

# The representation of context in the simulation of complex systems

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*"neither hand or mind alone suffice; the tools and devices they employ finally shape them".*  
Francis Bacon

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## ABSTRACT

This paper moves from the recognition of the importance of the role of context in determining human action. By context we mean social and cultural properties of an environment as defined by Activity Theory (Kaptelinin, 1996). According to Activity Theory, human beings live in an environment that is meaningful in itself. This environment consists of entities that combine all kinds of objective features, including the culturally determined ones, which, in turn, determine the way people act on these entities. This notion of context is fundamental for understanding the role of artefacts in mediating human action. In the paper, we adopt the Activity Theory framework to reflect upon how to represent “the context” for assessing the impact of new technologies in complex systems like the Air Traffic Control (ATC). Nowadays, the validation of such technologies is mostly performed through the simulation of the operational environment, where controllers perform their activity *as if* they were in a real situation. In the paper, we describe an experience we made simulating the activity of an air traffic control tower in managing aerodrome traffic. The simulation was carried out using structured scenarios to represent activities really observed in the control tower and adapted to fit the context of simulation (more advanced control tools, subset of controllers working together). These scenarios offered a valid contribution toward the representation of the context in complex systems like ATC. They successfully contributed to recreate realistic situations where the system

components were subject to the full variability of input data and situations that may occur in the real world. Through the description and discussion of the case study, we argue that social and cultural properties of the context need to be represented and analysed, as well as the physical and cognitive aspects of the human-system interaction. The analysis of these properties can be beneficial in particular for assessing the impact of the introduction of new technology or the application of new operational concepts on safety.

## 1 Introduction

Activity Theory is a research framework and set of basic principles originating in Soviet psychology that focuses on *practice* to understand everyday life activities as they are performed in the real world. Differently from the classical cognitive approach that has concentrated on *information*, its representation and propagation; Activity Theory is concerned with *practice* and *activity* which involve “the mastery of external devices and tools of labor activity” (Zinchenko, 1986). It was developed by the Russian psychologists Vygotsky, Rubinshtein, Leont'ev and others, with work beginning in the 1920's. Today there is a thriving Activity Theory tradition in HCI studies in Scandinavia (Bødker, 1991) and increasing interest in Activity Theory and HCI in other European countries, the U.S. (Nardi, 1996), Canada and Australia, as well as continuing work in Russia. We could say that Activity Theory continues and elaborates the tendency of HCI of ever-extending units of analysis (Grudin, 1990). While the early attempts to understand the factors influencing human-computer interaction concentrated on low-level input-output processes, the current focus is on long-term events and large-scale aspects of HCI, and in general on factors that are in no way limited to the sensorimotor level of interaction (even if they include them). However, albeit the need to enlarge the unit of analysis has been recognised by many theories of HCI, the solutions offered by each of them are deeply different. As an example, the cognitive approach focuses on the development of a conceptual scheme to describe a multilevel information processing in both human beings and computers. Activity Theory shifts the focus from interaction between user and computer to a larger context of interaction of human beings with their environment. In the environment, tools are used to reach meaningful goals that exist beyond the specific situation of human-computer interaction and that could even serve as intermediate

steps to higher level goals, more remotely related to the specific situation of computer use.

In what follows, we summarise the basic principles of the theory so that they can be applied later in the discussion of our case studies.

Activity theory is grounded on six basic principles: consciousness, object-orientedness, hierarchical structure of activity, internalization/externalization, tool mediation, and development (Kaptelinin, 1996).

### ***Consciousness***

The most fundamental principle of activity theory is the unity of consciousness and activity, where "consciousness" in this context means the human mind as a whole, and "activity" means human interaction with the external world. This principle states that the human mind emerges and exists as a special component of human interaction with the environment. In this sense, human cognition is fundamentally embodied, that is the way human being manipulate tools and materials is not incidental to their cognition but rather is part of their thinking process, part of their cognitive system. External resources are not mere stimuli for cognition but they are integrated in the way people perceive the world, in their thinking processes, in the way they control the activities. Thus, human mind can be analysed and understood only within the context of activity.

### ***Object-orientedness***

The second principle is object-orientedness. According to this principle, social and cultural properties of the environment are as objective as physical, chemical, or biological ones. So human beings live in an environment that is meaningful in itself. This environment consists of entities that combine all kinds of objective features, including the culturally determined ones, which, in turn, determine the way people act on these entities. This principle is in open opposition to the assumption behind the classical cognitive approach that considers that human mind enters in contact with the external environment only through low-level input output processes.

