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Modelling of Automation Degradation: a Case Study

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Abstract— This paper presents a modeling approach that has been developed within the SPAD project for analysing consequences of automation degradation in large socio-technical systems. This modeling approach involves two different notations: FRAM [6] and HAMSTERS [2], [8]. In previous work [7] we have proposed a synergistic approach integrating these two views for describing the evolution of system performances under automation degradation. The focus of the paper is on how the outcome of the models can be integrated to analyse system behavior. After describing the principles of such integration we exemplify it by using a standalone ATM simulator, and analysing the possible degradations of a system for managing unmanned aircraft (RPAS).

Keywords—component; Automation degradation, resilience, performance, ATC, RPAS

I. INTRODUCTION

The SESAR initiative intends to deal with the increase of traffic demand and the new business challenges that the ATM system will have to afford in the coming future. The increase of automation is one of the basic elements of all the solutions identified by SESAR to deal with such problems. Automation will support, and in some long term cases even completely replace human tasks, in order to meet the new capacity and efficiency needs. Human operators will be able in this way to manage a higher number of tasks and will shift toward more strategic roles and supervision activities in ATM. SESAR projects are validating tools and new operating procedures supporting controllers in conflict detection and resolution, as well as higher levels of automation for data gathering and management.

However, automation brings a range of new challenges including those related to possible degradations. In particular, high levels of automation imply low system flexibility. A system which has been carefully planned, and thus standardized and automated, is hardly able to deal with non-standard and unplanned events such as those caused by technical failures. In addition, the components of a highly automated system are usually tightly interconnected. The consolidation programme of the ATM architecture will lead to fewer and fewer control centres through Europe. Contribution to this increased interconnection will also come from the new gate-to-gate solutions, from the implementation of the SWIM architecture with less information asymmetries, and from the

tighter links among all the stakeholders needed to offer a coherent and homogeneous service and interoperability. Increased coupling may make harder to identify and isolate failures when they occur, and to detect minor malfunctions before they propagate to the whole system. Then, coupling and lack of flexibility can bring to a higher sensitivity of the ATM system to degradation problems.

Current models that support safety evaluation focus on systems before operation or on post-accident analysis. These models consider possible deviations, malfunctions, errors, or "after the fact" information. Even if these models have been very successful in the past and contributed to the very good safety achievements of the ATM system, they risk to be less adequate in a highly dynamic, and coupled system, that adapt dynamically to ensure user-preferred trajectories and to balance the demand. To manage properly the consequences of automation degradation we would need to be in condition to understand, monitor and control its propagation. We also need to be able to confine and absorb degradation problems (both with and without human contribution), and to understand and estimate the implications of degradations for the overall ATM system performances.

In this paper we describe the use of a federation of models (advancing other the limit of the current models) supporting safety evaluation. The approach has been developed within the project System Performances under Automation Degradation (SPAD). Within the course of the project the federation has been applied on a large case study to evaluate its ability to:

- understand, model and estimate the propagation of automation degradation in ATM;
- evaluate and estimate the consequences on ATM performances;
- support an effective intervention for the containment of automation degradation.

Section II introduces the models that have been selected to build the federation discussing how they collaborate to the system analysis. Section III describes how the federation can be applied and how the different models collaborate in order to support assessment of degradations impact. Section IV describes a case study regarding a large system with high level of automation, and how different types of failures and the

related propagation of degradation were simulated. Section V shows an example of the information, provided by the federation, to support the evaluation of the system under analysis. Section VI concludes with a discussion of the problems and limitation experienced using the SPAD approach.

II. FEDERATION AND INTERACTION BETWEEN MODELS

The federation defined in SPAD combines models offering different perspectives of the system under study and analysing it at different levels of granularity. Since we focus on a specific aspect of ATM (its ability to contain and manage automation degradation) we don't need a full abstraction of the ATM system. We can select models whose joint capabilities offer sufficient information for the questions of interest. In particular, we focussed on the propagation of automation degradation and the related influences on performances, limiting our investigation to the related aspects of the ATM system. We did not develop a large scale stand-alone model but combined in a federation a set of selected models, focussing on essential specific aspects of the systems. Each model investigates specific characteristics and represents a part of the whole ATM system with variable levels of granularity (from coarse to fine grain) depending on the interest of the analysis.

