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FROM INNOVATION TO SOLUTION

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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Agenda

- Introduction
- Preliminary Definitions
  - Scenario
  - Flow, KPAs and KPIs
  - Flow State
  - Flow Distance
- SAFECORAM Resilience Loss Metric
- Statement of Resilience Management Problem
- Considerations about Distances
- Questions

Introduction (1)

- 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 disturbances**, in order to **minimize the 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.
- In the present paper, the selection of the optimization methodology better suited to support the resilience engineering problem as approached in SAFECORAM is discussed, with an introduction to the state-of-the-art of methodologies suitable for application.

Introduction (2)

- Several quantitative metrics and analytical frameworks have been proposed for resilience measurement

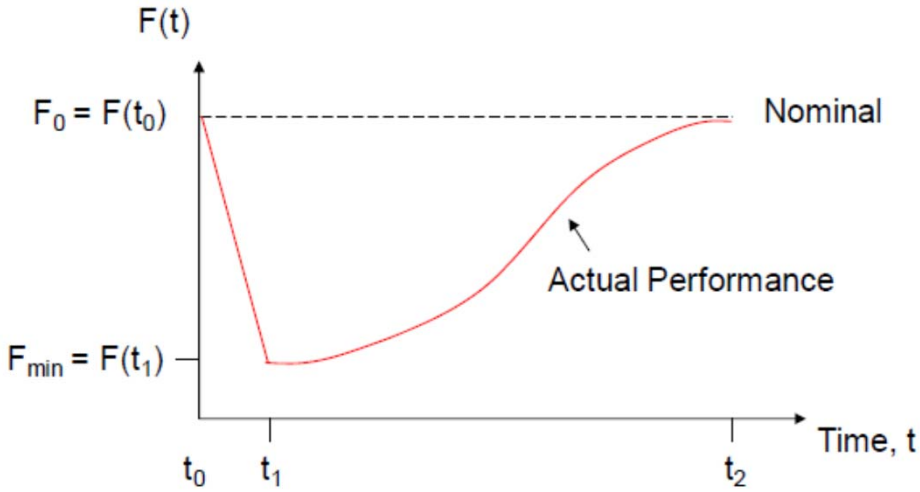
- There is currently a lack of standardization for a quantitative definition and a measurement of resilience, especially for **socio-technical systems**
  - "*We can only measure the potential for resilience but not resilience itself*" (D. Woods)

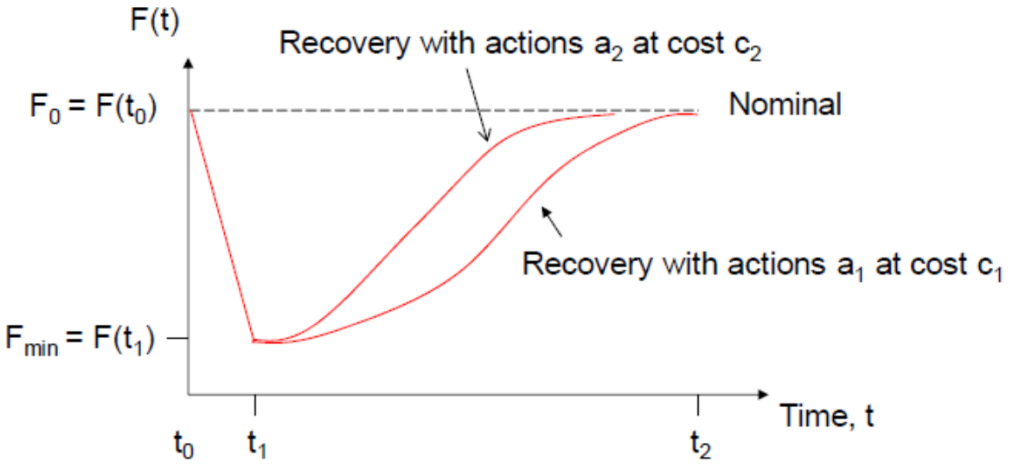
- **Resilience metrics** may be divided in:
  - **attribute-focused metrics**, which typically consists of indices that rely on subjective assessments
  - **data-based indicators**, which quantify system attributes that are asserted to contribute to resilience
  - **performance-based methods**, which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

- Performance-based methods do not quantify attributes that impact on the system functioning, but they directly measure the system outputs during the recovery period
  - A **system performance metric** $F(\cdot)$ is used as a basis for the resilience computation
  - This is a time-dependent function, which represents the **system delivery function** or **figure-of-merit**

Introduction (3)

