cacciabue, 1998).

A cognitive simulation can be quantitative or qualitative. A qualitative simulation describes the evolution of a cognitive process, i.e. from the reception of an external stimulus to the subsequent action whereas a quantitative one is based on the structure of a qualitative one with the addition of a computational model for the human error probability assessment.

The final outcome of a quantitative simulation can be the list of the types of actions or errors performed by the operator while executing a specific task or a probability value for each type of error, calculated through the simulation runs. Table 1 reports a brief summary of some of the main simulation projects developed in the past twenty years.

Table 1: Review of Cognitive simulators

Name	Model for human-environment interaction	Quantitative or Qualitative	Model for Interaction between operators	Main Characteristics
PROCRU (Baron et al. 1980)	Yes	Qualitative	Yes	It reproduces the behaviour of an aircraft crew made up of three members. Only a qualitative analysis of the communication processes among the member of the crew is performed.
CES (Woods et al 1987)	No	Qualitative and Quantitative	No	It simulates the behaviour of a control room operator in a nuclear power plant in emergency scenarios. Developed using Artificial Intelligence programming. It can not simulate Livewere-Livewere interactions (it does not include a communication module).
COSIMO (Cacciabue et al 1992)	No	Qualitative and Quantitative	No	It simulates the behavior of an operator coupled with a model for the system specific for the one be considered. Can not simulate Livewere-Livewere interactions (it does not include a communication module).
MIDAS (Gore,2002)	Yes	Quantitative	Yes	It is an integrated suite of software components developed to aid designers, and analysts to apply human factors principles and human performance models to the design of complex human-machine systems in aviation.
SYBORG (Takano, 1995)	Yes	Qualitative	Yes	It simulates a group of nuclear power plant operators. It needs input coming from a specific plant simulator. It highlights some possible combinations of operator errors and plant condition that can lead to accident sequences.
TBNM (Shu et al. 2002)	No	Qualitative	Yes	The simulation is made up of three components: a model for the task to be executed, the model of the event development after an initiating event and the model of the team which comprise a human machine interaction model as well. It is focused on Nuclear Power Plants applications.
AITRAM (Mauri et al. 2002)	Yes	Qualitative	Yes	It is able to provide information regarding the possible errors that an aircraft maintenance technician can commit. Only a qualitative analysis is performed.
TOPAZ (Stroeve et al 2006)	Yes	Quantitative	Yes	Based on very complex structure that makes use of Petri Nets. It can implement both quantitative and qualitative analysis; It presents a model for human environment interaction; it is designed for the analysis of very detailed scenarios that are time dependent.
IDAC (Chang and Mosleh 2007)	Yes	Quantitative	Yes	Designed for the application in a Nuclear Field. It simulates the response of a crew in accident conditions (control room). The simulator works only if coupled with a code for accident scenarios simulation that is generated in a discrete dynamic event tree format.

2.1 A semi static approach for a cognitive simulator

The simulator proposed in the present paper is based on a so called "semi-static approach". The word "semi-static" indicates that the dynamism is focused on the cognitive simulation and, therefore, on the cognitive flow chart,while the operator actions are able to modify only the state of some equipment of the plant according to:

- a limited set of the states in which the equipment can be turned;
- the error mode identified through a previous analysis (in this case through HERA) and extracted as a result of the cognitive simulation of the operator;
- an explicit relation between the actions outcomes (correct execution or Error modes) and equipment status modifications (the relation has been derived from a previous qualitative analysis).

Its focus is mainly in conveying a quantitative result, comparable to those of a "first generation" HRA method, taking into account a cognitive analysis of the operator as well.

As a further step the simulator considers the evaluation of error management as part of the overall assessment from the same cognitive point of view, differing from the way traditional human reliability methods (e.g. THERP) consider the recovery phase.

2.2 Cognitive Model of the operator in PROCOS

The model used for configuring the flow chart representing the operators is based on a combination of PIPE (Cacciabue, 1998) and SHELL. PIPE represents the process of human cognition according to the "Minimal Modelling Manifesto" (Hollnagel, 1993). The PIPE model is in fact based on the four main cognitive functions:

- Perception;
- Interpretation;
- Planning;
- Execution.

The cognitive functions are influenced or triggered by input parameters such as hardware stimuli and context stimuli. The human cognitive path followed through these functions leads to a response (output). The cognitive process involved makes use of the memory/knowledge base and allocation of resources of the individual.

The role of PIPE in the simulator entails the structure of the flow chart representing the main possible cognitive processes that an operator could perform in order to perform an action.

SHELL (Software Hardware, Environment, Liveware, Liveware; Edward, 1988) has been considered as a configuration of the elements of the socio-technical environment which entails the human elements in its focal point. In the simulator this configuration has been used for organizing the information regarding the context and the interactions between the controller and other members of the ATM team or the pilots (Liveware), the equipment (Hardware), the procedures (Software) and so on.

The development of flow charts for representing the cognitive process is within a “information processing perspective” and it could be a good approach for case studies where the tasks to be analyzed are highly proceduralised. Furthermore it presents the advantage of mapping the possible information and decision making processes in an intuitive way that can be followed and revised even from external reviewers.

The taxonomy chosen for describing possible erroneous outcomes of a human performance in the simulator relates to the “presumed origin of an error within the stages involved in conceiving and then carrying out an action sequence” (Reason, 1990), they are therefore called “Error Types”. They are classified according to Wickens (1992).:

- Error in Perception: errors regarding issues related to the picking up and understanding of information;
- Error in Memory: errors related to both short-term storage and more permanent information based on the person’s training and experience;
- Error in Decision: errors related to the judgment and decision making process required to the operators;
- Error in Response: it is sometimes possible to carry out actions that have not been intended, an example of this is often referred as a slip of the tongue.

2.3 Architecture of the simulator

The structure of the simulator is represented in Figure 1 and it is based on:

- the Operator Module, which imply the cognitive flow charts for Action execution and Recovery phase, plus an error types/error modes matrix that puts in relation each error type category with a set of possible error modes (which are the analogous of the error details). A critical underlying feature of this module is the mathematical model for decision block criteria of the flow charts, since it is the engine of the stocasticity in the simulation;
- the Task Execution Module, based on the Task Analysis referred to the procedure that has to be simulated;
- the Human Machine Interface Module, made up of tables relating the hardware state with the operator actions (task executed or error modes committed).

The Inputs required for the simulation process are:

- Contextual Conditions (CCs) affecting the task to be simulated;
- hardware involved in the execution of the task and its possible states;
- steps of the task (Task Analysis);
- possible error modes to be considered.

The task execution module consists of the task analysis developed through a flow chart and its translation into the simulation code which normally happens through a table format (an example of it is reported in Table 2).