Using multiple models to represent different facets of the system under consideration has been the trend for many years in the area of software (with the 9 notations of UML [11]) and more recently of systems (with 2 additional notations of SysML [12] with respect to UML). The approach we adopted extends that kind of work to encompass the multiple and more diverse facets of Large Socio-Technical Systems (LSSTS). In addition, we use compatible representations and format across models and reference a shared and correlated environment facilitating the integration of information and the analysis.

The federation of models can work at different levels of abstractions from the single system till the top system of systems level. At the system level models consider what is required for the system to carry out its operations and to manage and possibly tolerate possible degradations. When considering this system in integration with other systems the models consider interaction and coupling between the different systems, to understand and measure degradation propagation and the link with the overall performances.

The federation of models used in SPAD consists of the Functional Resonance Analysis Method (FRAM) and of the Human-centered Assessment and Modeling to Support Task Engineering for Resilient Systems (HAMSTERS). FRAM [1] is a safety management method aiming to support both accident investigation and risk assessment processes based on a set of principle related to complex socio-technical systems structure and dynamic. FRAM describes system functions characterising six basic relationships between them: input, output, preconditions, resources, controls, and timing. For example, the left side of figure 1 shows the six basic aspects of the function “Monitor traffic and separation”. This characterisation can be used to derive all the potential couplings among functions, even if they were not part of system design, and to instantiate them in specific scenarios.

The functional modelling of FRAM is recursive and this facilitates its application at different levels of granularity, very high level when large portions of the ATM system are considered or more detailed when focussing on a small set of systems. This refinement is illustrated in the right part of figure 1, where the function “Monitor traffic and separation” (left-hand side of the figure) is refined into five sub-functions. This refinement ability provides support for the representation of a larger number of functions while keeping the model

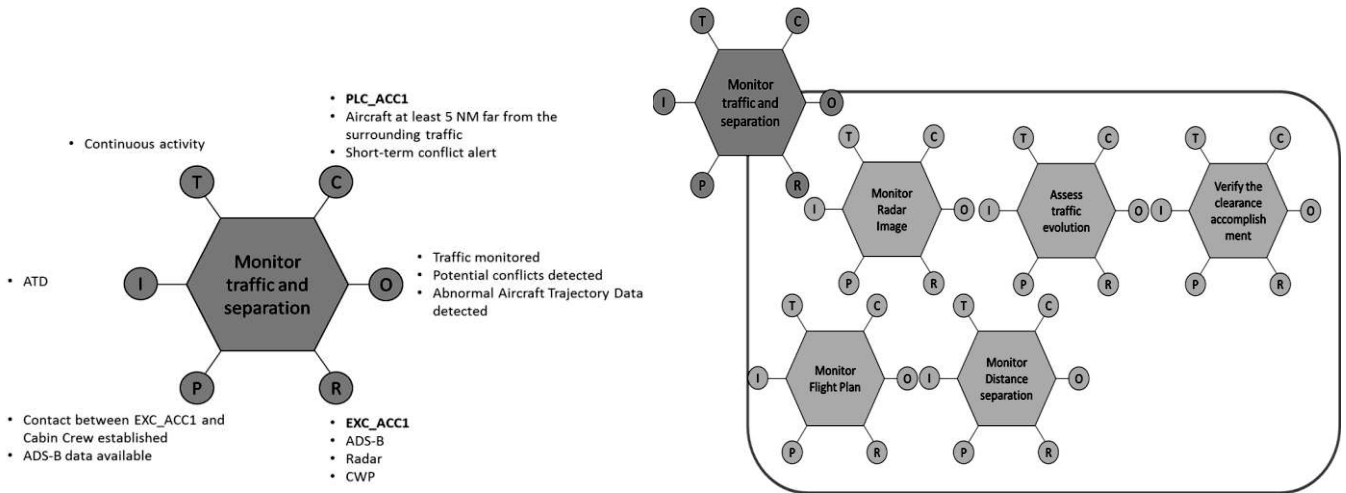


Figure 1: Function “Monitor traffic and separation” represented with FRAM

representation understandable.

HAMSTERS [2], [8] is a notation designed for representing the decomposition of human goals into tasks. The notation embeds several types of tasks that include: tasks done by a human, by an automated system, interactive tasks (between human and system), and generic. Tasks are represented as special nodes in a hierarchical structure. Temporal relationships are described by operators and quantitative time is represented by expressing task duration, minimum and maximum execution time and delay before tasks availability. The HAMSTERS notation supports the analysis of the complexity of the operators' tasks and thus can also support the identification of which tasks are good candidate for allocation to the system [3].