### ***Hierarchical structure of activity***

The third basic principle of Activity Theory is the hierarchical structure of activity, articulated in *activities*, *actions* and *operations*. In Activity Theory the unit of

analysis is an activity directed to an object which motivates activity, giving it a specific direction. Activities are composed of goal-directed actions that must be undertaken to fulfil the object. Actions are conscious, and different actions may be undertaken to meet the same goal. Actions are implemented through automatic operations. Operations do not have their own goals; rather they provide an adjustment of actions to current situations. It follows that the constituents of activity are not fixed, but can dynamically change as conditions change. The distinction between activity/motives, actions/goals and operations/conditions is fundamental for activity theorists to explain the difficulty related to the prediction of the human behaviour, in particular moving bottom up through the hierarchy. For example, if during an operation a familiar condition changes, so the usual conditions are frustrated, people are able to adapt to the new situation even without any negative emotional impact. For example, in an air traffic control room, this could happen when a new sectorisation is adopted due to high traffic conditions. Since controllers share the general motive of the activity, even if the conditions for their operations change, they can adapt without major problems. But when a motive is frustrated, people can react negatively and their behaviour could be difficult to predict. For example, in the en-route control often pilots asks for a "direct route" to the next fix point as a sort of shortcut to save time and fuel. The request is authorised by controllers when both pilots and controllers share the motive of an expedite and safe activity. However, it is not rare to observe that after a few requests of a direct route authorised by the controller, a new incoming one is not accepted. The reasons could be different: difficulty in maintaining spacing when quite a few aircraft are on the same direct route, cultural problems (the pilot has a strange accent, so in order to avoid misunderstandings it is better to stick to the original route). When the motive for an activity is not shared, people can be frustrated in their goal and the overall process can be negatively impacted.

### ***Internalization/externalization***

Activity Theory differentiates between internal and external activities (fourth principle). It emphasizes that internal activities cannot be understood if they are analysed separately from external activities, because they transform into each other. Internalisation is the transformation of external activities into internal ones. Internalisation provides a means for people to try potential interactions with reality without performing actual manipulation with real objects (mental simulations,

imaginings, considering alternative plans, etc.). Externalisation transforms internal activities into external ones. It is also important when a collaboration between several people requires their activities to be performed externally in order to be coordinated. Examples of externalisation in ATC is the use of shared external memories like flight strips that make explicit the internal mental activities of controllers (memorisation, planning, anticipation of future configurations of traffic).

### ***Tool mediation***

In the fifth principle, Activity Theory emphasizes that human activity is mediated by tools in a broad sense. Tools can be external (radar screen, flight strips) or internal (ATC concepts or heuristics, procedures). These tools convey the memory of their cultural-historical origin, the memory of the practice and knowledge produced by the specific community that created and evolved them. The use of such cultural objects shapes and influences the way people use them. These objects influence the nature of external behaviour and also the mental functioning of individuals. Even tools in highly standardised work settings are culturally determined. For examples, flight strips differ in the ATC communities as well as the way in which they have been evolved and used (see Lanzi and Marti, 2002 for a detailed discussion).

The role of the external world in mediating cognitive activities is widely recognised by many researchers. Scribner (1984) records, for instance, how complex calculations can be performed by practitioners using their environment directly. In the case she studied, dairy loaders used the configuration of crates they were filling and emptying almost like an elaborate abacus. The resulting cognitive activity can then only be explained in relation to its context. As Hutchins (1995), Pea (1988) point out, the structure of cognition is widely distributed across the environment, both social and physical. The environment, therefore, contributes importantly to indexical representations people form in activity. These representations, in turn, contribute to future activity. Indexical representations developed through engagement in a task may greatly increase the efficiency with which subsequent tasks can be done, if part of the environment that structures the representations remains invariant. This is evident in the ability to perform tasks that cannot be described or remembered in the absence of the situation. Recurring features of the environment may thus afford recurrent sequences of actions. Memory and subsequent actions, as knots in handkerchiefs and

other memory aids reveal (Marti, Pucci, Rizzo, 2000), are not context-independent processes.

### ***Development***

The last principle of Activity Theory is that of development. Activity theorists claim that to understand a phenomenon it is necessary to know how it developed into its existing form. This principle is directly inspired by the “genetic method” of Vygotsky, who stated that mental processes can be properly understood only by considering how and where they occurred in the development. The principle of development shifts the focus from analysis of the product/object *per se* to the process that determined it. In ATC, it is not possible to fully understand the nature and the use of progress flight strips without considering the history that evolved these tools as we know them today (the fundamental steps of evolution are from procedural control performed via radio contact, to radar-based ATC until electronic, augmented or fully stripless environments).

After having introduced the theoretical framework that inspired the work described in this paper, in the following, we provide a review of the simulation techniques that are adopted in the ATC domain to validate systems in real or realistic conditions. Even if, to some extent, these techniques recognise the importance of the role of context on human performance in interaction with highly technological tools, however they fail in taking into account, as parameters of assessment, social and cultural properties of the environment. In reviewing these techniques, we argue that the simulation of realistic work situations is not sufficient to assess the safety of the system without an accurate representation of the context in the way in which this is defined by Activity Theory.

## **2 Simulation in Air Traffic Control**

Simulations in Air Traffic Control can take different formats, according to the objectives of the validation, the nature of the tasks supported by the new technology and the activity context itself.

The first, and simplest, simulation technique is the fast-time simulation, where all the resources at stake are simulated, and there is no real human subject involved. The

system is run on the basis of analytical models that represent the displacement of traffic over time, with the models usually incorporating rule-based decisions that control the interactions between the actors being simulated.

Fast time simulations will not be considered in this paper, since there is no direct involvement of human agents.