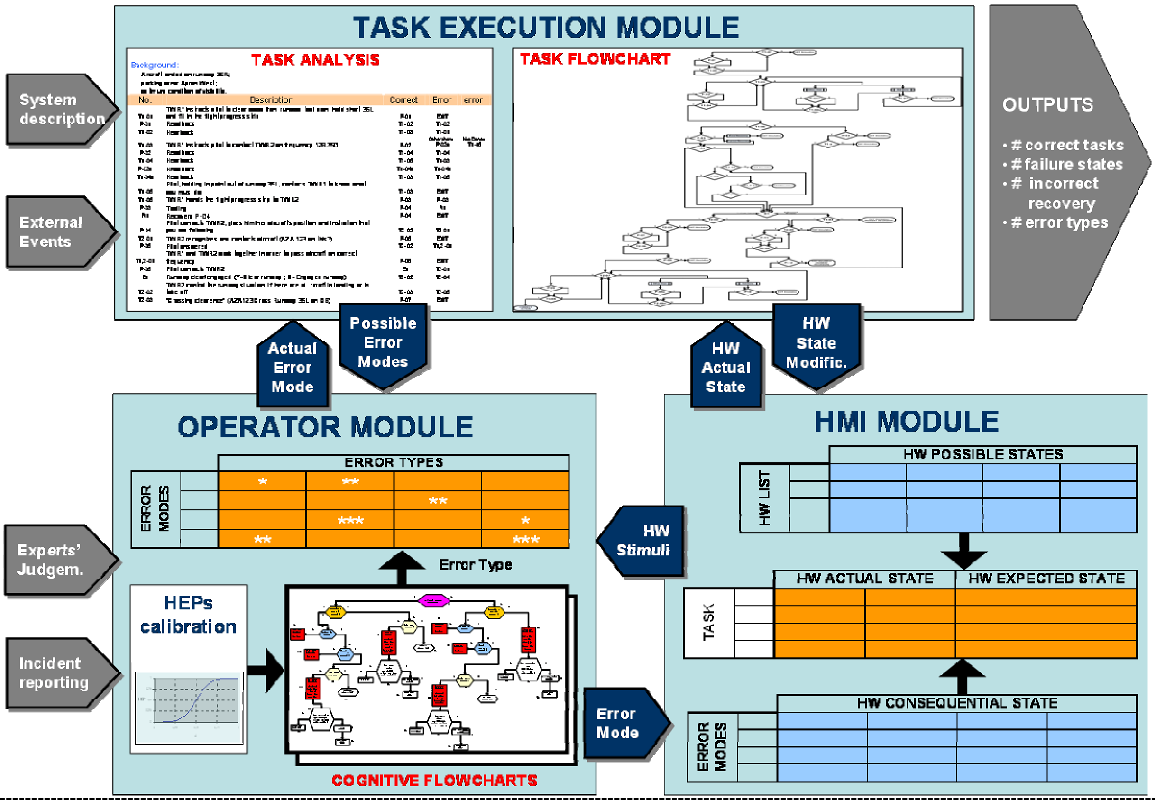


Figure 1: Architecture of the simulator PROCOS

Table 2: Extract of the tabular translation of the task analysis flow-chart

	Description	Correct	Error Type Execution		E T Perception		ET Interpretation		Error Type Decision	
		Correct	EM1	EM2	EM1	EM2	EM1	EM2	EM1	EM2
e1	object on runway	yes: e2	no: e9							
e9	visibility is good	yes: ta16	no: ta17							
ta16	ATCO verifies visually runway availability and issues landing clearance	e10			Not done: ta17		Not done: ta17		Warning clearance plan: ta24	
ta17	ATCO verifies,using the radar, runway availability and issues landing clearance	e10			Not done: (Warning / Error) ta18		Other than: ta24		Warning clearance plan: ta24	
ta18	ATCO issues the landing clearance	e10	Slip of the tongue: e10							

The main Output of the simulator is to provide a probability value in respect of ATCs procedures executions identified as critical (with multiple trial generation) and a probability value for the corrective actions in the recovery phase as well. These probability values depend on the CCs, directly connected to the decision boxes of the flow charts through the decision block criteria. In this way it is possible to take into account a cognitive point of view in the Human Error Probability generation, enabling to consider a more formalized connection with the CCs, which are the key points for identifying organizational corrective or preventive actions.
The architecture of the simulator is centered on the flow chart of the cognitive process which in turn has its fulcrum in the decision blocks.
Each Decision Block has two possible exits: “Yes” and “No”. The exit process is stochastic and it depends on the CCs values and the influence they have on each decision block.
If we indicate with X the possible outcome of a decision Block, X is a Bernoulli’s variable and the following values are associated with X:

Yes → X = 1
No → X = 0

Then the probability density function $f_x(x)$ is equal to:

$$f_x(x) = f_x(x,p) = \begin{cases} p^x(1-p)^{1-x} & per\; x=0 \; or\; x=1 \\ \\ 0 & otherwise \end{cases} \qquad (1)$$

where $0 < p < 1$ and $1 - p = q$.

The probability of having “Yes” as a possible exit of the block can be expressed as [P(X = 1)] and it is equal to *p*, while the probability of having the “No” exit is [P(X = 0)] equal to *q*. In order to calibrate each decision block, the value of p, that is the success probability of the cognitive process in the block, has been expressed as a function of the CCs involved for the same block.For a complete description of PROCOS approach features refer to Trucco and Leva (2007).
An example of part of the cognitive flow chart used for representing the Liveware-Hardware interaction is reported in Figure 2.

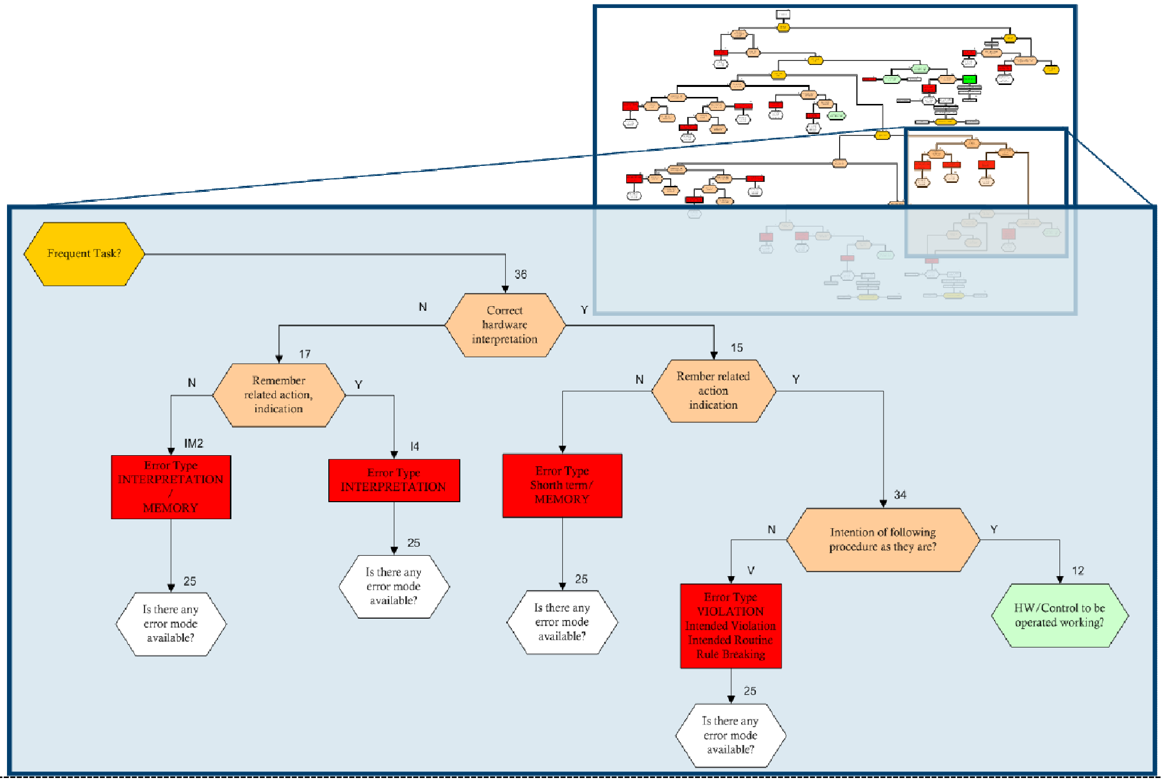


Figure 2: Extract of part of the cognitive flow chart used for representing Liveware-Hardware interaction

3 The trial application: selection and implementation of a case study

The trial application of a case study using PROCOS is aimed at calibrating the simulation process on data available by the analysis of past accident obtained using HERA retrospectively.
The trial application of the simulator was directed towards a case study developed within the ConOps framework (Eurocontrol, 2005). The framework identifies the functions and processes, and their corresponding interactions and information flows; concerned actors, their roles and responsibilities in possible future ATM European Operations. The case studies in Conops are normally referred as use cases and they serve to provide a more detailed elaboration of particular aspects of ATM possible scenarios, especially "what-if" situations (the alternative flows). The scenarios and use case selected for the trial application is: "Handle Aircraft Landing" (OATA-P2-WP3 2-1, 2004). It describes how a Tower Runway Controller manages the landing of an aircraft. It starts when the intermediary approach phase is completed and the aircraft is ready for the final approach and ends when the Tower Runway Controller is ensured that the aircraft has vacated the runway.
The use case is set up as a main flow (everything goes as planned), some possible alternative flows (deviations from the "as planned" path, which not necessary lead to failures) and failures flows (where an error has occurred). The flows are sequences of

subtasks. The use case constitutes the base for the task analysis to be analysed through the simulator chosen for the trial application (PROCOS).