Within some past project case studies [16] we also evaluated the possible use in the federation of ICO [13], [14]. ICO is a formal description technique dedicated to the modeling of interactive applications. This formalism makes it possible to describe the entire interactive application including both behavioral aspects (states and state changes) and interaction aspects (events triggered by the user interface and the graphical rendering) [4]. However, for the large case study described in this paper the complexity of the representation and the difficulties in information compatibility suggested to restrict the federation to FRAM and HAMSTERS only.

III. USE OF THE FEDERATION

A. The Application Process defined in SPAD

The models of the SPAD federation are not intended to be used as stand-alone models but rather to support the analyst during his analysis. The analyst is the mediator of the interaction between the models and he is the manager of the federation, as shown in figure 2.

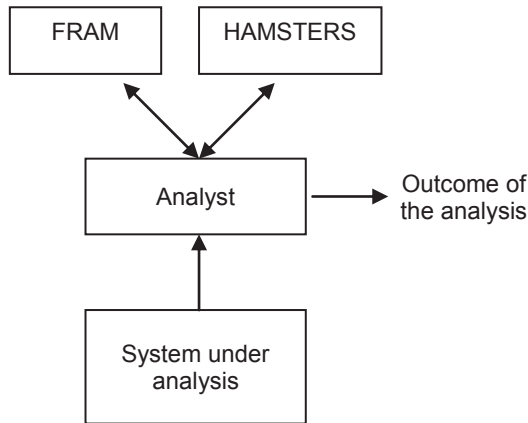


Figure 2: Role of the analyst

The process defined within SPAD to apply the federation starts with the identification and characterisation of the system under analysis. The aim is to identify the object under investigation, that is the system under analysis to which the federation will be applied, and the conditions under which we

intend to evaluate it. This entails the identification of the system components that will be considered during the modelling and evaluation, its operational condition and the main assumptions and simplifications that are adopted for the analysis. This allowed a shared understanding of the system so that both models refer to the same object, under the same operational conditions and assumptions. During this phase we identify not only the nominal condition, but also those perturbations we may want to explore during the analysis. For example, we may be interested in the consequences associated to different types of possible degradations.

In the following step the system description is translated into functions that are then modelled with FRAM with the characterisation of the six basic relationships, for example control (one function controls the execution or timing of another one), input/output (the output of one function serves as input of another one), timing, resources and so on. A full and satisfactory representation of the system may require different iterations in which details are identified and added. Representations may include different levels of granularity (from coarse to fine grain) depending on the interest of the analysis as already shown in figure 1.

All the relationships are dynamic and depend from the situation in which the system is operating and are specific for the scenario under study. Once the scenario has been chosen the analyst identifies all the relationships between the functions, ending up with a graphical representation similar to the one shown in figure 3. This is called an instantiation of the system under a specific scenario and is the basis for studying the possible evolution of the interrelation between the functions for that scenario.

Last step is the study of the interrelation between the functions, for a given scenario. This step focusses on the possible consequences that may affect system performance adversely, identifying the downstream functions that are more influenced. On the basis of this study the analyst can identify ways for monitoring and control the output of the functions (e.g. introducing indicators and barriers, modifying the design or the procedures, etc.) limiting the possible negative consequences.

The behaviour of each function, that is, what is produced as output (e.g. timing, resource, constraint) for a specific input, is identified using the FRAM methodology and associated tables [6]. When humans are a key element of the function or when temporal and quantitative aspects are important the behaviour is defined using HAMSTERS notation and tool. For example, HAMSTERS can help in understanding the temporal properties of the function and the temporal relationships during its execution.

HAMSTERS offers representations and format compatible with FRAM, ensuring meaningful and compatible analysis about the entities used for the analysis. The federation employs repositories and representations where data used by the models are recorded, ensuring an easy transfer of information between

them. These include the functional representation of the system and the different system instantiations.