Instead, we will analyse simulation techniques where humans actually interact with the systems under investigation, in a quasi-experimental environment in which some of the variables are designed in a way to be as close as possible to the real operational context. In particular we will describe real-time simulations, shadow mode simulations and operational trials.

## **2.1 Real-time Simulation**

Real-Time Simulation is a real-time validation technique applied to an environment where the main elements are simulated, especially air traffic. This makes the real-time simulation technique especially suited to the validation, with a focus on human performance. In this technique, controllers and other human participants interact with and react to the simulated aspects which, to maintain realism, must operate in near-real time.

Real-time techniques are characterised by the participation of one or more subject matter experts (controllers, pilots, ...) that perform their operational tasks in a realistic real-time environment. Assessing the controller's and pilot's response and decision taking is an essential element of this technique. The environment in which this technique is applied can range from a fully simulated system to an operational system in control of commercial or operational air traffic. The simulation of air traffic can be performed at different reality levels. A traffic generator can simulate part of the traffic fully automatically. Pseudo pilots making inputs to a traffic generator normally control most of the traffic. A very special implementation of this occurs when these pseudo-pilots are all located at different locations and are connected to the central simulation over a network (e.g. the Internet).

Real-Time Simulations give the opportunity to assess different aspects involved in the simulated environment. In particular, Air Traffic Control concepts can be developed to increase capacity; in this case a real-time exercise offers the first opportunity to see whether it operates as expected and actually provides the theoretical capacity

improvements. When, instead, the Air Traffic Control concept is being developed to increase or maintain safety, a real-time exercise offers the first opportunity to see whether it operates as expected, since several safety factors can be assessed, from overload to human errors, to number of conflicts. In any case, one of the major objectives of real-time simulations is to assess the impact of the new system on human involvement and commitment, allowing to focus the attention on the role that human resources play in the context under investigation and to assess the impact of the new Air Traffic Control concept on end users.

At a more technical level, simulations can be developed to assess the relationships among different systems or different modules of the same system. Objectives of the research are, in these cases, the interoperability between systems, which is one of the most significant uniformity factors, and/or the seamless transition between systems.

For the successful participation of human experts it is essential that both the operational concept and procedures for interacting with the supporting systems be described to the level of detail of tasks and responsibilities of the participants.

A very powerful aspect of the Real-Time Simulation technique is the possibility to adapt it to the activity and the specific tasks to be assessed. In this sense, the amount of working functionality of the system can be tuned to the nature of the task to be assessed. This scalability is often integrated with techniques coming from the tradition of ethnographic studies and user centred design, like interviews, talking aloud or the Wizard of Oz technique.

## **2.2 Shadow Mode Simulation**

The methodology that is usually used for testing systems in the real operational context is known as “*Shadow-mode trials*”. It represents a way to conduct relevant validation steps for an operational prototype, namely a system designed and built to satisfy operational standards through an incremental development process. Usually in a shadow-mode trial of an operational prototype, the Air Traffic Control support tool is fed with live data from the environment (e.g. radar and other data), but the prototype is not actually used to control or influence the live traffic. The prototype is operated by an off-duty controller or other trial staff and measurements and observations are recorded for the following off-line analysis.

As a variation of real-time techniques, shadow mode is characterised by the non-interfering use of a new system or function in a real operational environment. The new system or function is driven by inputs from the operational system but does not feed its output back into it (there is a one-way interface). A characteristic difference with the field test technique is that a human operator is using the new function in real-time without interfering with the actual operational system.

There are very few parameters that can be varied when considering the experimental design for a shadow mode trial. This must have an impact on the validation aims that are possible, however it is a most valuable step in the process of bringing a new concept into operations. The feasibility of the aims needs to be considered in order to ensure that appropriate system configurations are possible for the measured runs. Multiple measurements are possible, however it is not possible to ensure that a full range of conditions are experienced (emergencies and extreme conditions would not be requested).

### **2.3 Operational Trials**

In a trial, the set of one or more validation activities to be undertaken in a generally contiguous time period, are used to fulfil a defined set of strategic and subsidiary objectives. An operational trial is closest to real operations as it involves the use of a new system or function, which has already been extensively validated with other techniques, on a limited scale in an operational environment. As in shadow mode, there are limited parameters that are within the control of the validation team for the experimental design. The validation aims again need to be considered carefully to ensure that they are feasible and relevant. Multiple measurements can be made easily both in terms of participants and elapsed time over which measurements can be recorded.

## **3 Complexity and simulations**

In general terms, we can consider complexity as the condition that concerns the nature and consequences of interactions and non *linearities* of systems with many different agents. These systems are too rich and varied to understand in simple, mechanistic or linear ways. We can understand many parts of them but the larger and more intricately related phenomena can only be understood by principles and patterns and

not predicted in detail. In human organisations, complexity plays a crucial role since it deals with dynamic and emergent patterns of behaviour, innovation and change, learning and adaptation.

Air Traffic Management (ATM) is an example of complex system: even if controllers' tasks are structured and well documented, the activity itself produces adaptations that make the tasks less stable (from personal strategies of task execution to serious violation of procedures). Tasks assigned to controllers can be performed in different ways, and the performance is very dependent on the specific configuration the "human-machine system" acquires (external environment, individual capabilities, confidence, procedures, history of the interaction, status of the system). More in detail ATM can be considered a complex system since the cognitive properties of the whole can radically differ from the cognitive properties of the individuals who perform the activity.

