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Resilience management problem in ATM systems as a shortest path problem

A proposal for definition of an ATM system resilience metric through an optimal scheduling strategy for the re-allocation of the system tasks

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ABSTRACT

As a preliminary study about the methodology for resilience management in ATM systems, this paper identifies the key aspects that should be taken into account in the formal definition of the problem. It provides an overview of the definitions and concepts related to resilience in ATM systems. Finally, the paper introduces a proposal for a definition of a resilience metric for an ATM system and formally states the resilience management problem as an optimization problem. The latter aims at finding an optimal scheduling strategy for the re-allocation of system tasks. The paper also inspects the nature of the proposed metric, highlights the constraints of the problem and makes a comparison with other approaches. A specific Case Study is discussed in detail in the paper, which allows to demonstrate the applicability of the proposed methodology. Results discussed in the paper can foster the studies on the resilience of the ATM system through a task re-allocation approach.

1. Introduction

An approach to resilience engineering in ATM is the high level objective of the SAFECORAM project. The approach proposed in this project eventually deals with the re-allocation of tasks between residual resources of the system after a disturbance, in order to minimize the system loss of global performance. Improving the resilience of the system is then translated in a minimization of performance decay in presence of failures, emergency conditions, disrupts of the ATM system. The description of the idea as a whole is presented in (Errico et al., 2014).

The ATM is an open system in the sense that its operation is constantly perturbed by disturbances. These disturbances may interact with each other, potentially creating a cascade of adverse events, that may span over different spatial and time scales. The adverse events in ATM may have different nature and impact ((Members. "ComplexWorld, 2012) (Francis, 2013),): they may pass without any discomfort for passengers, they may result in a small passenger discomfort or they may produce a discomfort that is out of any proportion. In the latter case, there are two categories of events: catastrophic accidents involving one or more aircraft; events that affect the performance of the system. These events are rare and exceptional in ATM, but they have large economic and safety impacts, so they have triggered several studies. While the use of safety analyses of catastrophic events and of human performances has led to an ultra-safe ATM system, there are very few studies which address other performance parameters, such as capacity, cost/benefit and environment in non-nominal conditions. In the paper, an approach to the ATM resilience engineering, which integrates both safety and all other performance parameters (KPAs) of the ATM system, as identified in the SESAR performance Framework, is proposed. It is difficult or even impossible to establish the resilience role in realizing these high safety and high performance levels of the system. Currently, there is only a

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qualitative analysis of resilience assessment in ATM, and few quantitative approaches have started, only very recently, to be proposed in scientific literature (Herrera et al., 2014), so we are not able to assess whether an ATM system design is more or less resilient then another ATM system arrangement ((Members. "ComplexWorld, 2012) (Francis, 2013),). The way we propose to escape from this situation is a systematic implementation of resilience in ATM, in SESAR and NextGen programs.

This paper deepens reference (Gargiulo et al., 2014). It discusses the design of the optimization methodology to support the resilience engineering problem as approached in SAFECORAM, with an introduction about the state-of-the-art of resilience management methodologies. In addition to what stated in the reference paper, in this work a relevant case study is introduced, and the paper reports the achieved experimental results obtained by using a suitable software environment. The proposed methodology demonstrated as promising for the application to resilience engineering of ATM system problem.

2. Resilience definitions and related concepts in ATM systems

A few scientific papers and books have been progressively published on resilience, covering different research domains. A detailed description is supplied in (Francis, 2013). The meanings and the interpretations of resilience may be summarized in three different forms.

The first form is **engineering resilience**. As specified in (Hoffman, 1948), this form corresponds to the more traditional definition of resilience and focuses on efficiency, constancy and predictability. It concentrates on stability near an equilibrium steady state, on the resistance to disturbance and on the speed of return to the equilibrium. Here, resilience is the time required for a system or the ability of a system or the capability of a substance to return to an equilibrium steady state (Gluchshenko and Foerster, 2013). This view is coherent with the definition of (Hoffman, 1948) and represents a foundation for economic theory, too.

The second form is **ecological resilience**. As specified in (Holling, 1996), this form focuses on persistence, change and unpredictability. It concentrates on disturbances that can flip a system into another behavior space (i.e., into another equilibrium state). Here, resilience is defined as the ability of a system to absorb a disturbance, whilst essentially retaining the same function, structure, identity and feedbacks. This view is compliant with the definition of Holling (Holling, 1973).

The first two forms of resilience address contrasting aspects. Engineering resilience tends to stability, whereas ecological resilience tends to robustness. From a safety-oriented perspective, engineering resilience focuses on maintaining efficiency of a function and ecological resilience focuses on maintaining existence of a function. In the following sections the peculiarities of the ATM system which justify the need for a specific new definition of resilience are detailed provided.

This paper refers to the third form, an interpretation of resilience named **resilience engineering**. This is a term that has emerged in conjunction with resilience as regards the development of resilient systems. Resilience engineering has been introduced in (Hollnagel et al., 2006) (Gargiulo et al., 2014), as "*a paradigm for safety management that focuses on how to help people cope with complexity under pressure to achieve success*" It is intended as a subdiscipline in the area of safety or performance analysis and it is especially directed to socio-technical systems. Here, the focus is on the ability to deal with the unexpected in order to achieve a more flexible approach for the compliance with safety and reliability objectives. Thus, resilience engineering aims at the design of systems that are able to continue to work even when faced with adverse situations (both anticipated and unanticipated) by possibly taking advantage of human endeavors.

An ATM system is a socio-technical system that is driven by economic interests of the participating stakeholders. Hence, it is performance-oriented. Moreover, the resilience framework shall address the ability of the ATM system to reduce both the magnitude and the duration of the deviation from targeted system performance levels. As a consequence, a set of **key performance indicators** (**KPIs**) for the ATM domain shall have to be rigorously established in order to include all the relevant performance dimensions. According to ICAO (ICAO, 2009), KPIs are quantitative indicators of current/past performance, expected future performance (estimated as part of forecasting and performance modeling), as well as actual progress in achieving performance. KPIs are grouped into **key performance areas** (**KPAs**). ICAO defines KPAs as "*a way of categorizing performance subjects related to high-level ambitions and expectations*" (ICAO, 2009). ICAO has defined eleven KPAs: safety, security, environmental impact, cost effectiveness, capacity, flight efficiency, flexibility, predictability, access and equity, participation and collaboration, interoperability.