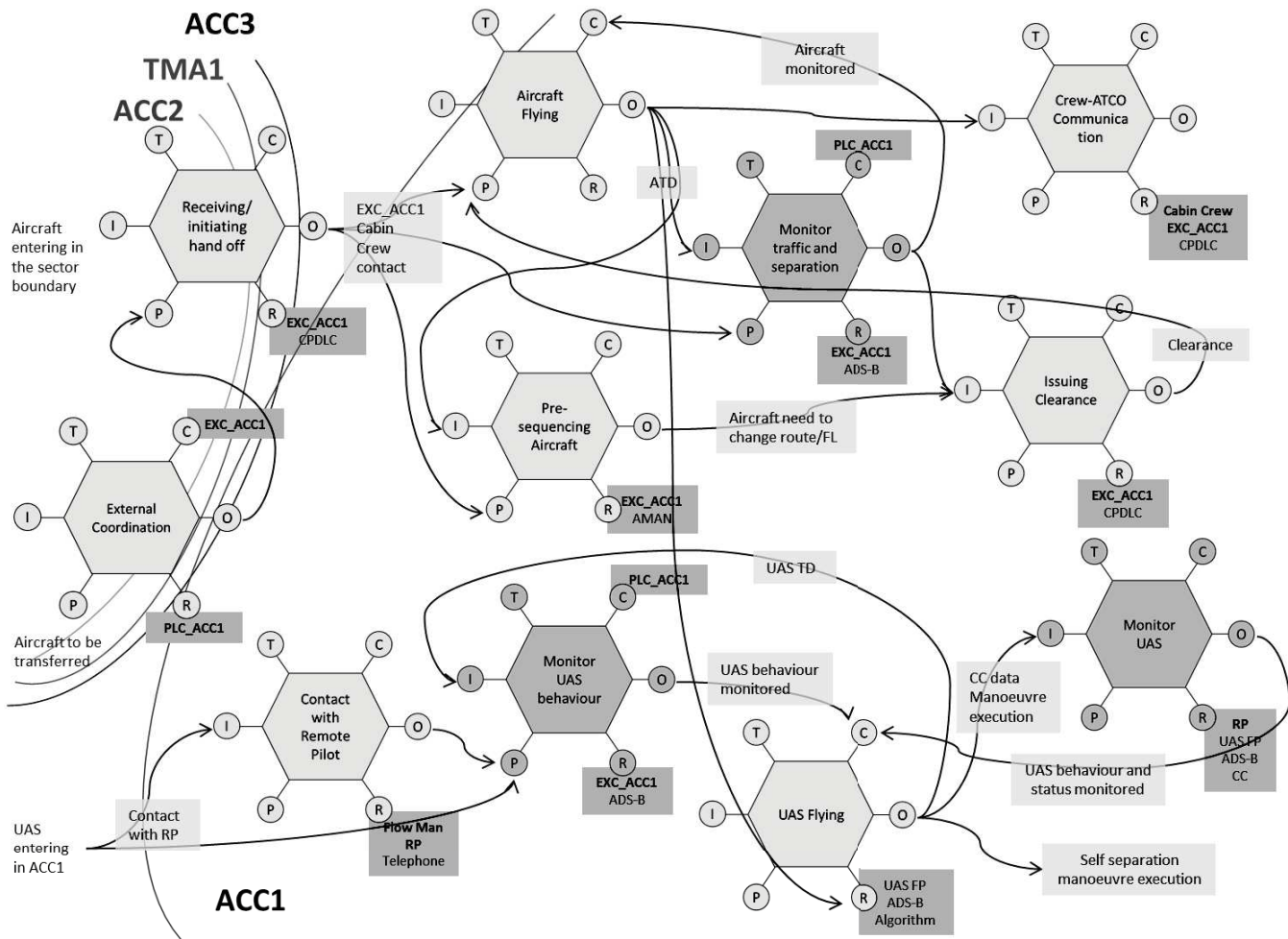


Figure 3: FRAM instantiation at of ATM function for an Unmanned Aircraft flying in non segregated airspace

B. Application for Monitoring Purposes

We have seen as the analyst remains the manager of the interactions between the models in the SPAD federation. The application process requires a significant contribution from the analysts and cannot be completely automated and used autonomously in real time conditions.