3.1 The PROCOS-ConOps Task Analysis

The use cases in ConOps are structured according to the following elements:

- Scope :
  - System, black-box. System means an Overall ATM/CNS Target Architecture compliant system;
- Summary:
  - This Use Case for instance, describes how a Tower Runway Controller uses the System to control the landing of an aircraft. It starts when the intermediary approach phase is completed and the aircraft is ready for final approach and ends when the Tower Runway Controller is ensured that the aircraft has vacated the runway;
- Actors:
  - Description of the main actors involved;
- Preconditions:
  - Scenario inputs to the analysis;
- Post conditions:
  - Possible success end states;
  - Possible failure end states;
- Definitions:
  - List of the main term and abbreviations used;
- Triggered:
  - Elements that triggered the use case events (i.e.: the use case starts when the system detects that the aircraft is on final approach);
- Main Flow:
  - Main path, or nominal path that should be followed by the chain of events that lead to a success end state;
- Alternative Flows:
  - Possible deviations from the nominal path that can be recovered by following procedures;
- Failure Flows:
  - Possible deviation from the nominal path that cause failures of the task.

The structure chosen for developing the task analysis in order to be compatible with both the PROCOS inputs and the ConOps framework is a Flow Chart based Task Analysis.
A flow chart depicts the progress through a system in terms of the decisions and actions which have to be performed. Decision elements are usually represented as diamonds and the possible outcomes are labelled on the exit lines. Although the questions are usually expressed in a form suitable for “Yes/No” answers, this is not a specific requirement of the technique and multiple choices are allowed. An example is presented in Figure 3. If it is accepted that the correct decision is not always taken, it seems then important to consider what the available outcomes are.

It was then possible with little effort to translate the information already available in ConOps, given in the structure highlighted above, in a flow chart format. Following this first translation it has then been necessary to refine the level of detail provided with the one necessary to match the analytical capability provided by the cognitive model of the operator. The task, in fact, has to be broken down into single human actions (subtasks) whose outcomes are compatible with the level of detail of the information processing involved in the cognitive flowchart (e.g. single actions, single decision making processes, etc.).
The refinement process also involved some further specification of the possible criticalities arising form external conditions that may have not been specified in the use case (such as visibility conditions).
The process was carried out in conjunction with two experienced Air Traffic Controllers, one of which is also the developer of the ConOps Use Case considered.

All the possible exits of the sub-steps are to be monitored by the simulation process and the effects on and from the equipment involved in the task were to be explicitly considered; up to the level of detail required by the use case itself. The task analysis flow chart has been developed using MS Visio (MS Visio is also a compatible software for developing the task analysis in UML).
It is important to underline that the flow chart for the task analysis has not to be confused with the flow chart developed for the information processing activities of the operator (cognitive flow charts of the Operator Module). The first in fact is used for mapping the task or activity the operators are supposed to perform, considering all the possible deviations from the nominal path, while the cognitive flow chart represent the information processing model underpinning the single actions reported in the task analysis flow. To every decision blocks of the task analysis flow chart is assigned a certain exit (correct execution or error modes) according to the run of the cognitive flow chart underpinning it, which simulates the actual human execution of the single sub-steps. All the possible exits of the sub-steps are recorded together with the effects on and from the equipment involved in the task.
The Task analysis flow chart is made up of:

- the sub-steps constituting the human actions within the task. The exit of a sub-step is a correct action that in turn changes some equipment status and goes further to the next step, or an error mode that can constitute an irrevocable failure and therefore recorded as such and ends the simulation process; an error mode can also be "labelled" as a warning instead of irrevocable failure, thus it can then be followed by other actions. This is carried out in accordance with what has been already described in the use case and detailed then by the analysts (HF practitioners and experts of the field of analysis). Each possible error type and error mode outcome should be explored. In accordance with ConOps use cases, during the development of this project it has not been considered the effects from and on hardware equipments. Therefore a sub-step is defined by:
    - code and description;
    - type of actions (communication or action triggered by hardware stimuli);
    - type of cognitive path required for performing the sub-step (skill, role or knowledge task);

- all possible exits of the sub-step (correct or error type and error mode) with the following step. Visualisation of the sub-step within task analysis flow chart.

- Events and pilot actions. This category comprises the possible occurrences of an external event (e.g. weather conditions), a technical failure on an aircraft that disables the plane to land as planned, or pilot actions (the pilot actions are not simulated referring to a cognitive model for the pilot because it was not considered to be in the scope of the preliminary application, whose focus was mainly on air traffic controllers). Events outcome are "Yes" or "No" exits ("Yes" the event takes place, "No" it does not take place), the probability density function according to which the events are generated in the simulation is Bernoullian. The assessment of the probability of occurrences of these events and pilot actions is based on historical data and experts' judgements. Table 3 reports a list of some events and pilot actions identified as important during the development of the task analysis for the use case. The estimated probability of occurrence for each event is reported in the third left column of Table 3, while the last column reports the source of the probability estimation. In the task analysis the events are linked to the sub-task the operators have to undertake as a consequence of the new scenario setting introduced by them.

Figure 3 reports an example of a sub-step identified within the task analysis flow chart. The exit of the box highlighted in blue is a possible correct performance or a possible error. The outcome is decided by a run of the cognitive flow chart referring to the action of the sub-step, which, in this case, is under the Liveware-Hardware interaction part.

The task analysis flow chart is then translated in a tabular format easier to be converted into the simulation code. An example of some sub-steps in the tabular format is reported in Table 2. The first column on the left is the Id of the element ("ta#" for a sub-step, "e#" for an event, etc..) followed by a column reporting a brief description of the task/event, The following columns report all the possible other actions/events that can follow the task/event in case it has a correct outcome or an error, for the event the outcomes are not correct or incorrect but simply yes-"it happens" no-"it does not happen".

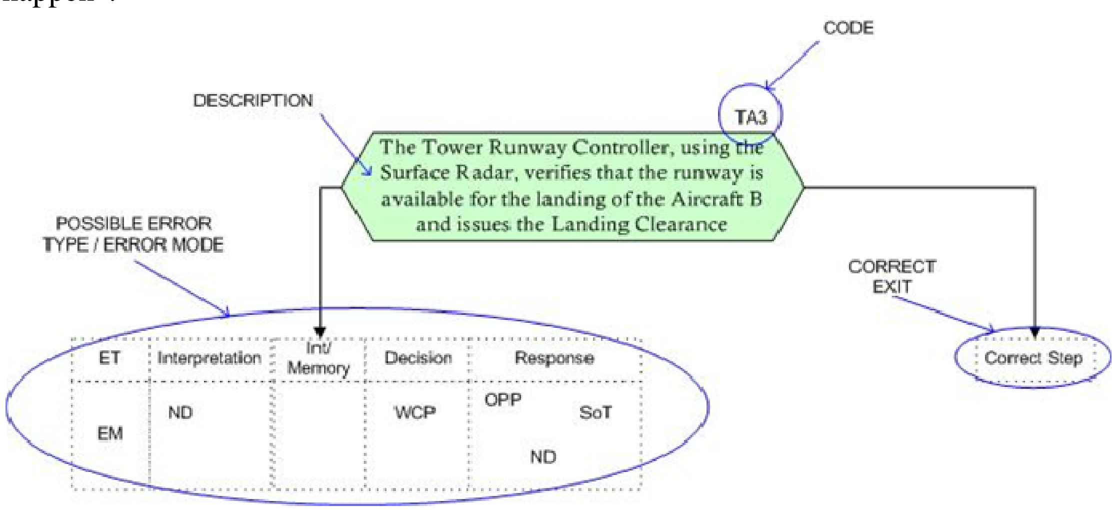


Figure 3: Visualisation of a sub-step within the task analysis flow chart

Table 3: Some External events and pilot actions within the task

Code	Description	Estimated Probability of the event	Source
E1	Object on runway	0.500000	Expert Judgment
E10	Pilot rejects the planned exit and requests a different one	0.000200	Expert judgement
E2	Aircraft A technical able to vacate	0.999980	Expert judgement Malpensa Airport
E20	Pilot B is able to land	0.999846	Data from Linate Airport
E9	Visibility is good	0.988300	Data from Malpensa Airport (2003-2004)

The simulator should be able to assess the probability of the deviations from the main flow by means of multiple trials. The task analysis and the sub-steps of which it is made of therefore constitute a very important input for the simulation process.