Coherently with the ICAO framework, the **current state** of an ATM system is defined by the set of the current values of its performance indicators. A **disturbance** is a phenomenon, factor or process, either internal or external, which may cause a stress in a system. A **stress** is the state of a system caused by a disturbance which differs from the reference state and is characterized by deviation from this reference condition. A stress can be, accordingly with (Gluchshenko and Foerster, 2013): **survival**, if the system can respond by perturbation without modification to change the current state or **lethal**, if the system cannot or should not respond by perturbation to change the current state and has to be modified. A **perturbation** is the response of a system to the possible or current significant undesirable changes of the state of the system caused by a disturbance. If the stress is unavoidable, but survival, perturbation can be: **transient**, if it enables a temporary deviation which becomes zero over time, with return to the reference state; **permanent**, if the deviation becomes fixed over time, leading to a state that is different from the reference state.

Several definitions of resilience have been introduced, with more qualitative statements than quantitative formulations having been suggested. Indeed, as pointed out in (Henry and Ramirez-Marquez, 2012), although resilience is becoming an essential component of systems and enterprises, there is currently a lack of standardization for a quantitative definition and a measurement of resilience. However, some of the aspects of resilience are measurable. These quantifiable aspects are more technical in nature and they are related to reliability, safety and capacity (Jackson, 2009). Anyway, the absence of a global quantitative definition of resilience is a significant limit for resilience applications.

In the following, we firstly examine the aspects and attributes that a quantitative resilience measure should involve. Thereafter, we review some of the main resilience metrics that have been proposed so far.

2.1. Resilience attributes

Reference (Bruneau et al., 2003) outlines the following "4 Rs" properties for the resiliency of a generic system:

→ **robustness**: strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress;
→ **redundancy**: the extent to which elements, systems, or other units of analysis are substitutable;
→ **resourcefulness**: the ability to identify problems, establish priorities, and mobilize resources when conditions exist that

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threaten to disrupt some element, system, or other unit of analysis;

→ **rapidity**: the ability to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

Reference (Cook et al., 2014) suggests the following key properties for resilience: resilience is an ability to respond to disruption through recovery; the response may be measured in terms of its magnitude, and its temporal and spatial extent; the magnitude may be expressed with respect to system performance targets.

In addition, a view of three capacities of resilience is presented for complex networks (but it may be related to a generic system). These three capacities are: **absorptive capacity**, to withstand disruptions; **adaptive capacity**, to accommodate flows through alternative paths into the network; **restorative capacity**, to quickly recover from a disruptive event at minimum cost. Therefore, resilience is interpreted as the ability of a complex network to retain performance during and after disruptions and their ability to return to the normal state of operation quickly after disruptions.

2.2. Main resilience metrics

Several quantitative metrics and analytical frameworks have been proposed for resilience measurement. References (Henry and Ramirez-Marquez, 2012) and (Vugrin et al., 2010) provide a survey about resilience measurement methodologies from a wide range of disciplines. Generally speaking, resilience metrics may be divided in (Vugrin et al., 2014):

- **attribute-focused metrics**, which typically consists of indices that rely on subjective assessments;
- **data-based indicators**, which quantify system attributes that are asserted to contribute to resilience;
- **performance-based methods**, which measure the consequences of system disruptions and the impact that system attributes have on mitigating those consequences.

The common framework underlying performance-based approaches employs a system performance metric $F(\bullet)$ as a basis for the resilience computation (Vugrin et al., 2014). This is a time-dependent function, which represents the system delivery function or figure-of-merit. $F(\cdot)$ has a nominal value F_0. The system operates at this level until a disruption occurs at time t_0, which causes a degradation in the performance F_0 to some level F_{min} at time t_1. At this point, recovery starts and likely improves the performance $F(\cdot)$. When the system achieves a targeted performance level (not necessarily F_0), recovery is completed (Fig. 1).

Fig. 1 is representative of a performance function for which increasing values are considered better. Multiple options usually exist for sequencing recovery activities, which may have different costs, may imply different targeted level of performance and may require different times to recovery (Fig. 2). A resilience performance-based metric should generically take into account these three aspects.

The approach proposed in the paper (and in the project it refers) addresses this last kind of metric for "engineering" the resilience concept in ATM. Specifically, the SESAR Performance Framework is the target performance metric to be fully adopted in the SAFECORAM proposed approach to resilience engineering in ATM, as following sections describe.

3. Resilience management in SAFECORAM

This section reports the SAFECORAM proposal to cope with the problem of resilience management in an ATM system. It starts with the description of a **scenario** and formalizes the resilience management framework as an optimization problem through the definition of the concepts of **flows** and **flows distance**.

3.1. Definition of scenario

A scenario represents the set of a nominal and non-nominal situations affecting the ATM system, with the aim of stimulating alternative behaviors of the system to be evaluated from the resilience point of view in order to select the best reaction to the considered situation. A scenario is described through the specification of following information:

→ Summary,
→ Preconditions/Settings
→ Main flow,
→ Failures and/or disturbances,
→ Alternative flows,
→ Involved actors, systems (agents) and procedures,
→ Involved KPAs and KPIs.

3.2. SAFECORAM resilience loss metric

The term flow refers to the flows listed both in Main flow and Alternative flows sections in each scenario. Then, a flow is simply a set of tasks that must be executed in order to reach a terminal condition. From this point of view, actors are less important, because we put the focus on the tasks (meant as functions performed by the actors) and the propaedeutic order between them. Resilience will be expressed as a function of the ATM system performances and, consequently, the statement of the resilience management problem within SAFECORAM project has to address a

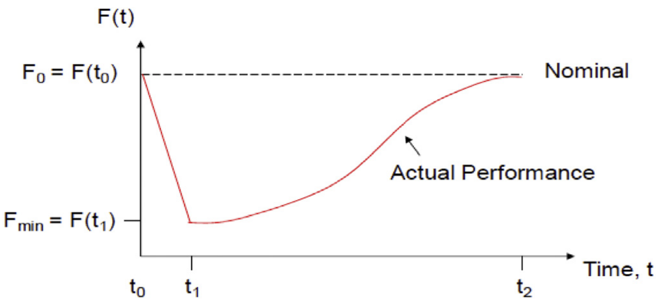

Fig. 1. Generic concept of disruption and recovery for resilience performance-based metrics (Vugrin et al., 2014).