The optimal way to use the SPAD federation is to investigate through scenarios a few different operational conditions (e.g. level of traffic, competence of staff) and the possible set of events that could generate from them, including different possible degradation. Let us represent the space of the possible operational conditions (normal and abnormal) as a two-dimensional space with one axis for all the possible normal operation conditions (that is, all possible combinations of aspects such as traffic levels, competences of staff, etc.) and one axis for all the possible degradations. We can then evidence the events analysed with the federation as grey areas

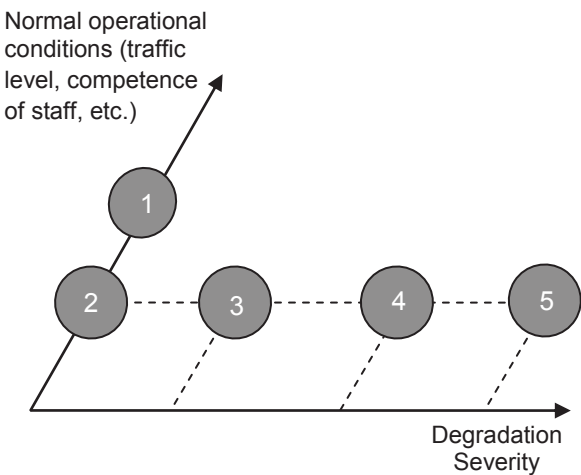


Figure 4: Space of the operational conditions

as in figure 4. For example, in the figure we studied two possible normal operational conditions between all those that are possible (areas 1 and 2), that is two possible combinations of traffic levels, competence of staff, etc. Then, for one of them (area 2) we studied also three degradation events of different severity (areas 3, 4 and 5).

This "off line" approach is very useful for system design or to contribute to system assessment, that is, to understand what may happen in the future to the system. However, it is of limited use for monitoring purposes, when we intend to monitor a system and understand what is happening to it at run time. Since real time monitoring was one of the SPAD objectives we studied also how to use the federation in such a case (even if with some significant limitations). In this monitoring application the federation has been used off line to explore in advance a limited number of possible future events and estimate their possible consequences. If we consider the space of the possible operational conditions (normal and abnormal) of figure 4, this means to investigate a portion of this space, like the one represented by the 5 grey areas. Then, the system functioning is monitored at real time and if there is evidence that one of the explored events is going to happen, the estimate about the possible consequences are used to manage the event.

Figure 5 shows in deep black the trajectory of the system within the space of the operational conditions evidencing how it degrades and then returns to the axis of the normal operational conditions. While doing this the system "crosses" some of the grey areas that have been explored by the federation and for which we have collected information during the off-line analysis. These information are used to manage the related event.

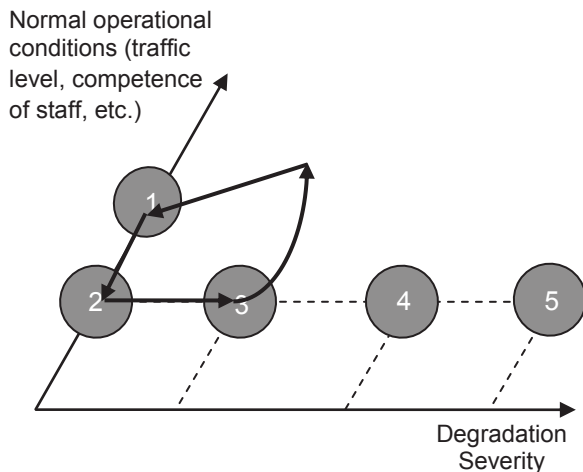


Figure 5: Real time monitoring

IV. CASE STUDY AND SIMULATOR

This section describes the application of the approach presented above in a case study regarding a system with a high level of automation and how this case study has been explored in a simulator.

The case study regards a large portion of airspace with a Remotely Piloted Aircraft System (RPAS), and where Remotely Piloted Aircraft (RPA) are able to self separate from each other and from the surrounding commercial traffic using automated self separation algorithms and ADS-B based localisation devices. Remote Pilots (RP) supervise the flight of the RPA and intervene only in case of malfunctions or unforeseen events. Commercial aircraft are managed by Air Traffic Controllers (ATCO) under the 4D concept. The RP can also intervene modifying the trajectory of the RPA if required by an ATCO or other authorised personnel. For this reason we adopted the acronym RPAS even if the aircraft is using its own self separation algorithm. The procedure adopted for both the RPAS flying procedures and the management of the possible malfunctions are in line with the strategy proposed in the SESAR study ICONUS (Initial CON OPS for UAS in SESAR).