4 The Calibration Process of the decision blocks in PROCOS using HERA Data

The taxonomy used by the simulator represented an advantage for the project because it matched the classification framework used for collecting the accident data.

Within Eurcontrol in fact, the retrospective analysis of incidents has been based on a conceptual framework of human performance that makes use of an information processing perspective. The technique and the related taxonomy are model-based. A model in fact "allows causes and their inter-relations to be better understood. An error model provides an 'organizing principle' to guide learning from errors. Trends and patterns tend to make more sense when seen against the background of a model and more 'strategic' approaches to error reduction may arise, rather than short term error reduction initiatives following each single error event.". (Isaac et al., 2003)

The cognitive simulator (PROCOS) previously presented comprises two cognitive flow charts. The flow charts are based on a model within an information processing perspective very similar to the one underlying the HERA-Predict classification. Therefore, it has been possible to modify the simulator in order to take into account a more detailed insight of the context of analysis (Air Traffic Management) and obtain suitable data for a possible quantification process. The main factors to be described in order to classify and analyze errors in HERA are shown in Table 4.

Table 4: Main Factors to consider for analyzing human error with HERA (Isaac et al., 2003)

Taxonomy	Description
Error	
Error Type	What keyword can be applied to the error (including rule breaking and violation), in terms of timing, selection or quality of performance or communication?
Error Detail (ED)	What cognitive process was implicated in the error?
Error Mechanism (EM)	What cognitive function failed, and in what way did it fail?
Information Processing Levels (IPs)	How did the error occur in terms of psychological mechanisms?
Context	

Task	What task(s) was/were being performed by the controllers(s) at the time that the error occurred?
Information & Equipment	What was the topic of the error, the equipment used in the error or the information involved? (e.g. what did the controller misperceive, forget, misjudge, etc.?) What HMI element was the controller using?
Contextual Conditions (CCs)	What other factors, either internal or external to the controller, affected the controller's performance?

The model used as the main skeleton, is extensively based on the one proposed by Wickens (1992). The retrospective accident analyses in HERA, is carried out following several steps associated to specific flow charts. The steps are:

a. defining the Error Type;
b. defining the error or rule breaking or violation behavior through a flowchart.
c. identifying the Error Detail through a flowchart;
d. identifying the Error Mechanism and associated information processing failures through flowcharts;
e. identifying the Tasks from tables:
f. identifying the Equipment and Information from tables;
g. identifying all the Contextual Conditions through a flowchart and tables.

An example of the flow chart used within HERA for providing guidance in the Error Type identification is reported in Figure 4, which illustrates how an HERA analyst would identify an error which may be classified as rule breaking or violation behaviour.

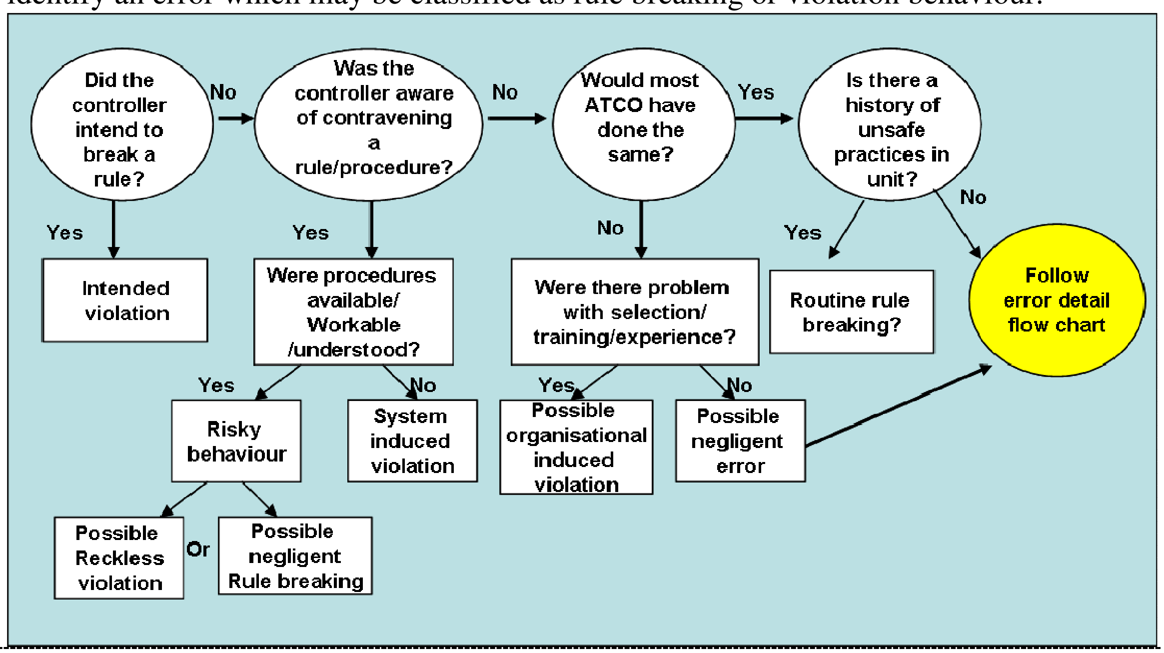


Figure 4: Guidance for Rule breaking and violations identification within HERA (Isaac et al., 2003)

Further details on how the HERA method can be used and the other flow charts used for guiding the accident analysts are provided in the references (Isaac et al., 2003). What is important to highlight in the present paper is that the Information Processing Level and the Error Mechanism proposed in HERA (partly displayed by Figure 4) and the ones embedded in the structure of the simulator, both in the cognitive flow chart and in the task analysis one (see Figure 2 and 3), are very much compatible. Furthermore the steps listed above constitute steps for the preparation of the simulation runs as well, and are mainly captured as part of one of the most important activities preceding the application of the simulator, which is to say the task analysis.

4.1 The PROCOS-HERA calibration process: challenges and constraints

In order to adapt the simulator to the use of the HERA data some changes have been made. A particular decision block with a filtering action needed to be introduced in the cognitive flow chart (Figure 2) in order to distinguish between the possible cognitive paths required by steps that may involve some decision making process as opposed to the ones that are very frequently performed by ATCO following fixed rules; the exit of this decision block (called "frequent step") is assigned in accordance with a check box to be used by the analyst during the specific task analysis.
The second major modification was the introduction of a better cognitive model for the communication among operators (Liveware-Liveware interaction), able to capture the processes and the possible deviations underpinning the "instruction-readback-hearback" procedures in a normal daily operation of the air traffic controllers and of the pilots.
Furthermore the cognitive flowcharts used for the first application of PROCOS have been modified in order to take into account the error type "violation" of HERA which was not yet included.

As already said the trial application of a case study using PROCOS was mainly aimed at verifying the possibility of calibrating the simulation process on the data coming from the analysis of past accident using HERA retrospectively. The first step was the identification of the correspondences between PROCOS calibrated decision blocks and the Error Types (and Error Modes) reported in HERA. The correspondences have been identified with the help of an HERA practitioner. The criteria adopted for the identification was the match between the error type category underlying the decision block (according to Wickens taxonomy) and the error types of HERA that could be referred to it. Table 5 reports some Blocks of the Cognitive Flow Charts (on the extreme left column) and the possible correspondent error types in the HERA taxonomy (identified on the extreme right column).