- $F(\cdot)$ has a **nominal value** F_0
- The system operates at the nominal level until a **disruption** occurs at time t_0, which causes a **degradation** in the performance $F(\cdot)$ 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
- Resilience is quantifiable only if $F(\cdot)$ is quantifiable

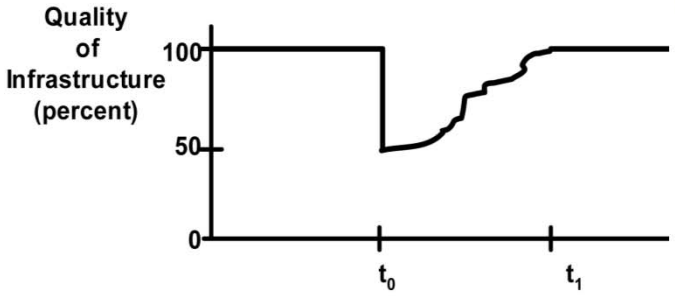


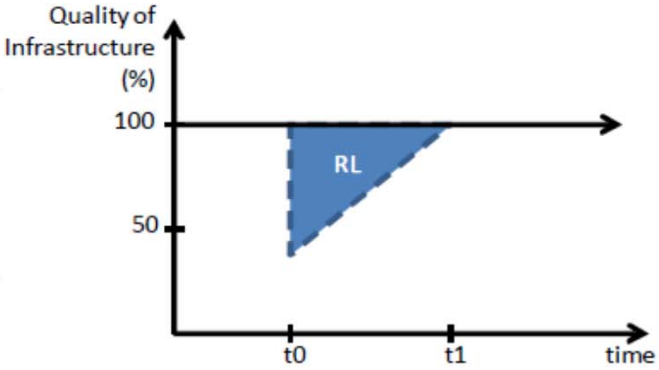


Introduction (4)

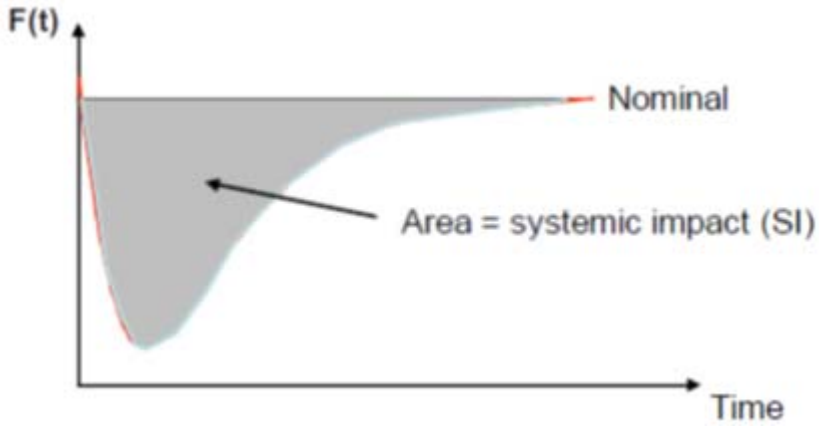
SEISMIC RESILIENCE LOSS

$$RL = \int_{t_0}^{t_1} [100 - Q(t)]\, dt$$





SYSTEMIC IMPACT AND RECOVERY EFFORT



$$SI = \int_{t_e}^{t_f} [TSP - F(t)]\, dt$$

$$TRE = \int_{t_e}^{t_f} RE(t)\, dt$$

$$Z = SI + \alpha TRE$$

Preliminary Definitions – Scenario

- WP3 has used the preliminary description of the adopted approach in SAFECORAM deliverables D1.1, D1.2 and D2.1 as an input for the statement of the problem
- D3.1 formalizes the resilience management framework as an optimization problem through the definition of some preliminary concepts
- 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
- Each proposed scenario reports:
  - the identification and description of relevant considered failures and/or disturbances
  - the identification and description of some possible alternative flows emerging from the considered non-nominal situation
  - the identification and description of the involved actors and possible applicable interactions in presence of non-nominal situations
  - the identification of the involved KPAs and KPIs
- Even if the description of the scenarios it is not exhaustive in terms of enumeration and exploitation of all the possible alternative flows, there are enough information to demonstrate that the proposed approach for resilience management can provide the evaluation of the best choices to be taken in order to optimize the reaction to the examined perturbations

Preliminary Definitions – Flow, KPAs and KPIs (1)