The airspace is inspired to the real Italian airspace as shown in figure 6. There are four ACC (Milano, Padova, Roma and Brindisi) whose borders are identified by dashed lines in figure 6. There are 40 waypoints that can be used to build different flight-paths, connecting 5 airports (Roma, Brindisi, Venezia, Catania and Milano) and foreign destinations outside the airspace.

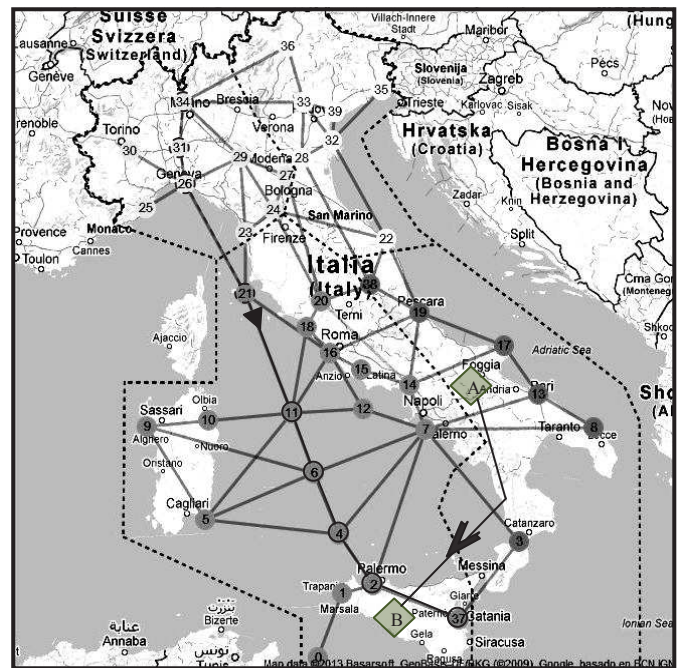


Figure 6: Airspace used by the simulator

The simulator is able to reproduce different commercial traffic levels and different RPA crossing portions of non segregated airspace while flying from one segregated airspace to another one.

For example in figure 6 there is a commercial aircraft (represented with a black arrow point) flying from Milan to Catania and a RPA (represented with a black V shaped arrow point) flying from the segregated area A in Apulia to the segregated area B in Sicily. During the flight the RPA crosses different possible commercial flight paths including the one of the flight from Milan to Catania, should this cause a possible conflict the RPA will leave the priority to the commercial flight.

The simulator is also able to reproduce possible RPAS failures and the possible consequences on traffic and airspace functionality. In particular, it can simulate three failures with growing levels of severity:

- interruption of the communication channel between RPA and RP (the RPA is still able to self-separate from the other aircraft, however it cannot be monitored and supervised effectively by the RP);
- interruption of the communication channel and failure of the self-separation algorithm (the ATCO is able to recognize that an emergency event is taking place and to identify the area of the problem);
- interruption of the communication channel, failure of the self-separation algorithm and failure of the self localisation device of the RPA (there is a failure of the ADS-B service and localisation is only possible through radar).

Figure 7 shows the way we use the simulator. We generate different possible operational conditions and analyse them applying the federation of models as described in the previous Section.

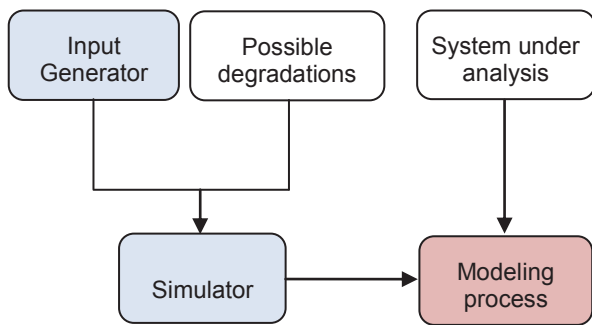


Figure 7: Role of the simulator

The input generator can create all the possible normal operational conditions (equivalent of the Y axis of figure 4). These normal operational conditions can be combined with the possible degradations (equivalent of the X axis of figure 4) in the simulator. We have as output of the simulation the operational conditions (equivalent of the X, Y space of fig. 4).

