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A Quantitative Approach to Resilience Engineering for the Future ATM System: Case Studies Results

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***Abstract*—This paper presents the application to some noticeable case studies of a novel methodology proposed for the resilience engineering of the future ATM system. The paper first summarizes an original resilience engineering definition and approach, as proposed by the authors in a SESAR Long-Term Research funded project. This approach is based on a quantitative measure of the ATM system global performance which is seen as the fulfillment of the performance expectations in the 11 Key Performance Areas defined by ICAO plus Human Performance. Resilience is thus expressed as the level of residual ATM global performance resulting from a task and authority re-allocation strategy required to mitigate a disruptive event. This methodology is then applied to two case studies and the discussion of the results highlights how the approach has been already translated into an algorithmic method suitable for deriving measurable results. Finally the paper discusses the current weaknesses of the approach and the required future developments to allow its actual application.**

***Keywords*— ATM performance; resilience engineering; graph design; optimal path search; task allocation**

I. INTRODUCTION

The growing density of air transportation operations and airspace users, has increased the complexity of the Air Traffic Management (ATM) system. For this reason, in recent years, several international programs such as SESAR (in Europe) and NextGEN (in the USA) are being carried out to reorganize the ATM system, improve its performance and develop new paradigms to cope with the ever-increasing complexity of this large socio-technical system.

Dealing with the complexity of socio-technical systems, is, in fact, one of the research topics that is still under investigation in many projects. Recently, the ATM research community is starting to give more attention to the concept of resilience, and more notably to resilience engineering, as a possible approach to the analysis of the behavior and capabilities of the ATM system under non-nominal conditions. In 2009, EUROCONTROL has given a specific interpretation of resilience as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [1]. While this definition is quite easily relatable to the desired behavior of the ATM system, it does not, however, provide a quantitative framework to evaluate the resilience of the ATM system. Although several relevant research programs [2, 3, 4] are trying to find a commonly accepted approach to resilience engineering, nonetheless there are still open questions regarding how to quantify the ATM system resilience, how to measure it and how to improve it.

Recently, the SESAR JU E2.21 SAFECORAM (Sharing of Authority in Failure/Emergency Condition for Resilience of Air traffic Management) project, described a methodological approach to resilience engineering for the future ATM system [5, 6, 7, 8]. The resilience interpretation proposed in this project is based on the quantitative measure of the global performance of the ATM system, as it is emerging from the SESAR performance framework. In addition, thanks to this quantitative evaluation, a possible approach to the optimization of resilience of the ATM system is also introduced. This optimization is conceptually based on the optimal re-allocation of tasks between different ATM actors within well-defined scenarios, in order to preserve the highest possible level of residual performance of the system.

In this paper, starting from the findings of the SAFECORAM project, we will analyze two case studies, evaluate their global performance and optimize their resilience in off-nominal scenarios. Finally we will discuss the results following SAFECORAM's validation approach aimed at evaluating the feasibility of the optimization solutions also through the implementation of time-based simulations of ATM scenarios.

II. SAFECORAM OVERVIEW

In this section, we will provide a short overview of the SAFECORAM approach and methodology. We will start from the definition of global performance of the ATM system, followed by its quantitative interpretation in the context of the project and the resulting definition of resilience. Finally we will explain the project assumptions and mathematical approach.

A. Global Performance and Resilience of the ATM System

The global performance of the ATM system can be thought as the fulfilment of the performance expectations in the 11 Key

Performance Areas (KPAs) defined by ICAO plus Human Performance [9].

For the sake of clarity, we will try to give the reader a graphical interpretation of the SAFECORAM approach to resilience evaluation in ATM.

The yellow area in the radar chart depicted in Fig. 1 can easily be interpreted as the global performance of the ATM system: in fact, in nominal conditions, the system is characterized by a certain level of performance in each of the eleven KPAs. When a disturbance occurs, the ATM system can no longer perform in its nominal conditions and its global performance will inevitably change, at least in one of the KPAs. From the graphical point of view, this situation can be seen as the reduction of the level of performance in at least one of the KPAs: this will certainly change the shape of the yellow area representing the global performance of the system. Of course the ATM system reacts to the disturbance applying a set of mitigation actions that are aimed at restoring the nominal conditions (i.e. the original yellow area) as much as possible. However, not all mitigation actions are alike: different mitigation actions may recover different levels of global performance restoring partially (or sometimes even totally) the performance level in each of the affected KPAs. Graphically, different mitigation actions may result in different shapes of the global performance area (Fig. 2). Clearly, in this perspective, performance loss can be pictured as the area difference between the nominal area and the degraded one.

These considerations have allowed a possible quantitative definition of resilience. In fact, in SAFECORAM, resilience is expressed as the level of residual global performance of the ATM system resulting from mitigation actions (in the form of tasks re-allocation and authority redistribution between human and machines), triggered by the occurrence of an off-nominal condition [5]. Therefore an ATM system is resilient if it is able to reorganize itself towards the most similar state with respect to the reference (or nominal) one.