- A **flow** is a set of tasks that must be executed in order to reach a terminal condition
  - We will refer with the term flow to the flows listed both in *Main flow* and *Alternative flows* sections in each scenario
  - 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
- As described in deliverable D1.1, resilience should be expressed as a function of the ATM system performances
  - The statement of the resilience management problem within SAFECORAM project has to address a **performance-based metric** for resilience
- As prescribed by the SESAR Performance Framework, the ATM system performances are related to specific **KPAs** and a **KPI** represents a quantitative measure for each specific area
- Among all KPAs selected from SESAR Performance Framework, the following KPAs are taken into account within SAFECORAM project:
  - **Safety**
  - **Efficiency**
  - **Capacity**
  - **Environment**

Preliminary Definitions – Flow, KPAs and KPIs (2)

- Suppose that there are n KPAs, named $\{A_1, \dots, A_n\}$
  - For example, A_1 may represent Safety, A_2 the Efficiency, etc.
- Suppose that the k-th KPA is related to a set of KPIs, named $\left\{KPI_1^{(A_k)}, \dots, KPI_{m_k}^{(A_k)}\right\}$, where m_k is the number of KPIs that are associated to A_k
- We group all the KPIs into the following set

$$\Theta = \left\{KPI_1^{(A_1)}, \dots, KPI_{m_1}^{(A_1)}, \dots, KPI_n^{(A_n)}, \dots, KPI_{m_n}^{(A_n)}\right\}$$

  and we denote with $m = m_1 + \cdots + m_n$ the total number of KPIs
- Suppose that S is a flow and $\{C_1, \dots, C_a\}$ are the actors involved in S
  - Each C_i can execute a set of tasks $T(C_i) = \{T_{i,1}, \dots, T_{i,h}\}$
  - Only a subset of $T(C_i)$ is typically required during the execution of the flow S
- From the performance point of view, each task $T_{i,j}$ may be also associated to a tuple $\left(k_{i,j}^{(1)}, \dots, k_{i,j}^{(m)}\right)$
  - $k_{i,j}^{(t)}$ represents the "contribution" of (the execution of) $T_{i,j}$ in the evaluation of the t-th KPI in Θ

Preliminary Definitions – Flow, KPAs and KPIs (3)

Example 1

Suppose that $n = 2$ and that A_1 represents Safety and A_2 represents Environment. Suppose also that there is only one KPI for every KPA.

In the simplest flow S_1, there is a unique actor C_1 with a single task $T_{1,1}$. The contributions of $T_{1,1}$ in the evaluation of KPAs are $\left(k_{1,1}^{(1)}, \mathrm{k}_{1,1}^{(2)}\right)$. Therefore, in this simple example the values of the KPIs for Safety and Environment are respectively

$$KPI_1^{(A_1)} = k_{1,1}^{(1)}$$

$$KPI_1^{(A_2)} = k_{1,1}^{(2)}$$

Example 2

Suppose that in the same flow of the Example 1 the actor C_1 has two tasks $T_{1,1}$ and $T_{1,2}$. In this case, the KPIs are

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

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

where $f(x, y)$ e $g(x, y)$ are functions that should be determined in accordance with the deliverable D2.2 of SAFECORAM project. For example, in the simplest cases they may be the average, the minimum value, etc.

Preliminary Definitions – Flow, KPAs and KPIs (4)

Example 3

Suppose that there are two actors C_1 e C_2 in the same flow with the tasks $T(C_1) = \{T_{1,1}, T_{1,2}\}$ and $T(C_2) = \{T_{2,1}, T_{2,2}\ T_{2,3}\}$ respectively.

Furthermore, suppose that $f(x, y)$ is the average function and $g(x, y)$ the minimum function.
The evaluation of the KPIs follows

$$KPI_1^{(A_1)} = \text{mean}\left(k_{i,j}^{(1)}\right) = \frac{k_{1,1}^{(1)} + k_{1,2}^{(1)} + k_{2,1}^{(1)} + k_{2,2}^{(1)} + k_{2,3}^{(1)}}{5}$$

$$KPI_1^{(A_2)} = \min_{i,j} k_{i,j}^{(2)} = \min\left\{k_{1,1}^{(2)}, k_{1,2}^{(2)}, k_{2,1}^{(2)}, k_{2,2}^{(2)}, k_{2,3}^{(2)}\right\}$$

Preliminary Definitions – Flow State

- We define the **flow state** (both nominal and non-nominal) as the set of the values of its KPIs
- The state of a flow $F(S)$ is the following tuple

$$F(S) = \langle KPI_1^{(A_1)}, \dots, KPI_{m_1}^{(A_1)}, \dots, KPI_n^{(A_n)}, \dots, KPI_{m_n}^{(A_n)} \rangle$$