Table 5. Example of the correspondence between decision blocks and HERA error types

ID	Block Description	Block type	Possible HERA correspondent ET
3	Recognize stimuli	calibrated decision block	PV-IP: Association Bias
			PV-EM: Misidentification of information
			PV-IP: Information overload
			PV-EM: Misreading of information
			PV-EM: Misperception of information
5	Visual Perception of alerting info (visual only)	calibrated decision block	PV-IP: Information overload
			PV-IP: Expectation Bias
			PV-EM: Late detection of visual information
6	Distinguish target info from	calibrated decision block	PV-IP: Discrimination Problem

	background info		PV-IP: Visual/Sound confusion PV-IP: Information overload
7	Correct HW interpretation	calibrated decision block	PDM-IP: Incorrect assumption PV-IP: Association Bias PV-EM: Misidentification of information PV-IP: Discrimination Problem PV-IP: Information overload PDM-IP: Failed to recognise risk

The probability density function of the variable representing the exit of the decision block is bernoullian and therefore $f_x(x)$ is equal to the one proposed in equaton (1). For the present application, the procedure for estimating, for each Decision Block, the value of q in equation (1) has been derived using the HERA Dataset provided by Eurocontrol. Indeed, the data available can provide indications for the rate of occurrence of specific error types and also for the role played by Contextual Conditions in a certain event where a certain type of error occurred. The HERA dataset used for this application has the following characteristics:

- Number of recorded accident/near miss events: 62
- Number of recorded ACTO errors: 91
    - Perception & Vigilance 38
    - Memory 7
    - Planning & Decision Making 36
    - Response Execution 10
- Number of recorded occurrences of Contextual Conditions (CCs): 130
- Number of movements during the reporting period: 4 million(estimated)
- Level of analysis of Contextual Conditions: Main Categories

In HERA the Contextual Conditions (CCs) are defined as "factors, internal or external to the controller, which influence the controller's performance of ATM tasks. Contextual Conditions (CCs) can help to explain why the error occurred." The set of CCs used in HERA was developed from an analysis of UK AIRPROX reports, discussions with Air Traffic Controllers and the human factors literature (Isaac et al., 2003).

The main categories of Contextual Conditions available in the HERA taxonomy are:

1. Pilot-Controller Communications;
2. Pilot actions;
3. Traffic and airspace;
4. Weather;
5. Documentation and procedures;
6. Training and experience;
7. Workplace design and HMI;
8. Environment;
9. Personal Factors;
10. Team factors;
11. Organisational factors.

The main categories then comprise a full range of possible elements, an example is reported in Table 6. A full description of the contextual conditions used in HERA is available in the references (Isaac et al., 2003; 2004).

Table 6. Example of specific CCs considered for three of the main categories within HERA

CONTEXTUAL CONDITIONS (CCs)
Training and experience
Inadequate knowledge for position
Inadequate experience on position
Inadequate time on position
Unfamiliar task in routine operations
Novel situation
Over training
Inadequate mentoring
Inadequate On-the-Job Training (OJT)
Inadequate emergency training
Inadequate Team Resource Management (TRM) training
Inadequate recurrent/continuation training
Controller under training
Controller under examination/check
Other – State:
Team factors
Controllers on the floor assisting one another with the traffic
Currency and availability of all necessary equipment
Position relief briefing
Cooperative effort to accommodate the flow of traffic
Team relations – conflicts / personality problems
Late returns to the position after breaks
Positions left temporarily unstaffed
New or temporary team assignments
Lack of responsibility
Unclear working methods
Confidence in others
Team pressures
Cooperation from supervisors from other areas in traffic flow initiatives
Support from others - flight data / maintenance
Management provision of resources and assistance as dictated by the
traffic needs
Support from other units
Staffing for the traffic requirements
Confidence in supervisor's ability to manage the air traffic activity
Supervisory cooperation to manage the traffic during this shift
Management cooperation to assist and support the sectors/positions/
areas/facilities
Higher management cooperation to assist and support the
sectors/positions/areas/facilities
Other – State:
Organisational factors
Work environment
Safety versus efficiency – for yourself / organisation
Numbers of qualified controllers
Job satisfaction
Roster/rest duty times
Work scheduling
Adherence to rules by ATCOs
Adherence to rules by supervisors
Terms and conditions of work
Supervisory decisions in staffing and facilities
Management decisions in staffing and facilities
Supervisory decisions in safety and efficiency policies
Management decisions in safety

In the HERA accident data set used for the pilot study however, the specific CCs taken into account were not detailed and only the main categories were reported. Furthermore it is important to note that in HERA the interdependences among CCs were not explicitly considered and the data available was not sufficient to estimate the correlations among them.
For the trial application PROCOS fully adopted the HERA CCs taxonomy with its current limitations so as to fully comply with the current data availability. The procedure for evaluating the *q* probability of the bernoullian law for the Decision Block was based on an ogivian-shaped curve expressed by the formula of Rasch (1980):

$$P_{Failure\ \ of\ \ type\ \ i} = \frac{e^{\frac{r_i - \mu}{s_n}}}{1 + e^{\frac{r_i - \mu}{s_n}}} \qquad (2)$$

Where:
r_i = Percentage of errors in a situation given all situations of the same type in the data base;
μ= 0.5; the adjustment of the location of the crossing point (0.5 assigns rational processing);
s_n= 0.075; empirical parameter to adjust the slope of the ogivian curve;
e= natural exponent (2.718).

Equation (2) has been proposed by Sträter (2005) for relating the absolute HEP=n/N with the empirical data collected by accident databases. In a method named CAHR, Sträter (2000) found that the Rasch equation was revealed as the closest line to approximate the relation between the percentage of errors in a certain situation given the number of situations of the same type in the database, and THERP data about absolute probability for a given type of error.
As an assumption, it was then decided to use the Rasch equation for describing also the relation between the FLI and r_i, where FLI is the Failure Likelihood Index.

$$r_i = \frac{e^{\frac{FLI - \mu'}{s_n'}}}{1 + e^{\frac{FLI - \mu'}{s_n'}}} \qquad (3)$$

The weight of the effect that the CCs can have on the situation is seen on a negative perspective, which is to say it takes into account only those Contextual Conditions whose presence negatively affect the performance of a human operator.

$$FLI = \sum_{i=1}^{N\,j} (w_i \cdot y_i) \qquad (4)$$

where*:*

w_i = normalised weight of the i-th CC for the cognitive process of the j-th block
y_i = i-th CC –value, i.e. a measure of the intensity or extent of presence of the i-th CC.
N_j = number of CCs for the j-th block

and $\sum_{i=1}^{N\,j} w_i = 1$

Equation 3 needs to be calibrated, that is for each Decision Block of the Cognitive Flowchart we need to identify the parameters μ' and s_n' using the empirical data available in the HERA Database. Three anchor points were fixed.

$\begin{cases} FLI = 0 \\ r_i = 10^{-3} \end{cases}$ which represents the ideal working conditions;

$\begin{cases} FLI = 1 \\ r_i = 0{,}9 \end{cases}$ which represents the worst possible working conditions;

$\begin{cases} FLI\,* \\ r_i\,* \end{cases}$ which represents the "nominal" working conditions extracted from HERA data.