V. APPLICATION OF THE MODEL

In this Section we show an example of application of the federation to one of the cases generated by the simulator. In particular, we are considering Normal Traffic Level and combining it with the most severe of the degradation. The communication channel and self-separation algorithm of the RPA fail in combination with an ADS-B failure. The RPA data (label, flight level and so on) become invisible to the ATCO and the RP. The ATCO can still locate the RPA position on the horizontal level through the radar, and use its position to set a no fly area for the commercial traffic to ensure separation with the (non responding) RPA. The safety area is defined taking into account the last known RPA FL and trajectory. The area must be wide enough to tolerate RPA unexpected trajectory deviations without violating safety distances with other aircraft. The ATCO working in the sector interested by the RPA failure inform about the problem the different ATCO of the surrounding sectors, which may be affected by traffic deviations or that are about to take the RPA in charge.

Through FRAM is it possible to identify a set of functions related to the scenario and provide a detailed description of each related factors (Time, Precondition and so on). We have already seen in figure 1 a function called “Monitor traffic and separation” in which the executive (EXC) controller monitors the current traffic situation (aircraft speed and positions, trajectories, separation) and anticipating future situations in his airspace of competence. Once all the functions are defined it is possible to create the instantiation.

Figure 3 shows an example of instantiation for this specific scenario, when the RPA is flying in the Air Control Center (ACC) of the ATCO (ACC1). The EXC controller of this ACC is “Monitoring traffic and separation” and the figure shows the relations between this function and all the other functions.

All the functions can be affected variability sources [5] (some of them are reported in the following table). These can be associated to human factors (i.e. Situational Awareness) and/or to system side (i.e. Traffic and its Complexity) and can affect both the function itself and/or also its output. The study of the variability is done using the supporting notation offered by FRAM, and an example shown in Figure 8 for the “Monitor traffic and separation” function. When needed the function can be decomposed into sub-functions and can be analysed with HAMSTERS if humans are a key element for that function.

ATD Time	ATD Precision	Traffic	Situation Awareness	Time Resource	Traffic Complexity
On time	Precise	Low	Low	Low	Low
Too late	Acceptable	Medium	Medium	Medium	Medium
Omission	Imprecise	High	High	High	High