- Our definition of flow state is coherent with the definitions of reference states and current states of an ATM system
- $F(S)$ is a quantitative indicator of the global performance achieved by the ATM system if it executes the flow S into the considered scenario
- By means of the KPI definition, it is possible to define an order relation within a KPI associated to different flows of the same scenario and it is always possible to decide which is the "best" value of a certain KPI
  - If $KPI_i^{(A_j)}(S_1)$ and $KPI_i^{(A_j)}(S_2)$ are the values of $KPI_i^{(A_j)}$ associated to the states of the flows S_1 and S_2, it is always possible to decide if S_1 is preferable to S_2 with respect to $KPI_i^{(A_j)}$
- More generally, we are interested in specifying an order relation amongst the whole states of the flows of a same scenario 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

Preliminary Definitions – Flow Distance

- We aim to identify an order relation between the following tuples $F(S_1)$ and $F(S_2)$

$$F(S_1) = \langle KPI_1^{(A_1)}(S_1), \dots, KPI_{m_1}^{(A_1)}(S_1), \dots, KPI_n^{(A_n)}(S_1), \dots, KPI_{m_n}^{(A_n)}(S_1)\rangle$$
$$F(S_2) = \langle KPI_1^{(A_1)}(S_2), \dots, KPI_{m_1}^{(A_1)}(S_2), \dots, KPI_n^{(A_n)}(S_2), \dots, KPI_{m_n}^{(A_n)}(S_2)\rangle$$

- Some "**conflicts**" may arise because the flow S_1 may be better than S_2 with respect a KPI and, on the other hand, S_2 may be more preferable than S_1 with respect to another KPI
  - These conflicts may be handled only by means of a global distance index for the whole state function $F(S)$
  - In order to establish a relation order amongst the flows of a scenario, we should define a **similarity index** for them, namely, a metric that quantifies their differences
- We introduce a **flow distance** function d, i. e., if Ω is the set of all the flows of the same scenario, a function $d\colon\ \Omega \longrightarrow \mathbb{R}$ is a flow distance if the following properties hold

$$d(S_1, S_1) = 0, \qquad \forall S_1 \in \Omega$$
$$d(S_1, S_2) = d(S_2, S_1), \qquad \forall S_1, S_2 \in \Omega$$
$$d(S_1, S_3) \leq d(S_1, S_2) + d(S_2, S_3), \qquad \forall S_1, S_2, S_3 \in \Omega$$

SAFECORAM Resilience Loss Metric (1)

- A flow distance represents a quantitative measure of the similarity between two flows of a scenario
  - The flow distance 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 the same scenario $\mathbb{S}$ of S_0
  - The **SAFECORAM resilience loss metric** $RL_{\mathbb{S}}(S_i)$ in the scenario $\mathbb{S}$ of the ATM system is

$$RL_{\mathbb{S}}(S_i) = d(S_0, S_{\mathrm{i}})$$

- The metric $RL_{\mathbb{S}}(S_i)$ is a function:
  - of the selected scenario $\mathbb{S}$ (and consequently of its nominal flow S_0) because of the scenario-based approach in SAFECORAM project
  - of the alternative flow S_{i} that has been triggered within $\mathbb{S}$
- The metric $RL_{\mathbb{S}}(S_i)$ 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 $RL_{\mathbb{S}}(S_i)$
  - 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

SAFECORAM Resilience Loss Metric (2)

Example 1 of $RL_{\mathbb{S}}(S_i)$

We chose four KPAs (but the same approach can be applied with any number of areas). We also suppose that there is a KPI for every KPA and that

$$KPI_1^{(A_i)} \in [0,1], \qquad i = 1,2,3,4$$

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 in every flow S of the scenario $\mathbb{S}$ may be drawn on a bi-dimensional Cartesian coordinate system.