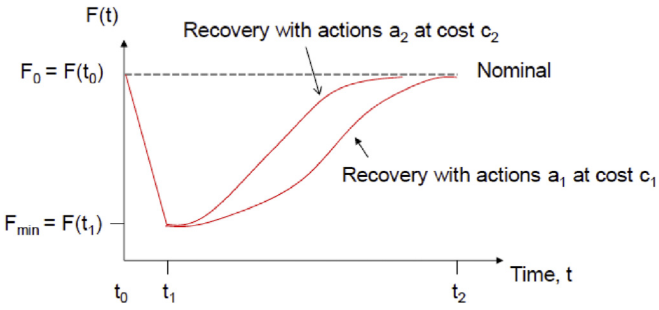

Fig. 2. Recovery strategies for resilience performance-based metrics (Vugrin et al., 2014).

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performance-based metric for resilience. As prescribed by the SESAR Performance Framework, the ATM system performances shall be related to specific KPAs and KPIs. A detailed description of these KPAs can be found in (ICAO, 2009).

In order to describe the general theoretic approach, suppose that there are n KPAs, named $\{A_1,\ldots,A_n\}$. Suppose that the k-th KPA is related to a set of KPIs, named:

$$\left\{KPI_1^{(A_k)},\ldots,KPI_{m_k}^{(A_k)}\right\}, \tag{1}$$

where m_k is the number of KPIs that are associated to A_k. We group all the KPIs into the following set:

$$\Theta=\left\{KPI_1^{(A_1)},\ldots,KPI_{m_1}^{(A_1)},\ldots,KPI_1^{(A_n)},\ldots,KPI_{m_n}^{(A_n)}\right\}, \tag{2}$$

Where $m=m_1+\ldots+m_n$ denotes the total number of KPIs. Note that in this approach to ATM performance, safety is simply one of the KPAs which contributes to the whole set of KPAs defining the performance of the system.

In the case study described, $n=3$ and $\{A_1,A_2,A_3\}=\{$*capacity area*, *efficiency area*, *environment area*$\}$. The choice of the three KPAs above defined is motivated because this areas are the only three for which, currently, specific measurable KPIs have been defined in the SESAR Performance Framework. The safety are not included among this three, therefore the resilience metric used in the case study does not account for safety measure. Specifically:

- *capacity area* has only one key performance indicator, that is $m_1=1$, $KPI_1^{(capacity\ area)}=capacity$;
- *efficiency area* has two key performance indicators, that is $m_2=2$, $KPI_1^{(efficiency\ area)}=fuel\ burn$ and $KPI_1^{(efficiency\ area)}=duration$;
- *environment area* has only one key performance indicator, that is $m_3=1$, $KPI_1^{(environment\ area)}=pollution$.

Assume that $T_{i,j}$ represents j-th task of actor i. From the performance point of view, each task $T_{i,j}$ may be also associated to a tuple $(k_{i,j}^{(1)},\ldots,k_{i,j}^{(m)})$, wherein $k_{i,j}^{(t)}$ represents the “contribution” of (the execution of) $T_{i,j}$ in the evaluation of the t-th KPI in Θ. For example, suppose that in a flow there is an actor C_1 that has two tasks $T_{1,1}$ and $T_{1,2}$. In this case, the KPIs are:

$$KPI_1^{(A_1)}=f\left(k_{1,1}^{(1)},k_{1,2}^{(1)}\right), \tag{3}$$

$$KPI_1^{(A_2)}=g\left(k_{1,1}^{(2)},k_{1,2}^{(2)}\right), \tag{4}$$

where $f(x,y)$ and $g(x,y)$ are functions as briefly explained in the descriptions of the absolute values of *Fuel burn*, *Pollution*, *Duration* and *Capacity* in section 4.B.

The **flow state** (both nominal and non-nominal) is the set of the values of KPIs identified in eq. (2), that is, the state of a flow $F(S)$ is the following tuple of values:

$$F(S)=\left(KPI_1^{(A_1)},\ldots,KPI_{m_1}^{(A_1)},\ldots,KPI_1^{(A_n)},\ldots,KPI_{m_n}^{(A_n)}\right) \tag{5}$$

$F(S)$ is a quantitative indicator of the global performance achieved by the ATM system if it executes the flow S into the considered scenario. The definition of the flow state implies a statement of the resilience management problem as a single objective optimization problem if it is possible to compare flows respect to only their flow state. An order relation amongst the whole states of the flows of a same scenario is needed in order to establish if a flow S_1 is better or worse than a flow S_2 (with respect to their states, i.e., their key performances).

For this reason, a **flow distance** function d is introduced.

If Ω is the set of all the flows of the scenario $\mathbb{S}$, a function $d:\Omega\times\Omega\rightarrow\mathbb{R}$ is a flow distance if it has the well-known distance properties: non-negativity, identity of indiscernible, symmetry and triangle inequality. A flow distance represents a quantitative measure of the similarity between two flows of a scenario and it should be related to the flow states for our purposes. Two flows S_1 and S_2 are similar and their distance $d(S_1,S_2)$ is low if their states $F(S_1)$ and $F(S_2)$ (i.e., their global ATM performances) are close.

Based on the previous considerations, we define the resilience metric in the following way. Let S_0 be the nominal flow of a scenario $\mathbb{S}$, that is, the main flow of $\mathbb{S}$. Let S_i be an alternative flow of S_0 in the scenario $\mathbb{S}$. The **SAFECORAM resilience loss metric** $\mathrm{RL}_{\mathbb{S}}(S_i)$ in the scenario $\mathbb{S}$ of the ATM system is:

$$RL_{\mathbb{S}}(S_i)=d(S_0,S_i) \tag{6}$$

This metric is a function of the selected scenario $\mathbb{S}$ (and its nominal flow). Moreover, it is a function of the alternative flow that has been triggered within $\mathbb{S}$.