One issue for the validation of new concepts and procedures in such complex systems is the simulation of the complexity of the context. Simulations can represent a way to conduct relevant validation steps but it is crucial the way in which the experimental setting is conceived. For example, in a real time simulation the ATC support tool is fed with real data previously stored, but the context of interaction has to be recreated including, as much as possible, the richness of potential interactions between social, cultural and technical components. In this respect, one of the desirable effect of real time simulation is the representation of how the system can be "naturally" subjected to the full variability of input data and situations that may occur in the real world. There is a need to reproduce a real environment in realistic scenarios. A fundamental challenge is therefore how to represent the context of work practice (both current practice and envisioned future work practice) in order that the simulation may be linked to safety issues.

Our approach is to consider not only the actions of "users", but also the contexts in which these actions take place and in which systems and devices are used. The literature on accident, incident, and near misses occurred in safety critical systems suggests that the usability of a control system and its ability to tolerate variances are strictly related to an adequate distribution of knowledge and the consequent correct interaction and co-operation between humans and tools. In order to simulate and analyse these interactions, it is necessary to adequately represent the context and to

have a high level analysis capability. In this respect, task analysis is not adequate since it tends to focus on fine granularity on specific human tasks, and is weak in analysing high level communication tasks and co-operative activities.

Carroll (1995) was perhaps amongst the first to question the task as the appropriate unit of analysis. He introduced the concept of the task artefact cycle, arguing that the introduction of technology into a work setting changes the nature of the tasks in that setting. For Carroll this was followed by a turn to scenario-based design where scenarios as representations of work were intended to capture rich aspects of the context of work that could be not captured by task representations alone. Inspired by the scenario-based design, we developed a methodology that exploits the concept of scenario to represent realistic situations in real time simulation. The method has been applied in different contexts of safety critical systems, from requirement specification, to incident analysis (Rizzo, et al., 2000), (Sujan, et al., 1999), and validation (Marti, et al. 2000). In the following sections, we firstly introduce the method and then discuss its application through a case study.

### **3.1 Structured scenarios and simulation**

In the current practices of ATC system validation, scarce attention is devoted to the problem of how to re-create/represent a “natural” context for simulating the ATC activity. Even if the issue of realism is reckoned to be of primary importance in order to observe, in safe conditions, the system performances as close as to the real operational ones, however current validation methodologies (see for reference the PHARE and MAEVA validation projects sponsored by Eurocontrol) do not really take into account the issue. They mainly use three kinds of methods during simulations:

- Non-intrusive data collection like data recording through the system software of, for example, aircraft on frequency and recording of all controller and pilot communications.
- Intrusive data collection like workload measures through, for example, Instantaneous Self-Assessment (ISA) – where the controller is required to push a numbered key every two minutes. Other intrusive techniques are

the salivary cortisone method to measure controllers' level of stress, eye-tracking and heart-rate variability as a reaction to traffic situations.

- Disruptive data collection that intermittently interrupt the controllers during the activity. For example, asking the controllers to complete another task in addition to that of controlling the aircraft in their sector whenever there is sufficient time. Such secondary tasks is often used also as an indicator of controller workload. For example, a number might be displayed at regular intervals to the controller, who must then perform a mental mathematical calculation based on that number and input the result via the keyboard. The length of time taken to respond, the accuracy of the result and other such factors are then used as a measure of the controller's workload.

All these techniques, even if deeply different in nature, share the same limitations:

- A lack of a clear theoretical framework to define experimental hypotheses and analyse the collected data.
- A clear rationale to select and combine different validation methodologies.
- The notion of "exercise", that is a number of traffic situations that are varied in terms of evolution of traffic and airspaces. In the design of exercises, there is no consideration of other more "situated" elements of the activity like motivational, cultural, social and emotional factors.
- The use of a baseline scenario against which the results of the simulation are compared. Again the baseline scenario is simply a traffic sample related to a specific time frame and airspace. The baseline scenario is an ideal abstraction of situations that normally the controllers manage. Contextual factors are totally neglected and there is no mention of them in the assessment criteria that are usually based on the comparison between the base line scenario and the simulation scenario along generic metrics like workload, safety, capacity etc.

CRIA (CRITICAL Interaction Analysis) is a validation technique for safety assessment in complex systems (Marti, Scrivani, Rizzo, 2001) developed to overcome the above mentioned limitations. It is directly inspired by the principles of Activity Theory but, in order to make it operational and usable even by people who are not experts of

Activity Theory, it is grounded in simple concepts that can be familiar to those who are not familiar with this theoretical background.

The concepts used by CRIA are borrowed from the conceptual model SHEL (Edwards, 1972) that describes the behaviour of interactive systems with special regard to human factors. SHEL is an acronym for Software, Hardware, Environment, and Liveware. Software refers not just to computer software but to the rules, procedures, practices that define the way in which the different components of the system interact among themselves and with the external environment. Hardware is used to refer to any physical and non-human component of the system such as vehicles, tools, manuals, signs and so on. Liveware refers to any human components of the system in the relational and communicational aspects. Environment refers to the socio-cultural and organisational environment in which the different components of the process interact.