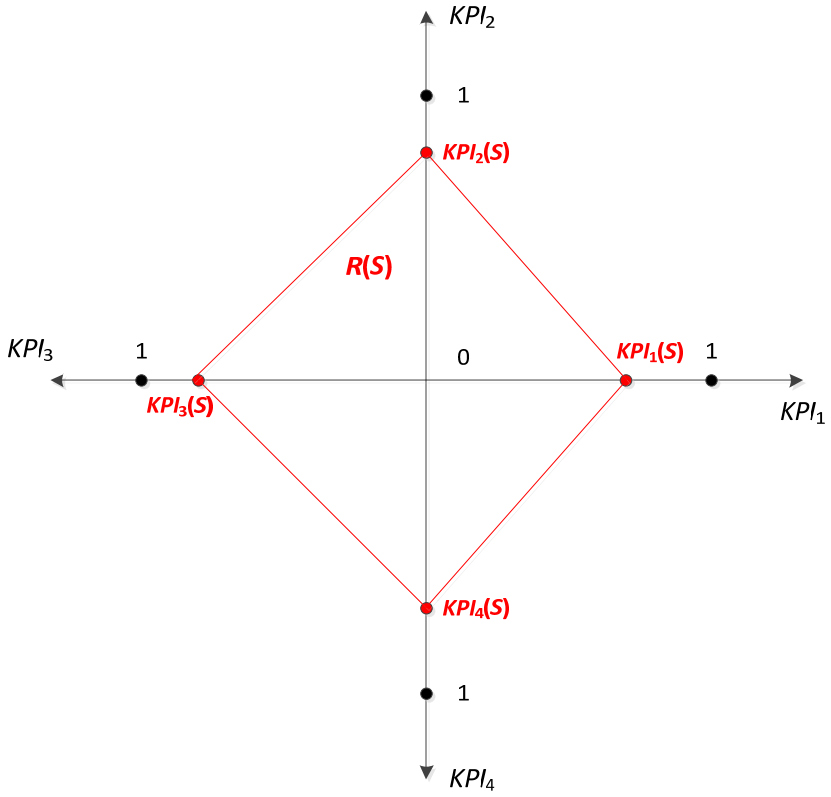
We denote with $\{KPI_1, KPI_2, KPI_3, KPI_4\}$ the set of the four KPIs and with $\{KPI_1(S), KPI_2(S), KPI_3(S), KPI_4(S)\}$ the set of the KPIs values for the flow S.

$R(S)$ 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

$$d(S_1, S_2) = |R(S_1) - R(S_2)|$$

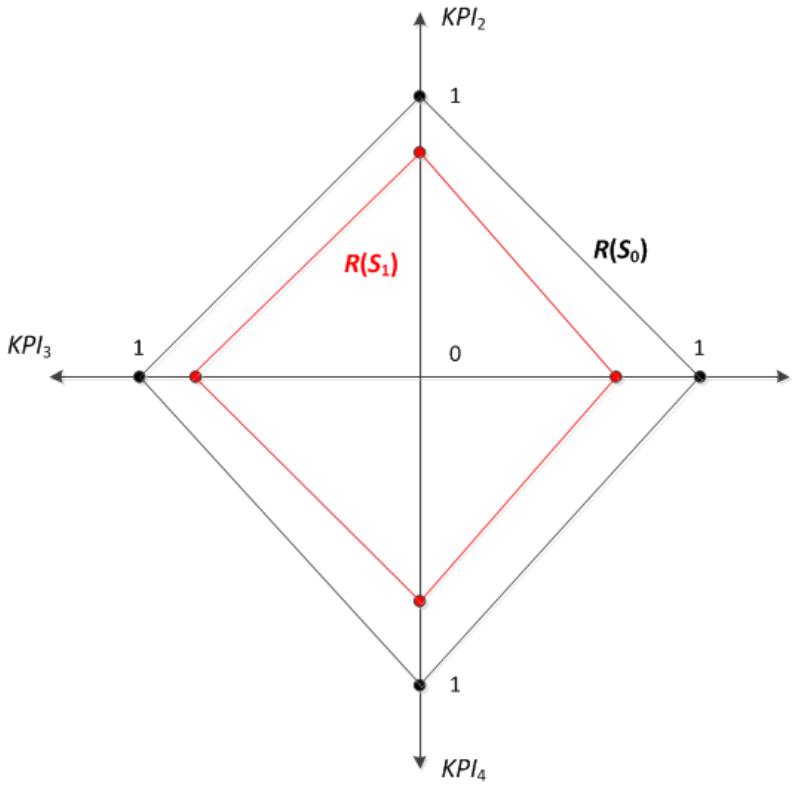
This index is a scalar real-valued function. Hence, two flows are similar if they entail similar global performance area.