The metric in (6) is a resilience loss metric because the more similar are the performed alternative flow S_i and the nominal flow S_0, the lower is $\mathrm{RL}_{\mathbb{S}}(S_i)$. In this way, the proposed metric confirms that the ATM system is more resilient if the chosen alternative flow is more similar to the nominal flow, i.e., if their states (and so their global performances) are closer.

Several characterizations of the SAFECORAM resilience loss metric may be provided according to the nature of the flow distance index. For example, in order to illustrate the approach, consider only one area A with four KPI and suppose that:

$$KPI_j\in[0,1],\quad j=1,2,3,4, \tag{7}$$

where a value close to 1 of the KPI indicates “good” performance and a value close to 0 represents “poor” performance. The values of the four KPIs of a flow S of the scenario $\mathbb{S}$ may be drawn on a bi-dimensional Cartesian coordinate system as shown in Fig. 3,

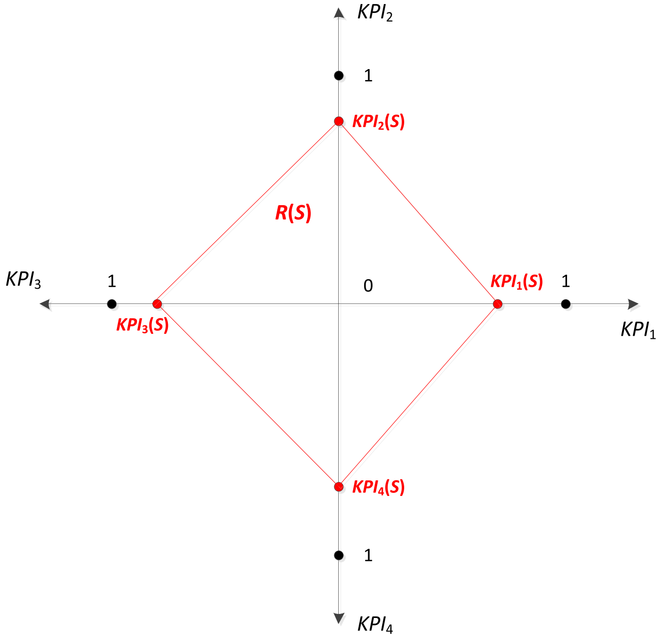

Fig. 3. Bi-dimensional graphical representation of the KPIs of a flow.

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wherein $\{KPI_1, KPI_2, KPI_3, KPI_4\}$ is the set of the four KPIs and $\{KPI_1(S), KPI_2(S), KPI_3(S), KPI_4(S)\}$ is the set of the KPIs values for the flow S.

$R(S)$ is the area of the quadrangle with vertices $\{KPI_1(S), KPI_2(S), KPI_3(S), KPI_4(S)\}$ and can be seen as a "state area" or a "global performance area" of the ATM system for the flow S.

In this case, an intuitive definition of the flow distance between the flows S_1 and S_2 is:

$$d(S_1, S_2) = |R(S_1) - R(S_2)| \tag{8}$$

It is not difficult to verify that the function (8) is a well-defined distance function. Hence, according to (8), two flows are similar if they entail similar global performance area. This metric is also named **area distance**.

Another scalar real-valued formulation for the flow distance between the flows S_1 and S_2 of a scenario $\mathbb{S}$ is the **difference distance**, which has the following expression:

$$\begin{aligned} d(S_1, S_2) = a_{1,1}&\left|KPI_1^{(A_1)}(S_1) - KPI_1^{(A_1)}(S_2)\right| + \ldots \\ &+ a_{1,m_1}\left|KPI_{m_1}^{(A_1)}(S_1) - KPI_{m_1}^{(A_1)}(S_2)\right| + \ldots \\ &+ a_{n,1}\left|KPI_1^{(A_n)}(S_1) - KPI_1^{(A_n)}(S_2)\right| + \ldots \\ &+ a_{n,m_n}\left|KPI_{m_n}^{(A_n)}(S_1) - KPI_{m_n}^{(A_1)}(S_2)\right|, \end{aligned} \tag{9}$$

wherein the terms $a_{i,j}$ are real-value coefficients. Therefore, the distance index in (9) is a linear combination of the deviations amongst the KPIs of the compared flows. It is a valid distance function because the single deviations amongst the KPIs are distance indexes and a linear combination of distance indexes is a distance index.

If we suppose that $a_{i,j} = 1$, $\forall i,j$, then two flows S_1 and S_2 are more similar if their related quadrangles in Fig. 3 are "superimposable", i.e., the single vertices pairs $(KPI_1(S_1), KPI_1(S_2))$, $(KPI_2(S_1), KPI_2(S_2))$, $(KPI_3(S_1), KPI_3(S_2))$, $(KPI_4(S_1), KPI_4(S_2))$ are closer among each other.

Note that the SAFECORAM resilience loss metric is time-independent, in the sense that it is a function of just the available resources and their related performance with respect to the adopted performance framework. The ATM system is, indeed, a complex hybrid system, encompassing both discrete (finite state) and continuous dynamics. While the complete evolution of the system needs consequently to take into account the whole dynamic characteristics, in the proposed task allocation problem it is considered that each set of available residual resources is related to a discrete state of the system. Consequently the task allocation approach can be dealt with just considering the system finite states, but not its explicit dependence on time, and it is then well suited to be handle by graphs and suitable for the family of adoptable resilience loss metrics and optimal search path methods, as in SAFECORAM.