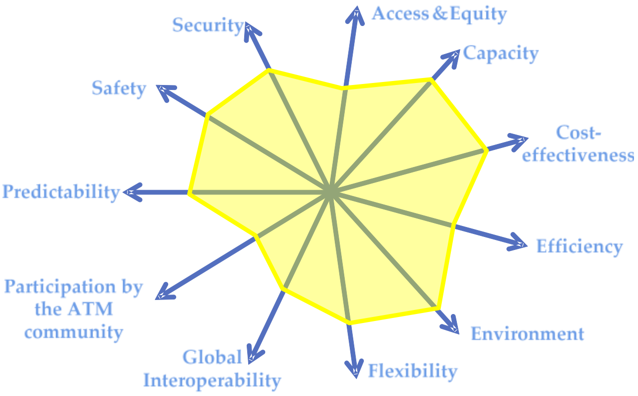

Figure 1. The yellow area can be seen as a graphical interpretation of the global performance of the ATM system.

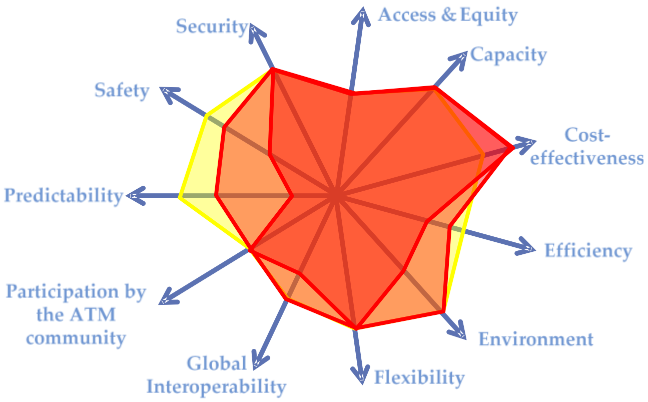

Figure 2. Different mitigation actions may recover different levels of global performance of the ATM system.

Going back again to the graphical interpretation of the global performance of the ATM system, we have stated that different mitigation actions may result in different shapes of the global performance area. This means that among all the possible sets of mitigation actions suitable to face the disruptive event, some of them are better at minimizing performance loss. In other words, it is possible to define an optimization problem aimed at maximizing the resilience of the system. This optimization is based on the optimal re-allocation of tasks between different ATM actors, in order to preserve the highest possible level of residual performance of the system when an off-nominal condition occurs. A key aspect is, therefore, the capability to quantify the performance levels of the KPAs and define a concept for allocation of tasks and authority sharing between humans and systems.

B. SAFECORAM Methodological Approach

The SAFECORAM methodology was developed following a scenario based approach. Several assumptions are made to create meaningful ATM scenarios and to allow a quantitative analysis of the ATM system and of its performance levels in the relevant KPAs:

- the framework is the European ATM system of year 2050 with SESAR ConOps fully deployed;
- the scenarios are limited to flight operations (no airport ground operations);
- the stochastic nature of the events that can affect the scenarios is not taken into account;

Basically, a scenario represents a set of a nominal and non-nominal situations affecting the ATM system. In SAFECROAM, the objective of a scenario is to explore alternative behaviors of the system when an off-nominal condition is triggered. During the development of the project, twelve study reference scenarios were analyzed (Table I).

To analyze a scenario several steps are, in fact, needed. First the scenario is analyzed to identify the actors (either human or automated) that populate the scenario. Next, the scenario is analyzed to identify the *flow* of tasks and actions performed by these actors within the scenario. In normal conditions the associated flow may be considered as the set of tasks and actions that guarantees a *nominal* global performance. When an off-nominal condition is triggered, there are, in general, several task reallocation alternatives and different flows of actions that may be performed to mitigate the effect of the disturbance (Fig. 3). Alternative flows (which basically represent different mitigation strategies) will usually degrade the global performance of the system by different amounts, thus identifying different task reallocation alternatives each with an associated level of residual system performance (Fig. 2).

As a result, an important aspect is how to quantify the key performance indicators (KPIs) in the related KPAs and the criteria with which these KPIs are degraded when an off-nominal condition occurs. By analyzing the SESAR Performance Framework [9] several supporting metrics and formulas for different Key Performance Indicators were found. Specifically the project takes into account the following 4 KPIs which have a specific quantitative interpretation in SESAR Performance Framework (Fig. 4):

- K1 - efficiency (fuel burn)
- K2 - efficiency (delay)
- K3 - environment (emissions)
- K4 - capacity (throughput)

Future studies should address the quantitative estimation of other indicators. In the SAFECORAM scenarios, the KPIs are related to the number of movements per hours and per unit airspace volume (i.e. sector or runway) and to a fixed time frame.