The SHEL model concentrates on the interfaces between people and all system components including other liveware resources. The important point about SHEL is that it offers a systemic view where humans are not considered as isolated from the other system components. Even if the model is an over-simplification with respect to the broad view offered by Activity Theory, it is consistent with the positions of Activity Theory and allows both to concretely apply the basic principles of the theory and to integrate them within a structured approach of scenario-based design and evaluation.

Indeed in CRIA, the SHEL model is enhanced by the introduction of structured scenarios that highlight aspects of the activity and exalt the social and cultural components theorised by Activity Theory. Scenarios in CRIA consider human activity as a socially and culturally organised ensemble where artefacts play a critical role in mediating human activity. They are structured in a way to represent the combination of liveware, software and hardware components of a process and consider that this combination changes as soon as the process evolves and that many combinations may occur during the process. As for Activity Theory, they aim to address a wide unit of analysis where knowledge is distributed among humans, procedures and tools and it is continually evolve through use.

CRIA develops in three main phases: preparation of test materials, execution of the test and data analysis. The first step of the evaluation process is the identification of

the basic Software (S), Hardware (H), Liveware (L) components that may affect the use of the new system. This phase of the method, as the following one, is carried out through an accurate activity analysis based on observation in the real operational context and the analysis of standard procedures and daily practices. From the activity analysis a set of safety issues are identified. Examples of safety issues are: information visibility (capability of tools to externally represent the knowledge necessary to execute a task), consistency and integration of the information needed to perform the activity, tool-mediated co-operation etc. The safety issues are macro validation objectives that have to be reflected in the scenarios during the real time simulations. They are elaborated later in the process to fit the validation context (operational conditions, actors involved, implementation details).

On the basis of activity analysis, scenarios are built to represent realistic situations similar to those that have been observed. The situation is refined to include potential critical interactions among H,S,L components. Indeed the validation does not aim to sequentially test each single procedure as standing alone, but to create a simulated realistic operational context, in which non linear interactions among components could emerge. Scenarios provide a representation of possible configurations of work processes being they an interpretation and a reconstruction of the work processes observed in the real operational context. For this reason, scenarios focus on some aspects or features of the process and neglect some others. In this respect scenarios are fundamentally different from simple configurations of “traffic samples”. They do not include only number and typology of traffic in a given unit of time but are realistic situations in which breakdowns may occur (exceptional circumstances, ambiguous procedures, controllers’ errors, communication misunderstandings). They are realistic since resulted from the analysis of the current work activity, including socio-cultural components of the observed environment. It is important to point out that scenarios in CRIA represent information coming from different sources (activity observations, standard documents, interviews, story telling) and different people with different knowledge and views (controllers, domain experts, human factors experts, developers).

During the simulation, these scenarios are executed by controllers and all the activity is observed and video recorded. After each scenario, the controllers are involved in a debriefing session based on the video recording of the test. They are asked to freely comment their performance and experimenters moderate the discussion focusing on

the assessment of safety issues. In this way it is possible to obtain a wide variety of views from a range of people (controllers coming from different operational realities, pilots) who might have different but equally relevant perspectives about the use and the impact of the system.

In what follows we describe the application of CRIA to MIDAS, a simulator of airport ground movements, developed by Alenia Marconi Systems. MIDAS simulates new technological tools that may be operational in the Control Tower in the near future. These include a data link system, a stripless environment, a short-term conflict detection tool and monitoring aids. The description will be complemented by a discussion of the benefits of using the particular scenarios proposed by the CRIA methodology.

## **4 The representation of context: a case study**

In what follows, we provide some extracts of evaluation process of MIDAS with specific regard to memory tasks performed by controllers in the Control Tower.

Flight Progress Strips are a fundamental tool that externally represent the traffic evolution and support the controllers in memorising in a stable and effective way dynamic traffic configurations. Moreover, they are an extremely flexible tool which allows controllers to keep track of the changes which happen in the real world and to dynamically adapt their strategies to the natural variations which systematically affect the way traffic is managed according to standards procedures and daily practices.

Role of the paper strips in Air Traffic Control is therefore multiple. Each strip supports controllers in remembering the general information about a specific flight, the characteristics of the aircraft, the flight plan and so on. Furthermore, their distribution over the stripboard helps controllers to maintain and update the departure and arrival sequences, transforming this activity from a memory task to a monitoring and planning task.

The physical handling of the strip and the passage to the adjacent controller implies the delivery of all the information necessary to manage a flight and the embodiment of a control procedure, that is the handing of a flight over. Again the ritual of exchanging a physical object mediates a cooperative activity tacitly recognized by the controllers. As a ritual, the passage of strip evokes trustfulness and mutual support. In this respect the execution of this procedure is particularly critical being dependent on

the way external tools mediate it both in terms of information exchange and mutual trust between the controllers.