3.3. Statement of the resilience management problem

In accordance with the definitions of the previous paragraphs, if a disturbance (or equivalently a failure) δ occurs in the nominal flow S_0 of the scenario $\mathbb{S}$ of the reference ATM system, a perturbation[1] is required in order to cope with the disturbance and its related stress.[2] Then, a set of alternative flows $\Gamma^{(\mathbb{S}\delta)} = \{S1, \ldots, Sk\}$ may be executed in order to reach the same terminal condition of S_0. Hence, the set of alternative flows $\Gamma^{(\mathbb{S}\delta)}$ strictly depends on the occurred disturbance δ in $\mathbb{S}$. Here, we assume that the disturbance δ is unique in $\mathbb{S}$. As a consequence, the set of alternative flows is a function of only the scenario $\mathbb{S}$, namely, $\Gamma^{(\mathbb{S}\delta)} = \Gamma^{(\mathbb{S})}$.

The set $\Gamma^{(\mathbb{S})}$ can be modeled as a **DAG** (**Directed Acyclic Graph**). This is a directed graph with no directed cycles, that is, it is formed by a set of vertices and directed edges with each edge connecting one vertex to another such that there is no way to start at a vertex v and follow a sequence of edges that eventually loops back to v again. We denote the DAG with $G = \mathrm{V,E}$, where V is the set the set of vertices and E is the set of edges. Every vertex $v \in \mathrm{V}$ corresponds to a single task $T_{i,j}$ and an edge $(u,v) \in \mathrm{E}$ – with $u,v \in \mathrm{V}$ – states that the task u must be executed before the task v starts. Hence, the edges represent the precedence relations of the alternative flows of $\mathbb{S}$, that is, of the equivalent DAG G.

Also assume that there are a starting vertex v_{start} and a ending vertex v_{end}. The starting vertex conventionally represents a null task and also depicts the triggering condition (the disturbance δ) of the set of alternative flows $\Gamma^{(\mathbb{S})}$. When all tasks/vertices are executed, then the scenario $\mathbb{S}$ finishes. In other words, $\mathbb{S}$ terminates successfully when v_{end} is completed. The vertex v_{end} is also named **terminal condition** of $\mathbb{S}$. Thereby, an alternative flow $\mathrm{S_l} \in \Gamma^{(\mathbb{S})}$ is a route (a sequence of vertices, i.e., of tasks) from v_{start} to v_{end} (Fig. 4).

In Fig. 4, every edge is labeled with the tuple $(k_{i,j}^{(1)}, \ldots, k_{i,j}^{(m)})$, which represents the contribution of the destination vertex (task) $T_{i,j}$ in the evaluation of the KPIs. At the end of the alternative flow S_l, the KPIs are evaluated and their values represent the current state $F(S_l)$ of the flow S_l, i.e., its current global performance.

Given a flow distance function$d(\bullet)$, we define the **resilience management problem** as the following optimization problem:

$$S_{opt} = \arg \min_{S_l \in \Gamma^{(\mathbb{S})}} RL_{\mathbb{S}}(S_l) = \arg \min_{S_l \in \Gamma^{(\mathbb{S})}} d(S_0, S_i) \tag{10}$$

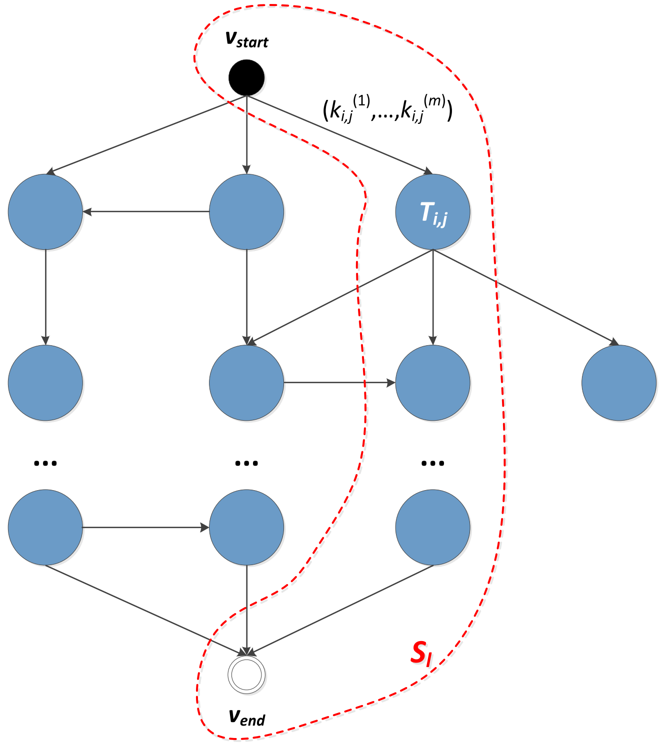

Fig. 4. Directed acyclic graph for the set of alternative flows of a scenario.

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[1] As regards resilience management, we suppose that the stress is survival and the perturbation is transient. In this way, we deal with resilience (and not robustness) actions (Vugrin et al., 2014).

[2] The stress typically implies a decrease in one or more KPIs.

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Table 1
Human and Machine actors system of the case study.

Humans		Machines	
Category	Actors	Category	Actors
Aircraft Crew	Pilots, PATS Remote Pilots	Vehicles	Aircraft PATS
ATC	ATC Sector, Executive Controller, ATC Sector Planning Controller, Approach Supervisor Airport Tower Supervisor	On-Board Systems	4D-FMS 4D-Flight Management System
Airport/Network Operations	Flight Operations Centre, Airport Operations Centre, Local Traffic Manager Network Manager Flow Manager	Ground Systems	SWIM System Wide Information Management
PATS	PATS Operation Management Center	Communication	Datalink

Table 2
Sets of coefficients for resilience loss metrics.

Coefficients				
Stakeholder	Fuel burn	Delay	Pollution	Capacity
Airline	1	0.5	0	0
Airport	0	0	0	1
General	1	1	1	1

This problem consists in scheduling the best alternative flow S_{opt} in the scenario $\mathbb{S}$ as the alternative flow in $\mathbb{S}$ that has the minimum resilience loss (i.e., the flow distance) with respect to the nominal flow S_0. The formulation of the problem (10) is independent from the definition of the flow distance.