The calibration procedure is set out in the following steps:

a) The r_i^* value is obtained through formula $r_i* = \dfrac{n_{ev\,i}}{N_{ev}}$ (5)

Where:

n_{evi} is the number of events that have at least an occurrence in the set of HERA Error Types linked to the decision block (number of events linked to the block);

N_{ev} is the total number of "accident/near miss" events in the dataset;

b) The contextual conditions linked to the block are identified (experts' judgments, and empirical data are used jointly);

c) The weight of CC_i is estimated as the probability of having an Error Type (linked to the decision block) given the occurrence of the i-th Contextual Condition; it is in fact possible to demonstrate that $w_i = \dfrac{N_{CCi}^{k}}{N_{CCi}}$

Where:

N_{CCi}^{k} is the number of occurrences of CC_i in the events linked to the decision block;

N_{CCi} is the total number of occurrences of CC_i in the database.

w_i is then normalized: $\overline{w}_i = \dfrac{w_i}{\sum w_i}$ (6)

d) Finally, an empirical mean value for FLI is calculated that refers to a specifics r_i (r_i^*) for the events linked to the decision block under calibration;

e) Using the three couples of value for FLI and related r_i:
   - (0 , 10^{-3}): optimal situation in which there are no Contextual Conditions;
   - (FLI* , r_i*): nominal situation extracted from the HERA database;
   - (1 , 0.9): the worst situation in which all Contextual Conditions are present at the same time.

   it is possible to find the two parameters μ' and s_n' for the Rasch equation (3) by applying the least square method. Experts' judgements are used as a second source for estimating the importance (w_i) of each CC.

4.2 The use of experts' Judgments for the confidence interval of Contextual Conditions.

To gather information about the absolute contribution of each Contextual Condition (CC) to the possible incorrect execution of a task performed by an Air Traffic Controller, a questionnaire has been addressed to some Air Traffic Controllers who are involved in the specific task. Twenty-nine Air Traffic Controllers, coming from different country and different airports, have been interviewed. The values collected are then used for establishing the range in which the mean value of the importance of each CC can actually vary. For each CC in fact, given the mean obtained from the HERA dataset and the value obtained from the interviews it is possible to calculate the sample mean and the sample variance of the CC weight.

Therefore, we can obtain a 100*(1- α) percent confidence interval for the mean value of the weight, which is:

$$\overline{w_i} - t_{\frac{\alpha}{2}} \frac{s}{\sqrt{n}} \le \mu \le \overline{w_i} + t_{\frac{\alpha}{2}} \frac{s}{\sqrt{n}} \qquad (10)$$

This provides an interval within which the value of the CC weight in question lies during a specific simulation run. After the percentage of the confidence interval is chosen, in fact, the value of w_i of each simulation run will be extracted within the related range of values. Therefore at each run the weight of each CC is randomly extracted by its related interval (assuming a uniform distribution). This values are then used for evaluating the FLI (equation 4), taking into account that the presence of the CCs depends on the scenario that we want to simulate, and the correspondent r_i by means of equation 3. This value of r_i is then substituted into the ogivian-shaped curve expressed by Rasch equation (2) and the final value for the q parameter of the bernoullian process described in the equation (1) is then finally used for deciding stochastically exit for each simulation run. This process needs to be performed for each decision block of the cognitive simulator since each Decision Block may present different values.

5. Results of the simulation campaign

5.1 Setting the simulation campaign

The simulation campaign for the trial application was organised into the following settings:

- Number of scenarios: 4
- Number of experiments for each scenario: 20
- Number of simulation runs for each experiment: 10^6 movements

For the trial application in fact only four basic scenarios have been selected. They refer to the possible different impact of the main category of Contextual Conditions. The CCs have been taken into account in a Boolean logic scheme: if the value is 0 the CC is not playing a role in the simulation scenario, while if the assigned value is 1 it is negative influencing the operator performance in the simulation scenario. The rationale behind the choice of the four scenarios lays mainly in the purpose of verifying the consistency of the simulator results.

- scenario S1: any CC is considered and ideal conditions are postulated, thus this is the best scenario from an ATCO point of view (base case);
- scenario S2: only the external Contextual Conditions play a negative role in the simulation;
- scenario S3: only Contextual Conditions expressing human and internal organizational factors play a negative role in the task execution;
- scenario S4: it is the worst possible scenario where all the Contextual Conditions are considered at their maximum potential negative affect on the ATCO performance.

For each scenario, different ranges of Failure Likelihood Index (FLI) have to be simulated corresponding to the different contributions that different sets of CCs have on the FLI value. As already shown in section 4 of the present paper the CC weight is extracted from confidence interval considered for the mean value of the weight (equation 10). At each run the weight of each CC is randomly extracted by its related interval assuming a uniform distribution. These values are then used for evaluating the FLI (equation 4), taking into account that the presence of the CCs depend on the scenario under study.

5.2 Number of repetition of simulation runs

In any experimental design problem and in any design of simulation campaign, a critical decision is represented by the choice of number of repetitions of simulation runs. The type of results to be taken out from the simulation, the structure of the task and the probability of the events within the task strongly influence both the minimum number of runs within a simulation experiments and the minimum number of experiments required runs requested to have statistically significant results.

The aim of this project is to estimate a Human Error Probability (HEP) that, in the nominal case where Contextual Conditions do not play any negative role, we expect to be not higher than 10-3.
Some uncertain events generated during the execution of the simulated task – i.e. handling of the aircraft landing - have probabilities of occurrence between 10-4 and 10-5; thus, some branches of the task flowchart have a very low probability of occurrence.
In order to have a meaningful number of occurrences for any branch of the task and according to an empirical rule that suggests to set a number of runs at least of one order of magnitude higher than the lower probability of occurrence, it has been decided to perform one million runs for each simulation experiment, corresponding to one million landings on the runway. Finally, considering the available time for performing the entire simulation campaign, it has been decided to execute 20 experiments for each scenario to build significant statistics.

5.3 Collection and processing of simulation

The results of the simulation were assembled and processed in different ways to calculate different statistics. First of all, the probabilities of correct or failed and state for the task were estimated. For each scenario, the mean value and the standard deviation of the probability of occurrence of correct/failed task were calculated for the assessment of the probability of correct task. The total probability of a failed task is the complement to 1, but it is important to remember that different failure end states of the task are considered and not all of them are irrevocable failures, some of them are simply warning errors, or a failure of the task due to an incorrect action of the pilot. Thus it was necessary to analyse the different exits from the task (Figure 5) in order to distinguish between the irrevocable and not irrevocable (warning) failures.

Table 7: Table used for computing the absolute probability of a correct task

Simulation experiment ID	Number of simulation runs ended with a failure for each scenario			
	S1	**S2**	**S3**	**S4**
R1	3040	5150	453736	832511
R2	2995	5799	455899	830410
R3	3082	5245	455834	831720
R4	3086	5684	456385	829724
R5	3083	5512	452302	831001
R6	3125	5349	456275	831598
R7	3038	5373	457717	830295
R8	2966	5816	456172	831379
R9	3076	5078	456358	830879
…	…	…	…	…
…	…	…	…	…
R19	3101	5563	454660	830974
R20	3134	5425	462703	829115
average	**3062**	**5487**	**456013**	**830517**
σ	82,53501649	231,5814055	1990,706684	1571,208315
Probability	**3,06E-03**	**5,49E-03**	**4,56E-01**	**8,31E-01**

(movement)