#### **4.1 Building Scenarios for simulation**

In what follows we describe the way in which scenarios were evolved from real accounts to simulated reconstructions of ATC to address the safety issues emerged during the activity analysis (inadequate interface, ambiguous procedures, pilots' and controllers' errors, communication misunderstandings). This evolution was grounded on an intense ethnographic observation in the Control Tower focusing on the interaction between individuals (pilots, controllers), artefacts (window, radar, strips, telephone) and procedures/practices (division of labour, taxing and hand over practices, safety procedures and so on).

More in detail, scenarios evolved through an iterative process of i) activity analysis and data collection, ii) definition, iii) structuring and refinement and was related to one or more safety issues observed in the Control Tower, that is hazardous situations, that could lead to incidents/accidents. The collection of such scenarios represented a set of safety-related break-downs of the current activity and/or a set of design requirements that different stakeholders agreed upon.

In the evaluation of MIDAS tools ten critical scenarios were developed from the activity analysis and these guided the actual system design and implementation. One of them is reported as an example below.

##### **Scenario: Runway Incursion**

The runway 25 is used for take off and the aircraft leaving the gate area has to reach the runway through the taxiway B (Figure 1 below). The situation is particularly critical in that the fog prevents the ground controller from properly monitoring the aircraft's movements; for that reason departures and arrivals are significantly reduced.

Aircraft 1 (DLH3901 in figure 1), which has already performed the start up procedure, is cleared to proceed to the runway 25; after 2 minutes, the aircraft 2 (AZA886 in figure 1), which is supposed to take off just after the aircraft 1, is also cleared to proceed to the runway 25. Aircraft 1, after having reached the holding position, is then handed over from the ground to the tower controller; at this point the pilot asks the tower controller the clearance to take off. At the same time, the pilot of the aircraft 2 makes a wrong turn and enters the departure runway through the taxiway BB; the pilot realises that something got wrong and calls the ground controller saying that he probably is in a wrong position. Immediately, the ground controller asks the tower controller to delay the take off of the aircraft 1 because the runway is

occupied. Finally, the ground controller issues the aircraft 2 to clear the runway, to enter the taxiway B through the taxiway BC and to repeat the taxiing procedure. The new departures sequence is then communicated to the departure co-ordinator.

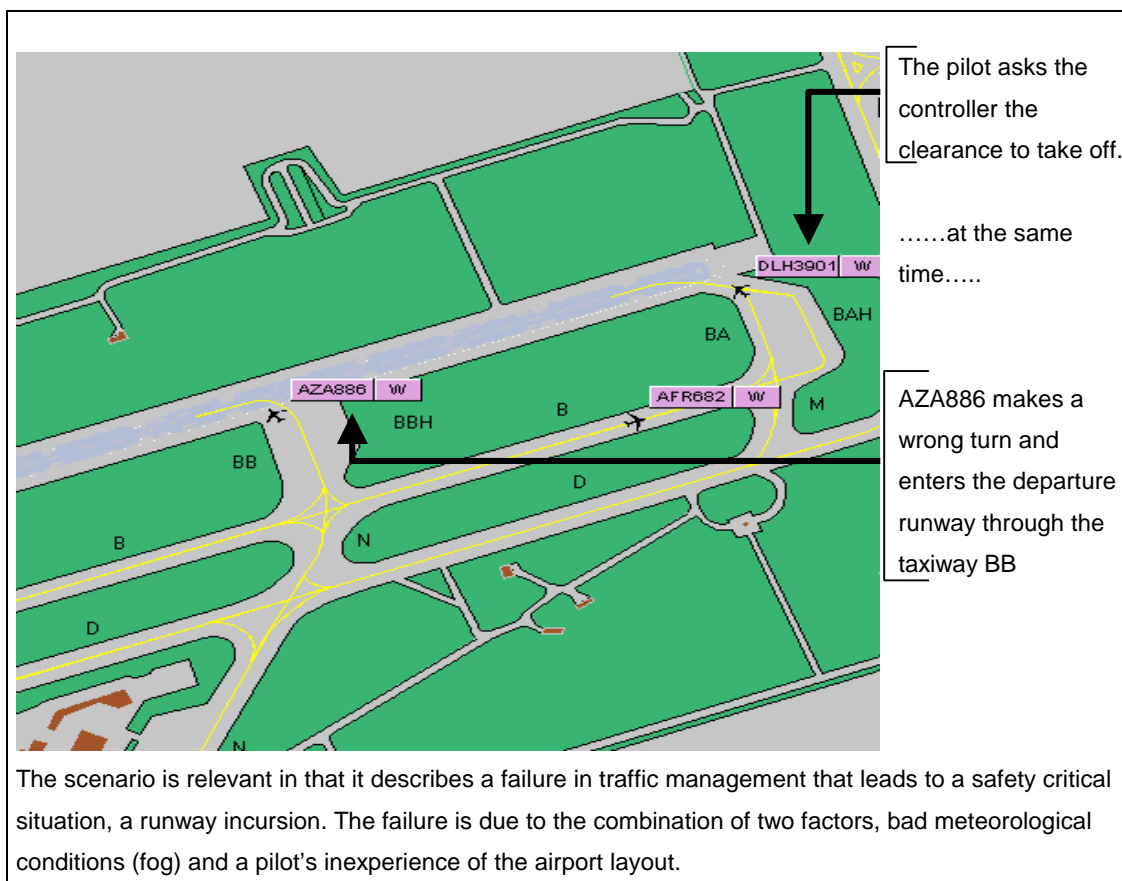


Figure 1: the Runway Incursion Scenario

The scenarios collected from the activity analysis phase served as a basis for defining new scenarios to run the simulation. These were selected and built according to the following criteria: criticality (low, medium, high), potential occurrence in real operational context (low, medium, high) and finally implementability in the MIDAS simulator (yes, no).