Note that this problem is also a constrained optimization problem, wherein the constraints are represented by the precedence relations of the alternative flows, i.e., by the set of edges of the DAG G that is associated to the set $\Gamma^{(\mathbb{S})}$ of alternative flows. Hence, the problem (10) is equivalent to find the optimal route from v_{start} to v_{end} in the DAG G of $\Gamma^{(\mathbb{S})}$, namely, the route that minimizes the resilience loss metric $\mathrm{RL}_{\mathbb{S}}(\cdot)$. From this point of view, every edge of G has a crossing cost, which is related to the tuple $(k_{i,j}^{(1)},\ \ldots, k_{i,j}^{(m)})$ of its destination task $T_{i,j}$. This cost represents the increase in $\mathrm{RL}_{\mathbb{S}}(\cdot)$ if the edge is crossed, i.e., if the task $T_{i,j}$ is performed.

This methodological approach assumes that the crossing cost of an edge depends only on the destination task, whereas it does not depend on the starting vertex. Indeed, the contribution of the task $T_{i,j}$ to the KPIs evaluation depends only on $T_{i,j}$ and it does not depend on the past evolution of the flow, i.e., the traversed sequence of tasks to reach $T_{i,j}$. Anyway, without loss of generality, the methodological approach would be the same even if this assumption was not true. In this case, the crossing cost of an edge would depend both on its starting vertex (the previous task) and on its destination vertex (the current task).

Moreover, the problem (10) refers to the ability of the ATM system to lead itself towards to the most similar state with respect to the reference state (the state of the main flow), that is, towards the target performance level $F(S_0)$. Hence, the formulated problem mainly refers to the definition of resilience as the ability to get back to the global performance level of the system by means of recovery actions. Here, the term recovery means a reallocation strategy of the tasks performed by the system components (as identified by the alternative flow) and does not mean restore (i.e., it does not deal with repairing actions of the failed components).

4. Case study

SAFECORAM project has developed a set of scenarios as application examples of the methodology. It has to be first taken into account that the project is within the SESAR long-term research domain. An ATM system for years 2050 has first been developed in the project, identifying possible highly automated functions and a specific identification of ATM system actors and function allocation. Here, we will consider one specific scenario, for which the following subsections provide a general description, identifies the actors and their tasks in the scenario, a trigger that requires a new tasks allocation and, finally, presents the results, as obtained by the application of the methodology to the problem.

It is worth noting, as already expressed in previous sections, that in the proposed approach, safety has to be considered as one of the twelve key performance areas identified by SESAR Performance Framework to define the whole ATM system performance. In the specific case study analyzed in the paper, moreover, the Safety Key Performance Area is not brought to account because there is not a quantitative expression for safety indices in the present Safety Assessment Methodology, through SESAR KPIs. The future availability of these KPIs for the Safety area will allow full integration of safety in the ATM performance metric. In particular, the following two ways are envisaged as potentially suitable for safety integration in the global ATM performance measure:

Table 3
KPI values for scenario.

	Fuel burn (kg/min per movement)		Pollution (kg of CO_2)		Duration (minutes)		Capacity (num. movements per one runway per hour)	
Flow	Absolute	Normalized	Absolute	Normalized	Absolute	Normalized	Absolute	Normalized
Nominal	1560.0	1	4093.7	1	20.0	1	5.0	1
1	1560.0	1	4093.7	1	20.0	1	5.0	1
2	1560.0	1	4093.7	1	20.0	1	5.0	1
3	1560.0	1	4093.7	1	20.0	1	5.0	1
4	1625.0	1.04166	4264.2	1.04166	25.0	1.25	4.7	0.9583
5	1791.4	1.1483	4700.9	1.1483	37.8	1.89	4.25	0.8516
6	1690.0	1.083	4434.8	1.083	30.0	1.5	4.58	0.916
7	2112.5	1.354	5543.5	1.354	62.5	3.125	3.22	0.645
8	2028.0	1.3	5321.8	1.3	56.0	2.8	3.5	0.7
9	2080.0	1.33	5458.2	1.33	60.0	3.0	3.33	0.66
10	1716.0	1.1	4503.0	1.1	32.0	1.6	4.5	0.9
11	1612.0	1.033	4230.1	1.033	24.0	1.2	4.83	0.966

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- By fixing a minimum threshold for Safety-related indexes, so that all the flows that have values less than this threshold, will be eliminated from the process of identifying the optimal path;
- safety-related indexes may be appropriately weighed in comparison to all other KPIs of the Key Performance Areas accounted for the ATM performance metric.

With this interpretation, the case study described helps to highlight how the resilience can be interpreted and treated not just as a recovery method of security conditions, but performance recovery, expressed by KPIs, of the entire system.

4.1. Description of the reference scenario

In this scenario, a commercial aircraft while flying en-route experiences a failure that requires immediate rapid descent.

Preconditions/Settings of the Scenario are: a high level of traffic is present in the area of operations considered, and because the scenario applies to a possible long term future, not only Commercial vehicles are present, but also PATS (Personal Air Transport Vehicle) vehicles are considered. No critical weather and visibility conditions (conditions as expected) affect the area. The scenario is located over the Maastricht area during the en-route phase of a commercial passenger vehicle flying towards the Amsterdam (EHAM) destination airport. In nominal conditions, the vehicle is flying according to the assigned 4D contract, automatically guided by the 4D FMS while the Flight Crew is monitoring the flight. At lower flight levels, intense traffic of PATS vehicles is flying, according to their assigned 4D contracts and in a full automatic way.

Table 1 presents the set of the classes of actors that populate the scenario.

In this scenario the failure regards the pressurization system, leading to the need of immediate rapid descent. The descent may affect lower level flying vehicles, down to the PATS vehicles. So this failure stimulates many reactions that induce to alternative flows: at first the Flight Crew immediately starts a descent, so assuming the responsibility of self-separation from other airborne traffic and then the situation could require an immediate landing and an assessment of the risk associated to the situation from the Planning Controller. In order to assign the vehicle with a new 4D contract up to the nearest airport, the Collaborative Decision Making - CDM procedure can be trigged and the output can provide different solutions that led to different alternative flows.