As said, when an off-nominal condition is triggered, the reaction of the system corresponds to a different reallocation of tasks and actions among the actors of the scenario. Each new off-nominal task of the reallocation strategy may degrade the values of the KPIs of the system. Specific assumptions have to be made in order to define the criteria by which the KPIs are degraded.

TABLE I. SAFECORAM REFERENCE SCENARIOS

Scenario	Description of the Off-Nominal Event
1	FMS partial failure during approach and landing
2	Unexpected thunderstorm over airport in presence of mixed traffic (conventional, RPAS)
3	Uplink loss during en-route phase
4	Taxiway incursion during take-off taxiing
5	Pressurization system failure during en-route phase
6	ASAS activation during en-route phase of commercial vehicles
7	Big airport closure due to snow
8	Activation of a temporary segregated area due to natural disaster
9	GNSS failure over a wide area
10	PATS Remote Pilot Station communication link loss
11	Datalink disturbance for general aviation aircraft
12	Uncontrolled RPAS fully automatic vehicle

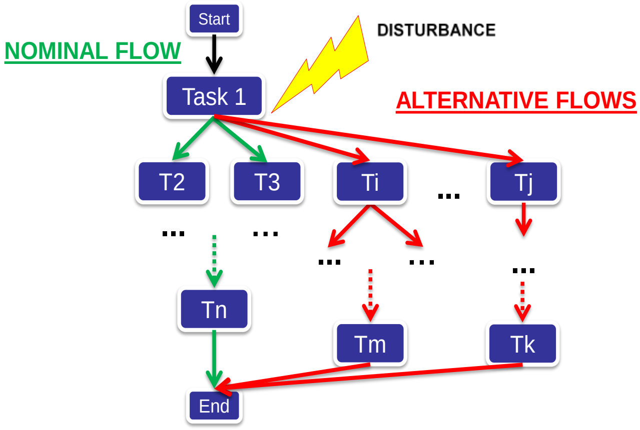

Figure 3. Several alternative task reallocations and different flows of actions may be performed to mitigate the effect of a disturbance affecting the system.

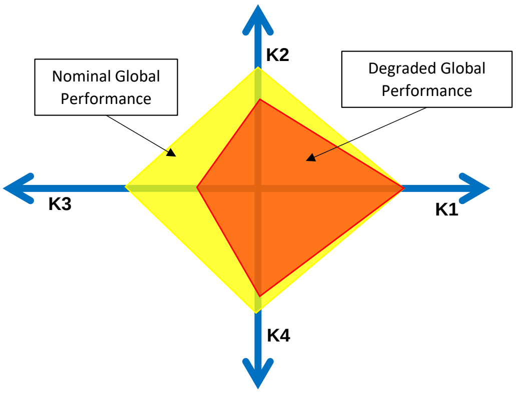

Figure 4. SAFECORAM takes into account the 4 KPIs that have a specific quantitative interpretation.

In SAFECORAM, performance degradation criteria were designed starting from the performance benefits foreseen in the Operational Focus Areas as expected by the full deployment of the SESAR ConOps. In this context, it was assumed that the mitigation tasks or actions (attributable to off-nominal conditions) that partially or totally compromise the expected SESAR performance increase, contribute to the partial or total removal of that benefit from its related KPI. For instance, let us assume that the disruptive event in the off-nominal scenario prevents the use of – for example – the 4D trajectory navigation system for an aircraft. In this case both capacity KPA and environment KPA would be affected, and the ATM system must be reorganized to accommodate the presence of an aircraft with such degraded navigation system. For this reason, the related KPIs would obviously be reduced by a certain amount. This amount is assumed to be a function of the expected quantitative benefits of the 4D trajectory navigation paradigm in both capacity and environment KPAs. Full details of this approach can be found in [10].

It is worth to note that the SAFECORAM methodology does not rely on the criteria with which the KPIs are degraded. These criteria and the quantification of the KPIs are here set in order to show the validity of the approach, but in general they may change and should be decided with the relevant stakeholders.

Reference [5] shows that given a scenario S, the set $\Gamma^{(S)}$ of all the possible flows in S (i.e. the nominal flow together with the “alternative flows” that allow the partial or total restoration of the global performance of the system) can be represented in the form of weighted directed acyclic graphs (DAGs). The vertices of these graphs are tasks, whose contribution to performance degradation is weighted along the connecting edges (Fig 5). For each scenario a starting vertex v_{start} and an ending vertex v_{end} can be assumed. All the possible flows of the scenario are, therefore, the paths between v_{start} and v_{end}. Every edge is labeled with the tuple $(k_{i,j}^{(1)}, \ldots, k_{i,j}^{(4)})$, which represents the contribution of the j-th task $T_{i,j}$ belonging to the i-th flow, to the evaluation of the 4 KPIs [5, 6].