In the following, we report in detail five steps necessary to evolve “observed scenarios” into “simulation scenarios”. For the sake of readability, the steps are presented using the “Runway Incursion” scenario as a guiding example.

### 1. Matching safety issues and MIDAS tools.

We verified which MIDAS tools could have an impact on the safety issues of each specific scenario.

## 2. Implementing scenarios on the simulator.

We checked that the observed scenarios could be implemented (run) on MIDAS to provide the controllers involved in the simulation with a situation as close as possible to the original scenario observed in the Control Tower.

## 3. Identifying SHEL components.

For each scenario we identified the constituent SHEL components. For the Runway Incursion Scenario they were the following:

*Hardware:* Functionality of MIDAS needed to execute a task or a procedure;

*Software:* all procedures and the action sequences needed to execute the scenario;

*Liveware:* the actors involved in the simulation, mainly Tower and Ground Controllers, plus the pilot and different pseudo-pilots.

*Environment:* the organisational setting of the Control Tower. In the following tables, the “environment” will be implicitly considered since it not varied for the considered activities.

Liveware	Software	Hardware
Ground Controller; Tower Controller (pseudo-controller), Pilot 1 (pseudo-pilot), Pilot 2 (Sw), Pilot 3 (Sw), Pilot 4 (Sw).	Issuing a Taxiroute Monitoring and Guidance Hand-over	Arrival / Departure Windows Message In /Out Enriched Flight Labels Data Link Routing and Monitoring tools

## 4. Envisioning interactions among components: the SHEL Question Table.

For each scenario we tried to identify critical interactions between the controllers and the other system components (L, S, H) when using the functionality implemented in MIDAS. A Shel Question Table, that is a list of questions related to the coupling of H,S,L components of the selected scenarios, was prepared addressing all these critical interactions. The table is used after the simulation to interview controllers. An extract of a Shel question table related to the Runway Incursion Scenario is provided below.

Procedure	L- Liveware	L- Software	L- Hardware
Issuing a taxi route	Does data-link support the pilot in following the Ground Controller' instructions?  In case of the route is busy, could the tower quickly communicate with the pilot via data-link?	Is the procedural knowledge needed to carry out the activity externalised and accessible?	Does the new tool integrate all the information that in the current activity come from different sources (window, strip, radar ASMI, etc.)?
Monitoring and Guidance	.....	Does the new tool enable the Ground to reconstruct the sequence of an action started but not completed?	Does the new tool support the Ground in case of bad weather conditions?
Hand-over	.....	.....	.....

### 5. Structuring scenarios for the simulation.

The last step of the process ends up with the definition of scenarios that are structured along the following components: rationale for running a scenario (which safety issue it addresses), estimated temporal duration for executing a scenario, actors, goal (the objective of the scenario), initial condition (status of the interface), operational context (meteorological and traffic conditions), MIDAS tools involved, other external supports available to the controllers.

<b>“Runway incursion” Scenario</b>	
<b>Estimated temporal duration</b>	10-15 min
<b>Actors</b>	<ul style="list-style-type: none"> <li>• Ground Controller</li> <li>• Tower Controller (pseudo-controller)</li> <li>• Pilot 1 (human pseudo-pilot)</li> <li>• Pilot 2 (software)</li> <li>• Pilot 3 (software)</li> <li>• Pilot 4 (software)</li> </ul>
<b>Goals</b>	To guide AZA 886 and AZA 7376 to RWY 25 and to hand-over them to the Tower Controller
<b>Simulated events</b>	Pilot 2 doesn't execute taxing correctly
<b>Initial condition</b>	<ul style="list-style-type: none"> <li>• Airport Map, Message In Window, Meteo Window, Departures/Arrivals Windows are opened.</li> <li>• The Departure Windows display 4 a/c: AZA 122, AFR 682, AZA 7376, AZA 886</li> <li>• Message In Window displays the taxi routing request of AZA 886.</li> <li>• The Meteo window displays critical condition: visibility 750.</li> </ul>
<b>Operational context</b>	<ul style="list-style-type: none"> <li>• Weather condition: fog.</li> <li>• Traffic: reduced.</li> </ul>
<b>Midas tools</b>	<ul style="list-style-type: none"> <li>• Arrival/ Departure Windows</li> <li>• Enriched Flight Labels</li> <li>• Taxiway Router</li> <li>• Data Link (Message In e Out)</li> </ul>
<b>External supports</b>	None
<b>Rationale</b>	<p>Basic Scenario. Potential occurrence: low. Criticality: high.</p> <p>Objective of evaluation: Usability and reliability of the MIDAS tools in routinely conditions.</p> <p>Safety Issues: Information visibility, software-mediated hand-over in substitution of strip-based hand-over, software-mediated co-operation between the controllers, data link communication vs elbow communication.</p>

## **4.2 Running scenarios during the simulation**

The simulation was run on the basis of the scenarios resulting from the process described above. During the simulation several critical interactions emerged. In particular, during the execution of the Runway Incursion Scenario, the controllers were not able to recover the error of pilots 2 who made a wrong turn, leading to a collision between aircraft 1 and 2. The analysis conducted on the coupling of H,S and L in the context recreated by the scenario rather than on the execution of single procedures on traffic samples, allowed us to reconstruct the complex interrelationships between the HLS system components that lead to the collision .