Figure 8: Example of table to support the study of the function variability

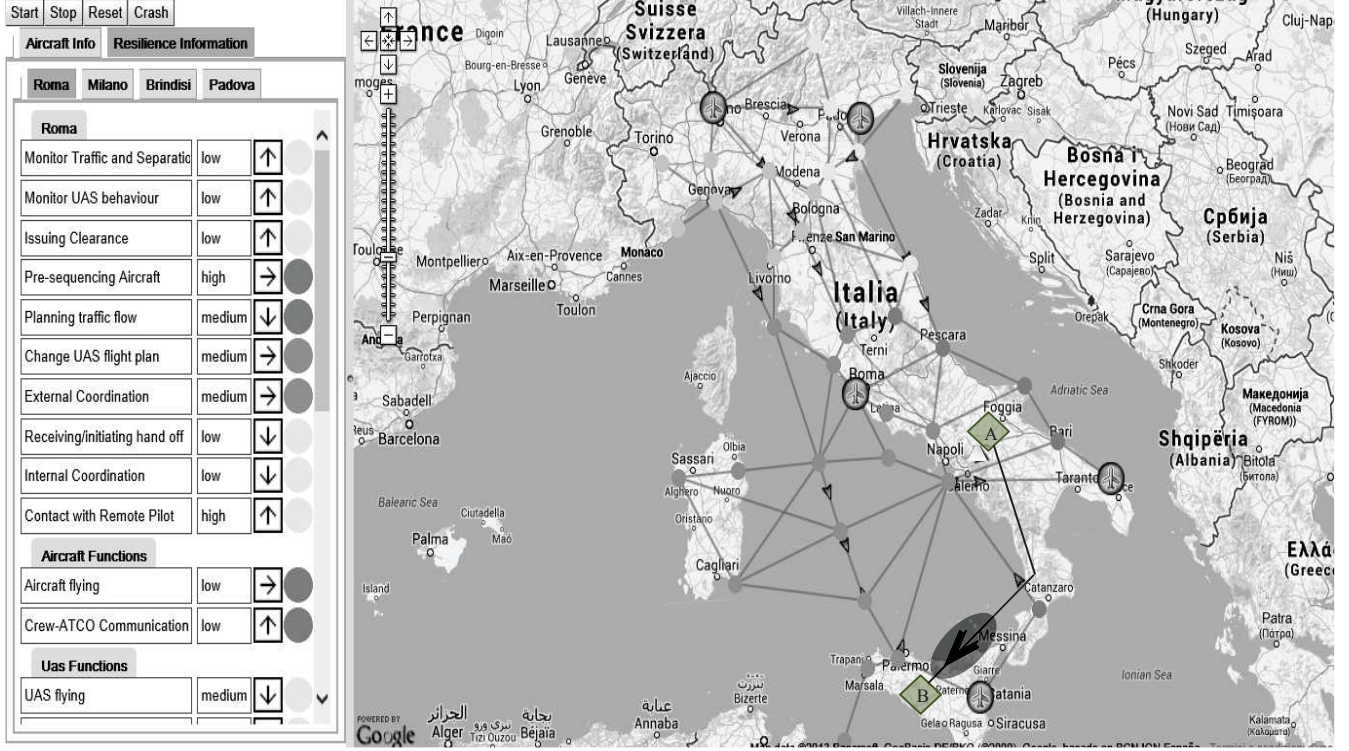


Figure 9: Status of the ATM functions as presented by the simulator

The SPAD simulator offers the possibility to show the outcome of the analysis, providing information about the status of the ATM functions of the different ACC. In particular, it can show the level of variability of the output of each function, the trend of the variability and the influence of the other functions. The output for the example described above is shown in figure 9. The RPA flying from the segregated area A to the segregated area B is experiencing a malfunction as described above and a no fly safety area (represented with a grey ellipse) is generated by the ATCO of the Rome ACC. The no fly area cut the commercial flight path between Palermo and Catania and the related traffic has to be re-directed and to follow different flight path. This causes traffic perturbations and delays and oblige the ATCO to re-organise continuously the commercial traffic. The influence of this perturbation in terms of function variability estimated by the federation is shown in the left side of the simulator screen for all the ACC considered in the case study. If the interrelation between the functions leads to a variability

that may affect system performance adversely, the analyst can adopt specific solutions and strategies to keep the output of the functions under control.

VI. CONCLUSIONS

The models of the federation are not intended to be used as stand-alone models but rather to support the analyst during his analysis. Then, the analyst is the mediator of the interaction between the models and he is the manager of the federation. The analysis remains human centred, that is, under the control and responsibility of the analyst and requires a significant contribution from analyst and operational experts with a significant degree of experience.

This prevented a complete application of the federation to monitor in real time the behavior of a system whose dynamic and evolution is not compatible with the time required for the human analysis. On the other hand the federation offers a well-structured and enlightening support to the analysis and

facilitate and guide the interaction between the analyst and the operational expert.

Our experience in applying the federation shown that its usefulness depends from the purpose of the application. It can be very useful to support accident analysis, that is, to understand what happened. In this role it can offer a new perspective and point of view to understand what happened. The effort required for the application of the model federation is acceptable, however the results can depend on the expertise and the operational knowledge of the analyst and the operational experts supporting the analysis.

The federation can also be useful as an instrument to support the analysis of a system, for example as a support to safety assessment and safety analysis, that is, to understand what may happen. However, in such a role the application effort is extensive because of the different instantiations required for each possible future event to be investigated. The effort can become unacceptable when the complexity of the system under analysis grows and if the analysis pretends to investigate all the possible future events. This implies the need to focus the analysis only on the most relevant parts of the system and choose the right combination of levels of granularity for its parts. Also in this role the federation can support interactions between the analyst and the operational experts. The representations and preliminary analysis of the federation can be used to elicit the opinion of the operational experts in a structured and stimulating way.

The federation is of limited use to monitor a system in real time, that is, to understand what is happening. The analysis requires a significant human involvement and in most of the cases cannot be automated. In the case study presented in this paper the federation of models has been used off line to explore in advance a limited number of possible future events and estimate their possible consequences. If we consider the space of the possible future events as a two dimensional like in figure 5, this means to investigate a small portion of it, like the one represented by the 4 grey areas. In our study the functioning of the system was monitored in real time, and if there was evidence that one of the explored events was going to happen, the estimate about the possible consequences was used to manage the event.

However, this procedure can be very expensive in terms of application effort, and the number of possible future events that can be investigated remains small. In addition, the selection of these events can be biased towards the most likely ones or those with the most severe consequences.

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