4.2. Experimental results

A software demonstrator has been implemented in order to prove the feasibility and the validity of the SAFECORAM resilience management process. The KPAs taken into account are efficiency, environment and capacity. The related KPIs are: K1-efficiency (fuel burn, kg/min per movement); K2-efficiency (delay, minutes); K3-enviroment (emission of pollutant, kg of CO_2); K6-capacity: (delay-predictivity, movements per one runway per hour). The assumptions of the scenario are:

1. movements per hour: $M = 15$;
2. fuel burn: the average value of 65 Kg per minute is used for all vehicles in all scenarios;
3. duration: the time including TMA and landing phases is 20 minutes for all scenarios;
4. emission of pollutant: $c_{CO2} = 3.149$ Kgs/Kg of fuel burnt.

The adopted resilience loss metrics are both the area (8) and the difference (9) distances. Moreover, it can be assigned a coefficient to each KPI that determines the importance of the KPI with respect to the others. Three sets of coefficients are defined and they roughly corresponds to three ATM stakeholders point of view: **General**, **Airline** and **Airport** (Table 2). The definitions of three stakeholders profiles aims to demonstrate the flexibility in the customization of the metric function, so that some aspects in the optimization

Table 4
Resilience values for the alternative flows in scenario.

Flow	Profile	Distance	Value
1	**General**	**Area**	**0.0**
		Difference	**0.0**
	Airline	Area	1.75
		Difference	2.5
	Airport	**Area**	**2.0**
		Difference	**3.0**
2	General	Area	0.0
		Difference	0.0
	Airline	Area	1.75
		Difference	2.5
	Airport	Area	2.0
		Difference	3.0
3	General	Area	0.0
		Difference	0.0
	Airline	Area	1.75
		Difference	2.5
	Airport	Area	2.0
		Difference	3.0
4	General	Area	0.2916
		Difference	0.3749
	Airline	Area	1.6744
		Difference	2.4166
	Airport	Area	2.0
		Difference	3.04166
5	General	Area	1.0383
		Difference	1.3349
	Airline	Area	1.4574
		Difference	**2.2033**
	Airport	Area	2.0
		Difference	3.1483
6	General	Area	0.58333
		Difference	0.74999
	Airline	Area	1.59375
		Difference	2.33333
	Airport	Area	2.0
		Difference	3.354
7	General	Area	2.47916
		Difference	3.1875
	Airline	**Area**	**0.9420**
		Difference	2.9166
	Airport	Area	2.0
		Difference	3.354
8	General	Area	2.0999
		Difference	2.6999
	Airline	Area	1.09
		Difference	2.7
	Airport	Area	2.0
		Difference	3.3
9	General	Area	2.333
		Difference	2.999
	Airline	Area	1.0
		Difference	2.8333
	Airport	Area	2.0
		Difference	3.33
10	General	Area	0.7
		Difference	0.9
	Airline	Area	1.56
		Difference	2.3
	Airport	Area	2.0
		Difference	3.1
11	General	Area	0.23
		Difference	0.3
	Airline	Area	1.69
		Difference	2.4333
	Airport	Area	2.0
		Difference	3.033

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process can be considered more important than others.

The choice of coefficients is actually a complex point of the procedure. In this case study, we resorted to the experience of Operational Experts who support the project. In general, the complexity of defining those indexes can also be seen as an element of flexibility in the adoption of the methodology. As regards the scenario of the proposed case study, Table 3 and Table 4 respectively report the KPIs values of every flow (both nominal and alternative) and the distance values of the alternative flows from the nominal flow. The "normalized" columns of Table 3 specify the ratio between the non-nominal KPI and the nominal KPI values. Moreover, a non-nominal value of a KPI may be degraded by assuming a greater value than the related nominal value. For example, this occurs for the KPIs that are related to delay, fuel consumption, pollution, etc. For this reason, a "normalized" column of the results may report a value greater than 1. Table 4 also shows the most resilient path for every profile according to both area and difference distances (the optimal values for each profile are highlighted in bold). The values in the columns "Absolute" in Table 3 are calculated in the following way:

- *Fuel burn absolute*: for the nominal flow, it is the sum of the fuel consumption of all aircraft involved in the scenario. For each aircraft the fuel consumption is based on the average value consumption per minute and the duration of the scenario. For the others flows, the value of the nominal flow is incremented of a quantity for each aircraft affected in the flow. The aircraft affected in the flow are those ones for which the contribution $k_{i,j}^{(k)}$ related to fuel consumption is not equal to 1. The increment of fuel for each aircraft is proportional to the value of $k_{i,j}^{(k)}$.
- *Pollution absolute*: for the nominal flow, it is related to the fuel consumption and to the emission of pollutant: (c_{CO2}) of each aircraft involved in the scenario. For the others flows the increment of value of the nominal flows is based on the increment of fuel consumption for each aircraft affected in the flow (as in the previous point).
- *Duration absolute*: for the nominal flow the duration is 20 min. For each aircraft in an alternative flow, the delay is proportional to the values $k_{i,j}^{(k)}$ and the duration of an alternative flow is the sum of the duration of the nominal flows and the delays of the aircraft affected in the flow.
- *Capacity absolute*: the capacity of the nominal flow is 5 movements. For each alternative flows, the values $k_{i,j}^{(k)}$ are used in order to adjust the number of movements.

The values in columns "Normalized" in Table 3 are the absolute values of the alternative flows normalized with respect the absolute values of the nominal flow.

It has to be noted that the application of the approach requires that several parameters can be "objectively" chosen. A first set of parameters is constituted by the weights which are used to "compose" the KPAs in a single global ATM performance index, that is the coefficients $a_{i,j}$ in (9). A second set of parameters are the coefficients which allow to build, for each KPA considered, the corresponding KPIs, that is the coefficients $k_{i,j}$ in (3) and (4) and, in addition, the corresponding ratio of degradation to be accounted for each of these parameters in non-nominal conditions. With respect to this aspect, it is primarily worth to consider that the proposed approach is minded to be applied in long term, and more precisely, in minded to be used with the SESAR Performance Framework fully defined. That framework, in fact, shall uniquely define all the set of parameters required by the approach. Anyway, notwithstanding the SESAR Framework is not currently available, an approach which allows to fix the parameters value in a rigorous way has been used in the study. For parameters $a_{i,j}$, the sets of values reported in Table 2 for different type of stakeholders, have been used. The different sets represent the different ways in which different classes of stakeholders suggested to compose the KPAs to generate the whole performance of the ATM system. This involvement of stakeholder is, indeed, a potential benefitting degree of freedom in applying the approach, at least since the unique performance measure in SESAR will be assessed.