Using this approach it is possible to quantify the global performance level of a given scenario both for the nominal path and for all the alternative paths.

At this point it should be remarked that, in principle, the importance of the KPIs may also be weighted according to a specific stakeholder’s perspective. For instance, an airline may give more importance to fuel consumption rather than capacity or emissions, while an airport could be more interested in capacity or delay. In this work we will assume a general point of view, considering each of the KPIs equally important.

Recalling the resilience definition given in the previous subsection, the level of residual global performance of the system can be determined by defining a path distance function $d(\cdot)$ between the nominal task flow and the alternative ones. As stated earlier, this leads also to the definition of an optimization problem aimed at finding the alternative path that minimizes the loss of performance (i.e. maximizes the level of resilience) of the system. In other words, the search for the most resilient task reallocation strategy results in the search for the shortest path in the weighted directed acyclic graph associated to the scenario.

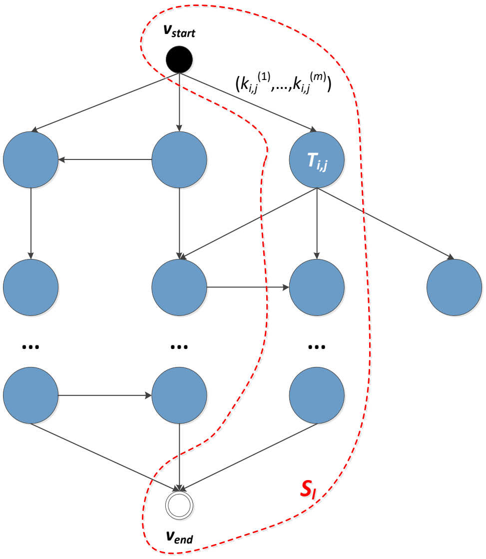

Figure 5. Directed acyclic graph (DAG) for the set of alternative flows of a scenario. In this picture, the generic flow S_l is highlighted together with the starting and the ending vertices.

In SAFECORAM, two different distance functions were considered: the area distance and the difference distance [5,6,7]. The former employs the performance area concept introduced in the previous subsection: two task reallocation strategies are similar if the area difference is small; the latter metric is simply the sum of the absolute differences of the corresponding KPIs.

While the resilience optimization methodology is general, the selection of the distance function can be arbitrary and should be selected involving the relevant ATM stakeholders. In SAFECORAM, ATM operational experts were involved in the selection of the distance functions. Such functions, however, should be considered preliminary and practical only for the validation of the methodology. More details on the mathematical approach can be found in [5, 6, 11].

The optimal solution found using the aforementioned approach is given in terms of allocations of actions and tasks to be performed by the actors of the scenario. However, a potential limitation of these flow solutions is that they do not take into account dynamic behavior explicitly. Nevertheless aircraft maneuvers, human behavior, computations, transmissions, collaborative decision making procedures, etc. take a finite amount of time to be completed and could disrupt the actual feasibility of the solution. For this reason, in SAFECORAM, a time-based air traffic simulator was built [7,12] in order to simulate, for each scenario, the solution flow that should minimize performance loss. In this way, the simulation of the solution flow “as is” within a real-time world can demonstrate if the optimal task flow is either compatible or incompatible with the physical evolution of the scenario.

The simulation of the ATM system in SAFECORAM is built using vsTasker v5.3 [13] a time-based object-oriented simulation toolkit designed to build complex environments based on scenarios, events, logics and behavioral models (Fig. 6). This allows to quickly set up multi-agent based scenarios. Logics and events can be easily programmed to emulate procedures, actions, decisions or clearances. Among the human actors, only pilots and air traffic controllers have an active role in the scenarios. In this context, they are treated as agents who complete their task without error and in a finite period of time. For this reason, their behavior is simply modeled as a time delay that emulates the cognitive processes and the reaction times related to their specific actions in the simulation.

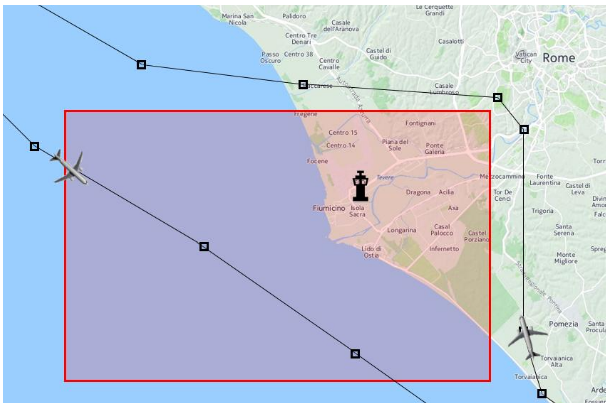

Figure 6. A screenshot of a time-based dynamic simulation for SAFECORAM case studies.