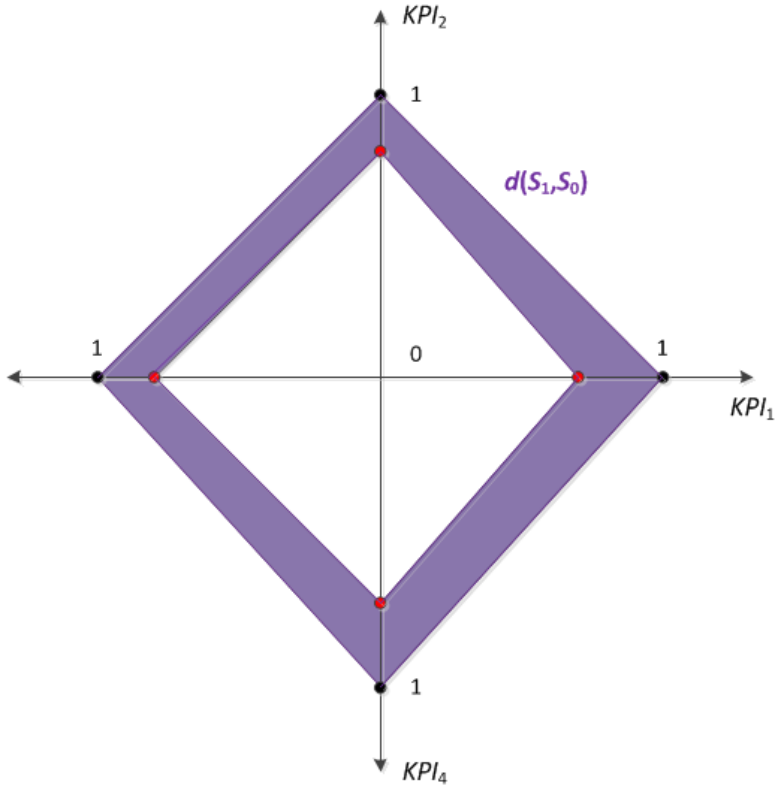


SAFECORAM Resilience Loss Metric (3)

Example 1 of $RL_{\mathbb{S}}(S_i)$

Here we suppose that the KPIs of the nominal flow are all 1 (not mandatory).





SAFECORAM Resilience Loss Metric (4)

Example 2 of $RL_{\mathbb{S}}(S_i)$

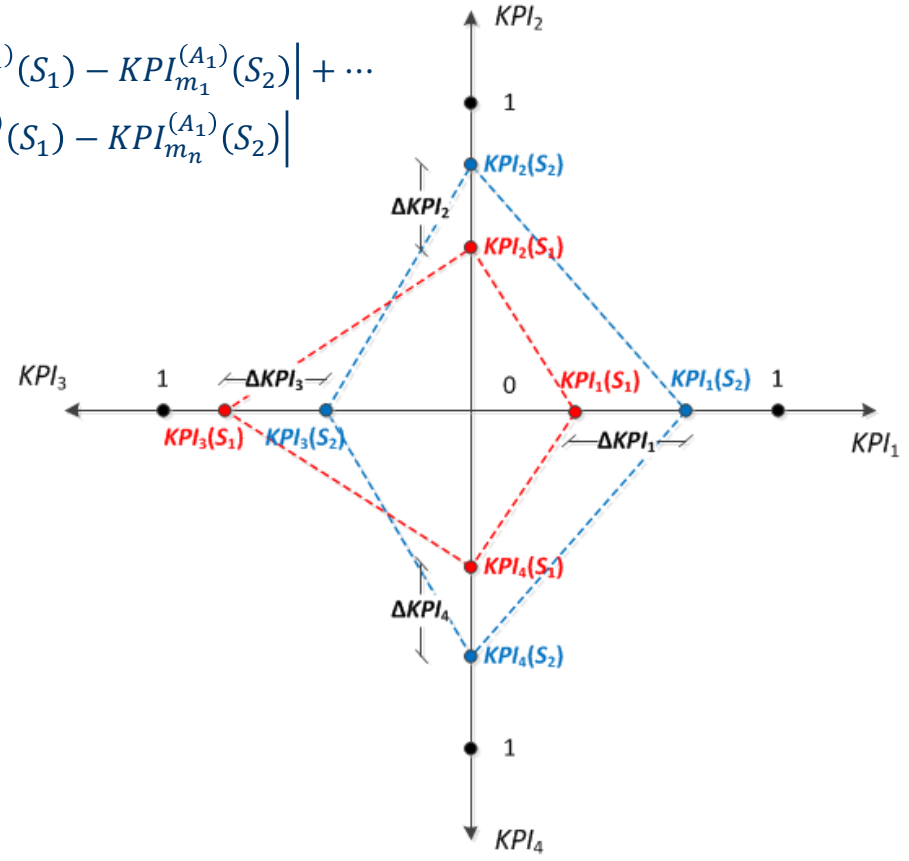
Another scalar real-valued formulation for the flow distance between the flows S_1 and S_2 of a scenario $\mathbb{S}$ is