In the following we report the comments of controllers after the simulation.

**What happened:** The visibility was reduced and the distance between AZA 886 and AFR7376 was only 4 km on the same runway. The Tower controller cleared AZA 886 to “line-up and take-off”. By mistake, the Ground controller handed AFR7376 over the Tower Controller. After a while the Ground Controller asked the Tower Controller for a confirmation of the hand-over procedure. The Tower Controller answered “yes” after checking the message window but he didn’t realise that the Ground Controller had made the error. Both the controllers detected a collision between AZA 886 and AFR7376 late in the scenario execution.

**Comments:**

Ground: ...I thought: “It’s better if I hand AFR7376 over soon and inform the Tower that AZA 886 will take off on the same runway crossed by the AFR7376... unfortunately I was not sure if I had already handed over the a/c so I asked the Tower for a confirmation. In the meantime I forgot to inform the Tower about the crossing of the runway because he immediately answered “Yes”.

Tower: ...I answered “Yes” because I quickly checked the departure window without checking the real position of the a/c...So my answer was correct, that is the a/c has been handed over but by mistake...

As it emerges from the transcriptions above, the hand over procedure is not adequately supported in MIDAS. Whilst the flight strips both mediate the execution of the procedure and externalise the knowledge produced by the cooperation between the two controllers, the computer-mediated hand over doesn’t. Indeed in MIDAS the hand over is executed sending a data link message to the controller who has to take the responsibility of the aircraft. This message is sent by clicking the label associated to an aircraft, the same physical action that is used to check the taxi route, to issue a clearance, to monitor the progress of the ground movements. Such action is detrimental in representing the ritual between the two controllers that allows them to mutually trust each other and rapidly execute the procedure. Without the ritual that distinguishes one procedure from another one, the controller is exposed to a memory overload resulting in a scarce performance. The interaction between Hardware (the label), Liveware (controllers) and Software (the hand over procedure) is not correctly balanced and the Liveware has to overcome the limitation of the Hardware being obliged to memorise the action of clicking the label and to associate it to the correct procedure. Such configuration of the three components drives back the human

activity from an organisational ritual that does not imply a cognitive effort to a memory task that consistently increases the controller's mental workload.

The use of structured scenarios designed to represent a wide unit of analysis like the one proposed by Activity Theory, allowed us to highlight situated components of the activity that could not be easily detected using more traditional approaches like those described at the beginning of section 3.1. The shift of attention from interaction between user and system to a larger context of interaction among controllers and pilots within a specific configuration of the environment, allows to analyse a hierarchy of goals that exist beyond the specific situation of controller-system interaction (a clearance issued by mistake, that traditional approached would categorise as "human error") and that serves as an intermediate step to higher level goals, more remotely related to the specific situation of system use (memorisation of an action that is not externally represented by the computer-based hand over and that makes it difficult the coordination among the controllers). Moreover, the use of scenarios derived from the observation of the real activity allows to maintain the richness (and complexity) of natural accounts of events that is lost when using generic baseline scenarios. The last but not less important advantage of the proposed approach is the use of the shel question table as a guide to conduct debriefing sessions with controllers after the simulations. The shel questions never address issues related to one of the system components in isolation. For the controllers, this way to reflect on the activity stimulates the discussion at all the different levels of activity/motive, action/goal and operation/condition, resulting in extremely rich brainstorming sessions.

## **5 Conclusions**

The use of structured scenarios in real time simulation seems to offer a valid contribution toward the representation of context in complex socio-technical systems like ATC. They seem an appropriate means to recreate realistic situations where the system components are subject to the full variability of input data and situations that may occur in the real world.

However, in order to significantly represent the context, scenarios have to be built on the basis of observations carried out in the real operational context and structured in

such a way that social, organisational and cultural factors can be fully exploited as equally determining factors.

In our approach, the structuring of scenarios implies an articulated process where the potential interactions between the different components of the system are represented to provide a meaningful context for the activity during the simulation. Indeed, the complexity of any socio-technical system is not a simple function of the number of interacting elements that compose the whole system. Rather, the complexity depends on the nature of interactions between those elements and the degree of knowledge held by subjects involved in this interaction. Structured scenarios present situations in which the systemic components may serve different functions so that each component interacts with the other components with different modes leading to unplanned states or reactions. This can highlight complex interactions among components that are either not visible or not immediately comprehensible to the operators leading to hazardous situations. The fact that scenarios are not static representations of the context but narrative accounts of activity, provides a context that favours the emergence of specific configurations of interactions among systemic components that are difficult to predict or anticipate in ordinary sessions of real time simulations.

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