Similarly, communication devices (datalink, SWIM, radio) and on-board or on-ground systems are also modeled as time delays taking into account their characterization in terms of transmission lags, system latencies or computational time. The dynamic behavior of aircraft is based on 3-degrees-of-freedom performance models. More details on the implementation of the simulation scenarios and of the models of the agents can be found in [7,12].

III. CASE STUDIES DESCRIPTION AND RESULTS

As mentioned earlier, SAFECORAM methodology was developed using a scenario based approach, analyzing 12 study reference scenarios. In this section, we present two case studies that were specifically developed in collaboration with ATS experts and that allow a comprehensive understanding of the SAFECORAM methodology and of its advantages and limitations.

We will first present a basic scenario whose analysis is simple but significant for the overall understanding of the methodology. The second case study is, instead, more complicated and shows how the analysis of the system can easily grow in complexity. These two case studies are essentially a revised version of Scenario 2 and 9 from the SAFECORAM reference scenarios. In both scenarios we assume that fuel burn and pollutant emissions are solely related to flight time.

The case studies are analyzed through the following steps:

1) Scenario Definition: the scenario is described and actors, tasks and all the resources to be managed are identified both in nominal and off-nominal conditions.

2) Failure Analysis and Task Allocation: the scenario description is reported in tabular form as a flow of tasks (see Table II). The table is constructed indicating the actors that perform the tasks or actions followed by the actors to which the action is addressed. To each non-nominal task a degradation weight is assigned. This way of describing the scenario can be directly mapped into a directed acyclic graph (DAG). As stated earlier we only consider 4 KPIs that have a quantitative interpretation in the SESAR Performance Framework. The description of the scenarios as a set of tasks and actions is certainly one of the limiting aspects of this approach. However, as stated earlier, in the SAFECORAM project it is assumed that the stochastic nature of the events that can affect the scenario evolution is not taken into account. This means that the performance variability of the actors is not taken into account and therefore there are no unexpected behaviors at the actors level. In addition SAFECORAM considers a highly automated future ATM system. High levels of automation usually imply low system flexibility [14], in the sense that some tasks are more or less bound to specific and automated procedures leaving out any kind of unexpected behavior even in off-nominal conditions. In fact, possible automation degradations in the SAFECORAM scenarios, fall into the "malfunctions" category rather than being the outcome of performance variability.

TABLE II. SCENARIO DESCRIPTION IN TABLUAR FORM

Vertex	**Task/Action**	**Destination Vertex**	**Impacted KPIs**
Input Actor	Description of the task/action	Destination Actor(s)	degradation weight for each impacted KPI
⋮	⋮	⋮	⋮
…	…	…	…

3) Graph Generation and Resilience Optimization: the tabular description of the scenario is read by the SAFECORAM software demonstrator which is capable of generating the DAG graph (using the open source java graph library [15]) and of carrying out the optimization in search of the task reallocation strategies with minimum performance loss. As explained earlier, the distance metrics (area distance and difference distance) are representative of the performance difference between the nominal scenario and the off-nominal one when the mitigation flow is carried out. Therefore the solution flow is better when the distance metric tends towards zero. Similarly, the normalized KPIs for the off-nominal flow are better when they tend to 1.

4) Results Analysis: the results of the optimization are analyzed and discussed with respect to the scenario.

5) Dynamic Simulation: the task reallocation solution is finally implemented in a time-based air traffic simulator to validate its actual feasibility.

A. Case A: GNSS Unavailability in Airspace Sector

The scenario description and analysis will follow the abovementioned steps.

1) Scenario Definition: the scenario consists of four en-route airplanes that travel across a specific air sector and 4 airplanes that depart from an airport inside that same air sector. The nominal flow of events is as follows: the four en-route airplanes fly their assigned 4D contract crossing the specific air sector, and the departing four airplanes depart from the airport inside the air sector. The unexpected event: the airspace sector is affected by a temporary GNSS unavailability.

2) Failure Analysis and Task Allocation: when the off-nominal condition of the scenario is triggered, the residual resources have to be managed to mitigate the disturbance: the ACC Manager must decide how to cope with the off-nominal condition inside the specific air sector. His options include the possibility either to close the airspace sector, resectorize the remaining area, deviate the airplanes and block all departures, or to allow only a limited number of airplanes through the airspace sector (either departing or crossing the area). Resectorization has an effect on the capacity of the airspace. If the ACC decides to resectorize, then the controllers can manage more airplanes with less degradation to the overall capacity and delay (although planes are deviated from their original trajectory. Allowing only a limited number of en-route airplanes through the affected air sector triggers a UDPP (User Driven Prioritization Process) to choose which planes are actually allowed through the area and which ones are deviated. The ACC Manager can decide the fraction of allowed en-route planes (either 25% or 50%) and the fraction of allowed departures (either 0%, 25%, or 50%).