$$d(S_1,S_2) = a_{1,1}\left|KPI_1^{(A_1)}(S_1) - KPI_1^{(A_1)}(S_2)\right| + \cdots + a_{1,m_1}\left|KPI_{m_1}^{(A_1)}(S_1) - KPI_{m_1}^{(A_1)}(S_2)\right| + \cdots$$
$$\ldots + a_{n,1}\left|KPI_1^{(A_n)}(S_1) - KPI_1^{(A_n)}(S_2)\right| + \cdots + a_{n,m_n}\left|KPI_{m_n}^{(A_n)}(S_1) - KPI_{m_n}^{(A_1)}(S_2)\right|$$

wherein the terms $a_{i,j}$ are real-value coefficients.

Therefore, this distance index 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 the same hypotheses of the previous example and 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 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.



SAFECORAM Resilience Loss Metric (5)

Example 3 of $RL_{\mathbb{S}}(S_i)$

Another definition of flow distance between the flows S_1 and S_2 of a scenario $\mathbb{S}$ is the following m-dimensional function $d\colon \Omega \longrightarrow \mathbb{R}^m$

$$d(S_1, S_2) = \left(\left|KPI_1^{(A_1)}(S_1) - KPI_1^{(A_1)}(S_2)\right|, \dots, \left|KPI_{m_1}^{(A_1)}(S_1) - KPI_{m_1}^{(A_1)}(S_2)\right|, \dots \right.$$
$$\left. \dots, \left|KPI_1^{(A_n)}(S_1) - KPI_1^{(A_n)}(S_2)\right|, \dots, \left|KPI_{m_n}^{(A_n)}(S_1) - KPI_{m_n}^{(A_1)}(S_2)\right|\right)$$

In this case, the flow distance is a vector that is composed by the distances amongst the single KPIs.

This metric formally is not a distance index because it is not a scalar real-valued function. However, for our purposes, we interpret it as a flow distance, i.e., as a similarity function amongst the flows of a scenario.

If we suppose the same hypotheses of the previous examples, the flow distance between S_1 and S_2 in (18) is a function $d\colon \Omega \longrightarrow \mathbb{R}^4$, defined as

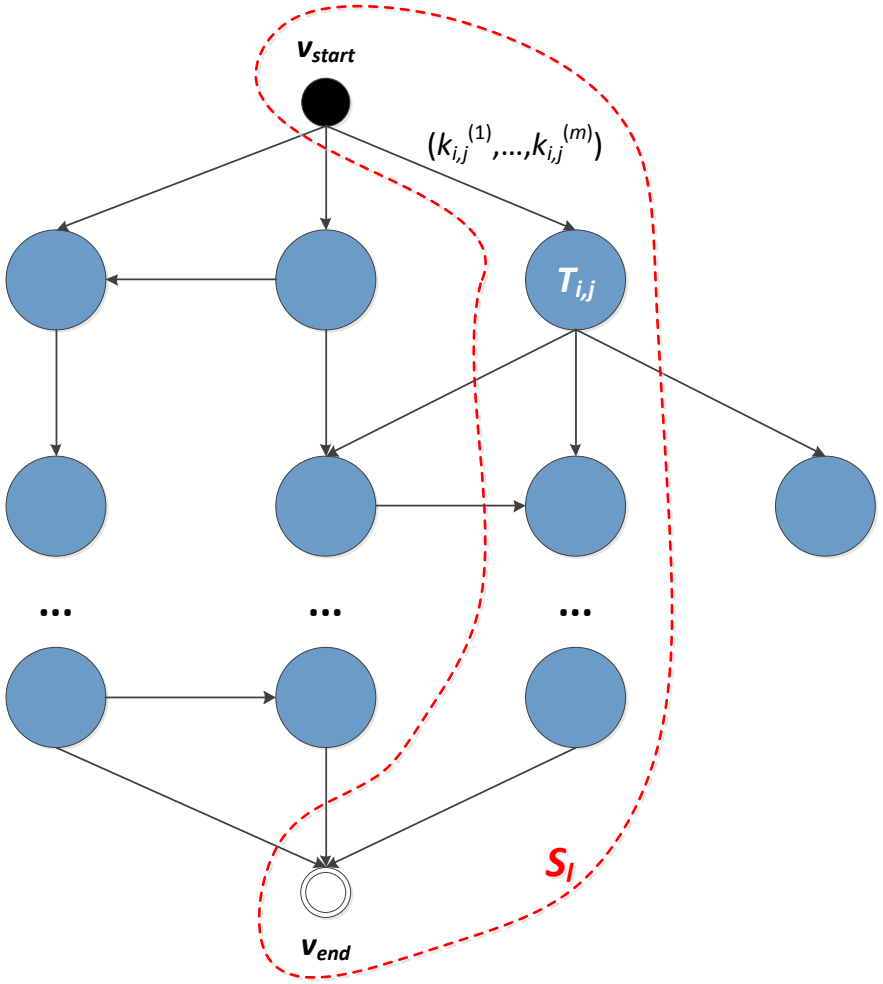
$$d(S_1, S_2) = (|KPI_1(S_1) - KPI_1(S_2)|, |KPI_2(S_1) - KPI_2(S_2)|,$$
$$|KPI_3(S_1) - KPI_3(S_2)|, |KPI_4(S_1) - KPI_4(S_2)|)$$