As far as the other parameters is concerned, Table 5 reports the unique definition of the KPI used, while a method that allows to associate tasks weights allocation in non-nominal conditions with quantitative Operational Improvements, as defined in SESAR, has been used in order to assure that parameters are fixed to value uniquely relied on the SESAR program.

Eventually, the results analysis of the case study is reported here following. The interpretation of the results could be done at different levels. First of all, it has to be considered that the sets of coefficients in Table 2, related to the different profiles of the Airline and the Airport, differently weight the importance of the KPIs in measuring the performance of each alternative flows, respectively for each possible metric corresponding to the different perspectives of the global performance system (General) and the two alternative of the Airline and the Airport. For example, if we consider the flow 4, the General profile achieves a balanced evaluation for all the KPIs deviations (i.e., without amplifying or reducing the effect of any KPI of the alternative flow in the resilience index). On the other hand, the Airline and the Airport profiles have worse resilience values (Table 4). Indeed, they weigh only some KPIs (the fuel burn and the delay for the Airline and the capacity for the Airport), whereas they null the others. Hence, they achieve greater (i.e., worse) values of

Table 5
K-coefficient definition.

K ID	Calculation
K1-(in relation to KPA efficiency)	Amount of fuel burn in taxi/En-Route/TMA phase divided by number of movements: $KPI_{fuelburn} = \frac{1}{M}\sum_{i=1}^{N} f_i,$ where M is the number of movements of vehicles (Aircraft/PATS/RPAS), N is the number of flights. f_i is the fuel burn in taxi/En-Route/TMA phase.
K2-(in relation to KPA efficiency)	The time difference between the scheduled time at a certain point and the actual time over that point: $KPI_{delay} = \frac{1}{N}\sum_{k=1}^{N} t_{a,k} - t_{s,k}$ where N is the total number of vehicles (Aircraft/PATS/RPAS), $t_{s,k}$ is the scheduled time at a certain point for aircraft k and $t_{a,k}$ is the actual time over that point for aircraft k.
K3-(in relation to KPA environment)	Amount of emissions of pollutant e per flight for a given set of flights: $E_e = \frac{1}{N}\sum_{k=1}^{N} c_e \Delta f_{F,k}$ where E_e is the amount of emissions of pollutant e per flight for a given set of flights, N is the total number of vehicles (Aircraft/PATS/RPAS), c_e is the emission factor for pollutant and $\Delta f_{F,k}$ is the amount of fuel consumed by aircraft k.
K4-(in relation to KPA capacity)	Total number of movements **M** per (volume of En-Route/TMA airspace) or per (one runway) per hour for specific traffic mix and density.

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the resilience metrics because the KPIs deviations from the nominal flow are maximum for the alternative null KPIs. In detail, the Airport profile represents the worst case since it includes only the evaluation of the capacity KPI.

As Table 3 shows, all the KPIs values of the flows 1, 2 and 3 are equal to the nominal KPIs values. As a consequence, their values of the difference metrics are null for the General profile and they represent the most resilient paths for this profile according to such a metric. On the contrary, the difference metrics for the other profiles of the same flows are not null due to the null weight of some KPIs.

In the end, the area distances are null only for the General profile of flows 1, 2 and 3, whereas they are always greater than zero for the other profiles (for the flows 1, 2 and 3, too) and for the other flows. This happens because only the fuel burn KPI (for the Airline profile) and the capacity KPI (for the Airport profile) have a non-null coefficient. For this reason, the quadrangle of the KPI values in Fig. 3 reduces to a segment and the area distances are equal for all the flows: 1.75 for the Airline profile and 2.0 for the Airport profile. As results of Table 4 interpretation, one can state that while the Flow 1 is the optimal alternative to the nominal operations from the General (global ATM performance) point of view, for an Airline the Flow 5 is better to follow if it assumes as performance metric the "Difference" formulation, while Flow 7 has to be selected if it is assumed the "Area" formulation as performance metric.

The deeper level of results analysis applies to the identification of the tasks allocation which builds the "optimal" path, which in our approach finally represents the allocation that allows the highest residual performance of the ATM system. The complete and meticulous description of the tasks allocation for the different "optimal" solutions proposed, one for each of the three considered stakeholders and for each kind of metric considered, could require a very large number of columns. Anyway, it would be here exemplified the kind of interpretation that could be derived. As before stated, the Flow 1 remains the best alternative from a General point of view, while Flow 5 and Flow 7 can be identified as the best tasks allocation for the Airline, depending on the kind of metrics used. By analyzing the related tasks allocation, indeed, it can be observed that for the Flow 5 it is suggested that the A/C re-contract the new path with ACC, instead of actuate a simple immediate descent to lower altitude, and that in the case of the Flow 7, a diversion of the A/C under pressurization failure to a alternate airport could be the best recovery solution, if the "Airline/Area" metric is used. While the specific results depend on the assumptions we used to compute the corresponding metrics, the discussed results finally highlights how the methodology proposed could effectively find different "optimal" tasks allocation, each being the one that improve the residual performance of the ATM system, in function of the performance metric utilized.

5. Conclusions and future works

This paper addresses the design of a strategy for the resilience management problem of the future ATM system. It defines a family of analytical resilience metrics for the reference system and formally defines the ATM resilience management problem as an optimal tasks reallocation problem. In the paper, the methodology has been discussed and its effectiveness has been tested by its application to a structured reference case study. Future work will involve the development of a software simulation environment to validate the proposed methodology with reference to a meaningful highly automated ATM scenario. Besides, the reaction time of the system for the resilience DAG building and exploration will be thoroughly analyzed.

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