These options were all organized in the abovementioned tabular form in order to be able to extract all the possible paths (i.e. mitigation solution flows). In this case all the paths can be easily described using a figure (Fig 7), but in general the number of off-nominal flows of a scenario can be extremely high and too complex to determine visually (as it will be shown in the next case study).

3) Graph Generation and Resilience Optimization: the SAFECORAM software demonstrator is capable of reading and analyzing the scenario in tabular form, generate the DAG (Fig. 8) and search for the task reallocation strategies with minimum performance loss (i.e maximum resilience). Table III and Table IV show a summary of the optimization results.

4) Results Analysis: this Case Study is quite basic but it has all the elements to understand the SAFECORAM methodology. As said, the optimization process tries to find the mitigation solution that keeps the normalized KPIs as close as possible to 1. The found solution is, in fact, the following: in order to retain the most similar state with respect to the nominal one, the ACC manager should choose to allow 50% of the en-route traffic in the airspace sector, deviate the others and allow only 50% of departures from the airport in the sector. Of course, the airplanes that are not allowed to depart have a negative impact on delay. The deviated airplanes that are not allowed in the airspace sector of course decrease the capacity KPI and have an impact on the overall fuel consumption and emissions.

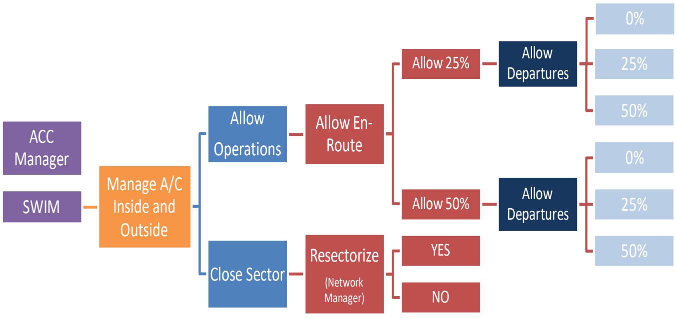

Figure 7. Possible flows of mitigation actions for Case Study A.

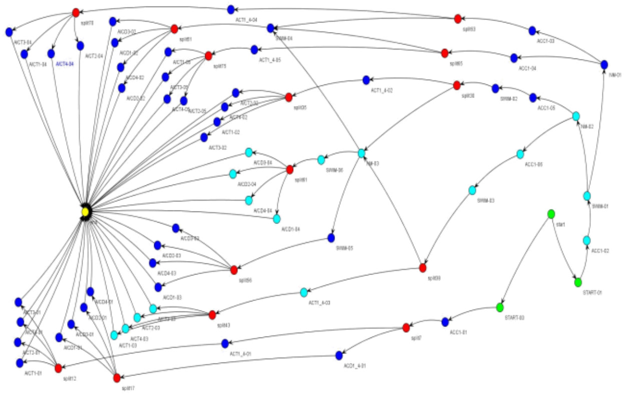

Figure 8. The directed acyclic graph (DAG) for Case Study A.

TABLE III. CASE A RESULTS: PERFORMANCE LOSS MINIMIZATION

Number of Alternative Paths	Best Area Distance	Worst Area Distance	Best Difference Distance	Worst Difference Distance
8	2.5	5.4	2.8	5.9

TABLE IV. CASE A RESULTS: NORMALIZED KPIS

KPIs	Nominal	Best	Worst
Efficiency (fuel)	1	1.1	1.2
Efficiency (delay)	1	3.6	6.4
Environment (emissions)	1	1.1	1.2
Capacity	1	0.9	0.8

TABLE V. CASE A. TIME SIMULATION: ALL AIRCRAFT

All Aircraft	Fuel Burn (kg)	CO2 Emissions (kg)
Nominal	4212	13268
Off-Nominal	3770	11875
Difference	-442	-1393

TABLE VI. CASE A. TIME SIMULATION: DEVIATED AIRCRAFT

Deviated Airplanes	Fuel Burn (kg)	CO2 Emissions (kg)
Nominal (no diversion needed)	1040	3276
Off-Nominal	1690	5323
Difference	+650	+2047

Of course the task reallocation solution proposed by the optimization process is strictly dependent on the scenario description (how many mitigation options are available for each actor) and on the degradation criteria for each KPI.

5) Dynamic Simulation: the time-based dynamic simulation allows to understand the feasibility of the scenario when the optimization solution is applied to the off-nominal conditions. The simulation also gives some quantitative insight on the fuel and emissions impact of the off-nominal condition. Table V reports the simulated fuel consumption and pollutant emissions for all the aircraft in the scenario both in nominal and off-nominal conditions. Table VI is reported in order to see the effect of the task reallocation solution on the deviated aircraft. Of course the overall fuel burn is lower in the off-nominal case because 50% of the departures are canceled. However the fuel burn for the two deviated aircraft is, of course, higher. The calculations of fuel burn and CO2 emissions are only indicative as they are derived from simplified formulas.