	S3																	
Exit Task	**TA29**	**TA12**		**TA12***		**TA34***	**TA35***	**TA36**	**TA7**	**TA7***	**TPA8**	**TP11**	**E20**	**TA21**	**TA23**	**TA25**	**TP3**	**TP5**
Type of exit	**Irrevocable Failure**	**Irrevocable Failure**	**No Simulation: Pilot Recall ATCO…**	**Irrevocable Failure**	**No Simulation: Pilot Recall ATCO…**	**Delay Confirmation**	**Delay Confirmation**	**Aircraft has safly vacated runway (ATCO doesn't verify visually)**	**No Simulation: Pilot Recall ATCO…**	**No Simulation: Pilot Recall ATCO…**	**Aircraft is obstructing the runway - Delay Understansing**	**Irrevocable failure (Pilot landing error)**	**No Simulation: Pilot Recall ATCO… (pilot is not able to land)**	**Irrevocable Failure (Hearback)**	**Irrevocable Failure (Hearback)**	**Aircraft is not landing (Hearback Communication error Warning)**	**Irrevocable Failure (Readback)**	**Irrevocable Failure (Readback)**
R1	316	6	6	2	1	9089	91	40874	18	2	2	302	68	6	239510	22888	167	379857
R2	328	10	9	0	0	8962	49	41835	30	1	3	292	67	11	237722	22434	141	381682
R3	322	6	8	1	0	8590	133	42810	16	0	2	352	57	10	231522	21840	164	381468
R4	302	8	13	0	1	8737	37	41583	25	0	3	283	59	9	236916	22226	170	382887
R5	382	7	3	0	0	7766	31	40020	19	1	6	346	59	7	237052	20927	153	382544
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
R18	335	9	14	1	1	8521	113	43111	16	2	2	330	47	3	230636	21980	169	381998
R19	326	6	3	1	0	8867	52	41258	23	1	5	310	70	9	237347	21951	170	381558
R20	366	8	8	0	0	9112	3	46701	24	4	2	425	70	7	222371	24398	169	381365
probability	**3,35E-04**	**7,50E-06**	**8,00E-06**	**6,25E-07**	**3,75E-07**	**8,71E-03**	**6,36E-05**	**4,23E-02**	**2,14E-05**	**1,38E-06**	**3,13E-06**	**3,30E-04**	**6,21E-05**	**7,75E-06**	**2,34E-01**	**2,23E-02**	**1,63E-04**	**3,82E-01**
σ	2,65E-05	1,51E-06	4,07E-06	7,44E-07	5,18E-07	4,37E-04	4,44E-05	2,05E-03	4,96E-06	1,30E-06	1,55E-06	4,57E-05	8,08E-06	2,55E-06	5,66E-03	1,01E-03	1,05E-05	9,09E-04

Figure 5: Example of the format used by the simulator for recording the final failures that ended each simulation run.

The exits of the task were ranked considering the magnitude of their potential negative consequences as reported in Table 8.

Table 8: Ranking of the possible exits of the simulated task according to the magnitude of potential negative consequences.

	Type of exit	**Exit task**
	ATCO doesn't issue the instruction. Pilot recalls ATCO and requests the instruction (no simulation)	TA7 TA7* TA7** TA12 TA12* TA13
	Aircraft has safely vacated runway but there is a Delaied Confirmation by ATCO	TA31 TA32 TA34* TA35*
	Aircraft has safely vacated runway (ATCO doesn't verify visually)	TA36
	Aircraft is obstructing the runway – Delay in Understanding	TPA8
	Irrevocable failure	TA29 TA29* TA12 TA12* TA21 TA22 TA23 TA30* TP3 TP4 TP5 TP6
Two more "failure end states" of the task refers to actions of the pilot:		
	Pilot is not able to land and calls ATCO… No Simulation	E20
	Pilot landing error (Irrevocable failure due to pilot action)	TP11

To complete the analysis of the task, the need of recovery actions of the ATCO was studied. Two different types of recovery have been identified:

- Recovery by procedure: it is placed at the task analysis level and represents the possible recovery procedure described as a “deviated” path within the task analysis;
- Recovery by clarification: it is placed at the cognitive flowchart level and represents the recovery capabilities provided by the communication process.

For each scenario, the average of occurrences of recovery actions and the average of occurrences of correct recovery for both “by procedure” and “by clarification” were recorded. Then the absolute probability of recovery action [recovery/movements] and the absolute probability of recovery failures [failures/recovery] were calculated.

After the analysis of the task, the occurrences of single error types have been analysed. Each probability is referred to the number of movements and then, using an estimate of number of movements in one year, it is also possible to refer the error probability to the operational time. In order to conclude the analysis of the results and to prove the stochastic nature of the simulation a normality test on the results has been conducted.

5.4 Discussion of the results of the case study

One of the results obtained shows how the failure probability of the task increases as the conditions of the scenario worsen, which is an assurance about the general consistency of the simulator results. The relationship between the number of Contextual Conditions (CCs) that affect the scenario and the value of the failure probability is not linear; namely, there is not a linear dependency between the number of CCs and the failure probability, but the increase from a scenario to another one depends on the weight of the Contextual Conditions that play a role within those scenarios. Specifically, Figure 6 indicates that the human and organisational factors (scenario S3) have a stronger impact than the external contextual conditions (scenario S2) on the performance of the ATCO. Indeed, compared to the base case (scenario S1), the failure probability of the task increases by two orders of magnitude when the human and organisational factors negatively affect the ATCO, while the order of magnitude of the failure probability remain the same also when all the negative external conditions are considered.

One last consideration can be made regarding the overall failure probability of the task. When the air traffic controller works in the best conditions (scenario 1), the failure probability of the task is not zero but 10^{-3}. This value might appear high but Figure 6 shows that the probability to have an irrevocable failure is only 10^{-6}. Another failure end state observed in the scenario S1 is the error of omission of the ATCO in verifying that the pilot has vacated the runway.

Table 9. Summary of results for the probability of correct/failed task.

	Probability of correct task	**Probability of failed task**	*Standard Deviation*
	Mean Value	*Mean Value*	
Scenario 1	0,9969	0,0031	8,254E-05
Scenario 2	0,9945	0,0055	2,316E-04
Scenario 3	0,5440	0,4560	2,991E-03
Scenario 4	0,1695	0,8305	1,571E-03

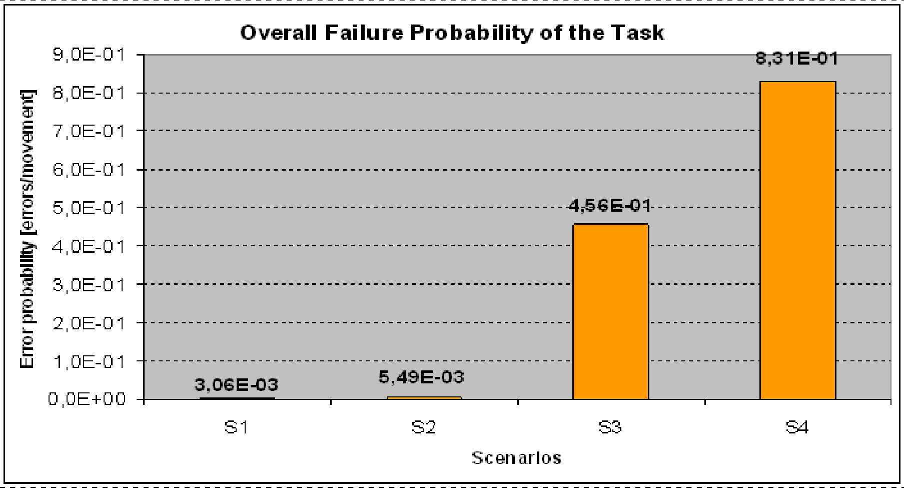


Figure 6: Overall failure probability of the task (mean value).

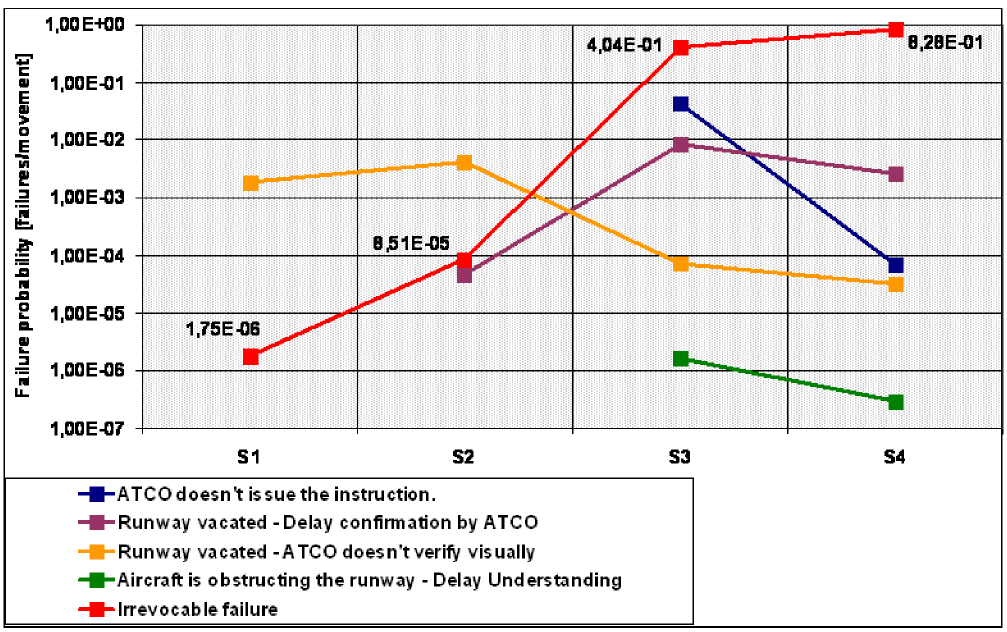
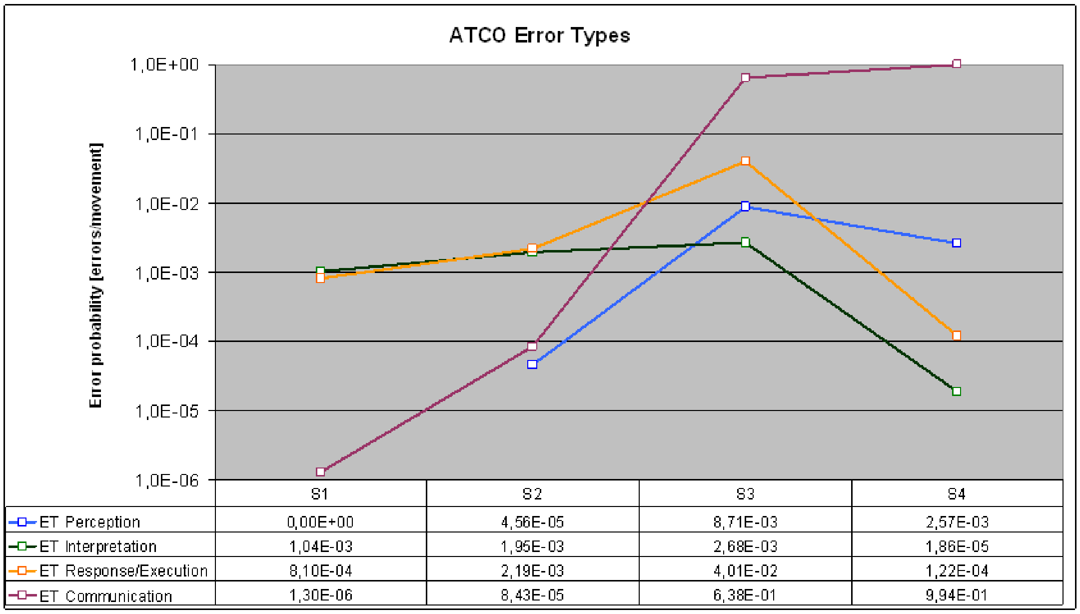


Figure 7: Probability of failure end states of the task.

Figure 7 shows as the probability of occurrence of an irrevocable failure grows as the work conditions worsen. According to what Figure 6 infers, Figure 7 outlines that the human and organisational factors are more impacting than the external contextual conditions. It can be observed that the failure end states displayed with the violet and orange colours are reversed between scenario S2 and scenario S3. This behaviour is due to the different way the two scenarios influence the operator. Excluding irrevocable failures, when the external conditions play a role in the task execution, the Tower Runway Controller is prone to do more ghastly errors. When the human and organisational factors affect the working conditions of the ATCO, a wider spectrum of possible failure end states of the task has been registered. Indeed, the simulation of scenarios S3 and S4 have recorded all kind of previously defined task failures.



	S1	S2	S3	S4
ET Perception	0,00E+00	4,56E-05	8,71E-03	2,57E-03
ET Interpretation	1,04E-03	1,95E-03	2,68E-03	1,86E-05
ET Response/Execution	8,10E-04	2,19E-03	4,01E-02	1,22E-04
ET Communication	1,30E-06	8,43E-05	6,38E-01	9,94E-01

Figure 8: ATCO's Error Types.

The simulator is built in such a way that the probability figures of different error types depend on both the calibration of each Decision Block within the cognitive flowchart and the frequency with which the specific error type can occur within the task analysis as well. Although, in general, the communication is very important in any task performed by ATCOs, Figure 8 shows how much this is true for the use case selected. For the scenario S2 the probability of errors in communication is low because the probability of correct recovery by clarification is very high.

The probability of having an interpretation error is almost invariable trough the scenarios because the handle of aircraft landing procedure does not comprise any relevant diagnostic or planning process. In general, the error types observed in the worst scenario focalize the attention on communication problems; indeed the errors in communication prevail if compared with the other error types that have a probability of occurrence of two orders of magnitude less. Looking at the scenarios S2 and S3 it is possible to observe that a wider spectrum of error types might occur, arguing that intermediate situations are more difficult to manage – thus to improve – than the boundary situations; indeed, if the aim is to work at the Contextual Conditions of scenario S4 and to focalise the effort to improve the communication process, it would be sure huge vantages in safety are reached, i.e. a high rate of reduction of the task failure probability. It is not exactly the same for scenarios S2 and S3.

Finally, comparing the probability of error in perception and in execution for the scenarios S3 and S4, it is possible to observe that, given an increase in communication errors, the rate of errors in perception is less than the one in execution because the ATCO reaches, error free, the execution phase of the task less often. Thus it is possible to conclude that the simulator clearly reproduces cognitive dependencies among different error types.

6. Conclusions and potential developments of the approach

The main evidences on the value of the proposed approach can be summarised as follows:

- the completion of a pilot application shows that PROCOS provides a stochastic model with statistically consistent results based on a large number of simulation samples taking into account the cognitive-related dependency among estimated probabilities and any dependency among different error types or error modes;
- the method is able to provide probability values also for correct task and, more important, for the corrective actions in the recovery phase;
- the use of a specific flowchart for the communication process assures an effective way to model the liveware-livewere interactions able to capture main aspects and criticalities;
- the method used for developing the task analysis (based on flow charts) is able to go beyond the more static fault tree/event tree modelling and yet it provided results able to be included into a more classical Probabilistic Safety Assessment Framework (that may make use of Fault Trees and Event Trees);
- a good integration has been reached and valuable synergies have been demonstrated among ConOps model of ATM, HERA retrospective and PROCOS approach to HRA, in particular referring to the way of modelling both the task and the context, and the calibration process based on HERA dataset.

The approach could be adapted to other fields of study with little efforts (e.g. process industry, nuclear, railway). The main elements that need to be considered are:

- the compatibility of the taxonomy used within the simulator and the one used for collecting accident data;
- the availability of suitable information about the contextual conditions in the retrospective data;
- the development of a task analysis for the new case study down to a level of detail suitable for interacting with the cognitive model.

Some weaknesses have emerged during the development of this project as well. First of all, it clearly appears that the results of the simulation are strongly affected by the available accident database or reports:

- the mathematical model for the relation among CCs and the error type has been derived from the available data set of HERA, which is still incomplete and relatively small;
- the description of the scenario to be simulated is influenced by the level of detail of CC recording within HERA database. Till now the HERA database classifies the CCs observed in a given accident only on their main category, whereas it would be better and more useful to report the precise description of the CCs identified for each event and not only the main category they belong to;
- the HERA database only reports the presence or not of each CC for a considered accident. Therefore, for the application of this study we only used discrete values (0 or 1). The description of the scenario would be more realistic if the CC influence could assume a real value (ranging from 0 to 1).

Future applications of the approach should tailor the task analysis in such a way that the effect of possible new equipment could be reflected both in the changing of task performed by ATCO and in description of the new scenario through the use of the CCs (PROCOS is already able to consider the equipment and the interaction between the operator actions and the equipment status).

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