B. *Case B: Weather Hazard on TMA*

The scenario description and analysis will follow the abovementioned steps.

1) Scenario Definition: the scenario considers a Terminal Area that includes 2 main airports (AP1 and AP2) for commercial flights, and 1 small airport for RPAS/PATS operations. In the nominal flow of events a total number of 10 commercial aircraft are expected to land on the 2 major airports and 3 RPAS and 2 PATS on the small airport. 10 additional commercial aircraft are expected to depart from the

2 commercial airports in the time window of interest. The acceptance rate is 1 aircraft every 3 minutes. The unexpected event: a relevant snow storm limits the nominal functioning of the airport runways. The small airport has to be closed while the 2 major airports can use just 1 runway each (of the 3 normally available). Two other airports are available for diversions outside the storm area (EAP1 and EAP2).

2) Failure Analysis and Task Allocation: when the off-nominal condition of the scenario is triggered, the residual resources have to be managed to mitigate the disturbance: the Flow Manager (FM) must decide how to cope with the airplanes departing and arriving. Broadly speaking (the different actions available to actors are thoroughly considered in the tabular description of the scenario), with respect to the departing airplanes, the FM can either decide to stop all departures, allow only half departures from each airport, or impose no limits at all. Considering the landing airplanes he can decide between three different strategies: segregated landing sequence (i.e. commercial airplanes on AP1 while PATS/RPAS on AP2), optimized landing sequence (i.e the landing sequence groups similar airplanes to reduce separation due to wake vortex), first come first served landing sequence. In addtion, airplanes that are not immediately cleared for landing may decide either to hold or to divert to one of the airports outside the area impacted by the snowstorm (EAP1 or EAP2).

It is clear that in this case the number of all the possible alternative mitigation paths that can be obtained is extremely high and the problem cannot be treated without relying on the graph search techniques.

3) Graph Generation and Resilience Optimization: the DAG graph for this scenario is extremely complex (Fig. 9). Table VII and Table VIII show a summary of the optimization results.

4) Results Analysis: this case study shows how the system can become extremely complex and impossible to treat without a graph structure. In fact 132 possible alternative mitigation paths can be found. Of course just a few of them preserve an acceptable level of global performance. The found solution has, in fact, the following characteristics: in order to retain the most similar state with respect to the nominal one, the optimization solution instructs to allow departures with no limitations and allow landings with first-come-first-serve sequence. Two airplanes are diverted to a different airport (AP1), but, in general, holding procedures (imposed to airplanes while waiting for landing clearance) are considered by the optimization solution as more beneficial than diverting to an alternative airport (outside the storm area) supposedly more distant.

As for the previous case study, the solution is strictly related to the task analysis and to the degradation criteria.

5) Dynamic Simulation: also in this case the time-based dynamic simulation allows to understand the feasibility of the scenario and it also gives some quantitative insight on the fuel and emissions impact of the off-nominal condition. In the nominal scenario the 25 airplanes land and depart normally with an acceptance rate of 1 aircraft every 3 minutes. In the off-nominal condition, 9 airplanes retain their normal departure or landing conditions, 9 must adjust landing or departing operations to accommodate the airspace capacity (with a small increase of fuel consumption), 2 other are diverted to a different airport (AP1) and 5 decide to hold before landing to their destination airport. Table IX to Table XII show the impact of the off-nominal flow on fuel consumption and emissions. Again, the calculations of fuel burn and CO2 emissions are only indicative as they are derived from simplified formulas.

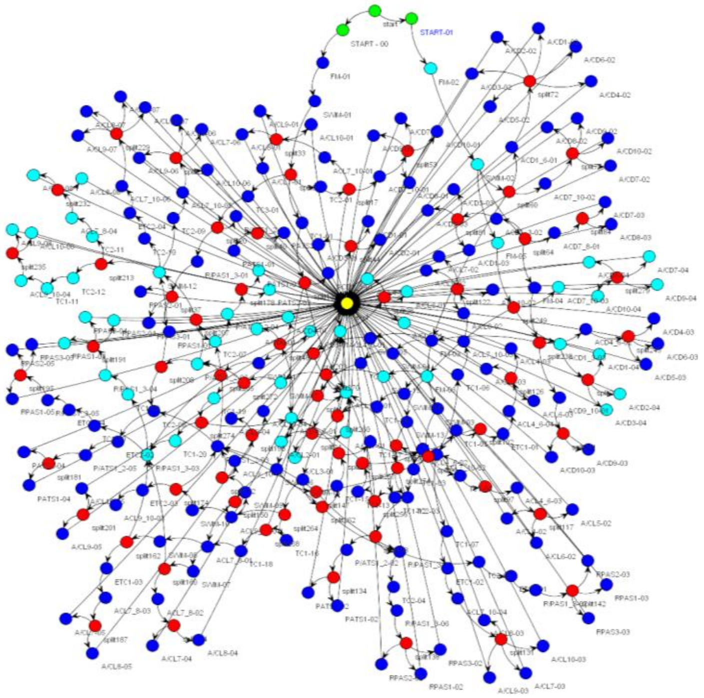

Figure 9. The directed acyclic graph (DAG) for Case Study B.

TABLE VII. CASE B RESULTS: PERFORMANCE LOSS MINIMIZATION

Number of Alternative Paths	Best Area Distance	Worst Area Distance	Best Difference Distance	Worst Difference Distance
132	1.4	13.6	1.9	14.0

TABLE VIII. CASE B RESULTS: NORMALIZED KPIS

KPIs	Nominal	Best Off-Nominal	Worst Off-Nominal
Efficiency (fuel)	1	1.1	1.1
Efficiency (delay)	1	2.6	6.4
Environment (emissions)	1	1.0	14.6
Capacity	1	0.8	0.9

TABLE IX. CASE B. SIMULATION: ALL AIRCRAFT

All Aircraft	Fuel Burn (kg)	CO2 Emissions (kg)
Nominal	4875	15351
Off-Nominal	10172	32033
Difference	+5297	+16682

TABLE X. CASE B. SIMULATION: HOLDING AIRPLANES

Airplanes that decide to Hold	**Fuel Burn (kg)**	**CO2 Emissions (kg)**
Nominal (no holding necessary)	975	3070
Off-Nominal	4387	13815
Difference	+3412	+10745

TABLE XI. CASE B. SIMULATION: DIVERTED AIRPLANES

Diverted Airplanes	**Fuel Burn (kg)**	**CO2 Emissions (kg)**
Nominal (no diversion needed)	390	1228
Off-Nominal	1690	5321
Difference	+1300	+4093

TABLE XII. CASE B. SIMULATION: AIRPLANES ADJUSTING OPERATIONS

Airplanes that adjust due to capacity	**Fuel Burn (kg)**	**CO2 Emissions (kg)**
Nominal (no adjustment needed)	1755	5526
Off-Nominal	2340	7369
Difference	+585	+1843

IV. FUTURE RESEARCH

Although the whole methodology has been implemented in a step-by-step algorithm producing measurable results, the method is far from being applicable in short time to actual situations. In fact, the method is based on the availability of a number of quantitative models not completely defined so far. For this reason the case studies discussed in this work are approached relying on simplifications and assumptions. The most relevant models necessary to apply the methodology are the ATM Performance model, and a quantitative Task Allocation model directly connected with the first. The ATM performance framework, as proposed by ICAO, for the quantitative performance measure of the ATM system, is one of the main objectives of both SESAR and NextGen programs, strictly required to support the PBO (Performance Based Operation) concept envisaged as the future of the ATM system paradigm. An approach to a quantitative task allocation method has been suggested in the SAFECORAM project, and other more advanced models can be found in scientific literature [16]. Anyway, in our opinion, relevant activities on this topic are still to be done.

Furthermore, in order to analyze the proposed scenarios, we used an approach which considers the global ATM operations as a sequence of operations (tasks) and consequently structuring the ATM operations as a flow diagram. As emerged in other projects (ZeFMaP, [17]), the use of flow diagrams to describe ATM processes is a simplification that necessarily causes information loss and limits the validity of any conclusions drawn from the diagrams. However, by keeping in mind these known possible criticalities, the task allocation approach we proposed involves the identification of actors, the tasks each actor is able to comply with, and, for each actor, all the possible connections with other actors. Therefore, the identification of the “flow” of actions which best preserves the ATM performance level is a result of the SAFECORAM methodology application rather than its precondition. If this approach is effectively capable of avoiding the above mentioned limitations, is not currently established. It will, however, be a relevant aspect to be deeply analyzed in future research activities.

Finally, specific developments in the method we selected for the optimal path search are still required. At the moment the method is not able to manage loops possibly present in the flow diagram used to schematize the alternative paths for task allocations. Cycling activities are, instead, possible in the ATM system and therefore such kind of improvement has to be considered.

V. CONCLUSIONS

In the SAFECORAM project, an original approach to the ATM system resilience engineering, in the long-term is proposed. In this paper, the application of the proposed approach to realistic case studies demonstrated the consistency of the methodology. In non-nominal conditions that could disrupt, locally or extensively, the ATM system operability, the proposed approach allows to select the proper task allocations which optimize the performance recovery of the ATM system. The whole methodology has been developed and applied successfully, but a number of assumptions are required, which can still represent an impediment to the actual applicability of the methodology. The development of a task allocation method able to quantify each task performance in terms of ATM performance indicators, and the possibility to describe the ATM system operations as a graph, are still the main open points to apply the SAFECORAM optimization methodology as a decision support system for future air transport managers.

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