Statement of Resilience Management Problem (1)

- 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** is required in order to cope with the disturbance and its related **stress**
  - 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
- A set of alternative flows $\Gamma^{(\mathbb{S},\delta)} = \{S_1, \dots, S_k\}$ may be executed in order to reach the same terminal condition of S_0
  - $\Gamma^{(\mathbb{S},\delta)}$ strictly depends on the occurred disturbance δ in $\mathbb{S}$
  - Here, we assume that the disturbance δ is unique in $\mathbb{S}$ in accordance with deliverable D1.2
  - As a consequence, $\Gamma^{(\mathbb{S},\delta)}$ is a function of only the scenario $\mathbb{S}$, namely, $\Gamma^{(\mathbb{S},\delta)} = \Gamma^{(\mathbb{S})}$
- $\Gamma^{(\mathbb{S})}$ can be modelled as a **DAG** (**Directed Acyclic Graph**)
  - This is a directed graph with no directed cycles (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 $G = \langle \mathrm{V}, \mathrm{E} \rangle$, 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: the edges represent the **precedence relations** of the alternative flows of $\mathbb{S}$, that is, of the equivalent DAG G

Statement of Resilience Management Problem (2)

- We 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: $\mathbb{S}$ terminates successfully when v_{end} is completed
  - The vertex v_{end} is also named **terminal condition** of $\mathbb{S}$
- An alternative flow $S_l \in \Gamma^{(\mathbb{S})}$ is a **route** (a sequence of vertices, i.e., of tasks) from v_{start} to v_{end}
- 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**



Statement of Resilience Management Problem (3)

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

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

  - 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 is independent from the adopted definition of the flow distance

- This problem is also a **constrained optimization problem**, wherein the constraints are represented by the precedence relations of the alternative flows (the set of edges of the DAG G)
  - Other constraints can be imposed (e.g., minimum thresholds on the KPIs)

- The problem 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 $RL_{\mathbb{S}}(\cdot)$
  - Every edge of G has a crossing cost, which is related to the tuple $\left(k_{i,j}^{(1)}, \dots, k_{i,j}^{(m)}\right)$ of its destination task $T_{i,j}$
  - This cost represents the increase in $RL_{\mathbb{S}}(\cdot)$ if the edge is crossed, i.e., if the task $T_{i,j}$ is performed

Statement of Resilience Management Problem (4)

- This approach assumes that the crossing cost of an edge depends only on the destination task, whereas it does not depend on the starting vertex
  - 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 $T_{i,j}$
  - The 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)
- The resilience management problem 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 $F(S_0)$
  - 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)

Considerations about Distances (1)

Let M, F_1, F_2 be the main and two alternative flows respectively and suppose that:

$$F(M) = \langle 1,1,1,1 \rangle; \quad F(F_1) = \langle k_1, k_2, k_3, k_4 \rangle; \quad F(F_2) = \langle h_1, h_2, h_3, h_4 \rangle;$$

Consider the distances: $d_1(F_1, F_2) = \sum_{i=1}^{4}(k_i - h_i)^2$ and $d_2(F_1, F_2) = |R(F_1) - R(F_2)|$

Suppose that:

$$F(F_1) = \langle 0.6, 0.6, 0.6, 0.6 \rangle; \quad F(F_2) = \langle 1, 1, 0.3, 0.3 \rangle;$$

It follows that:

$d_1(M, F_1) = 0.64$	$d_1(M, F_2) = 0.98$
$d_2(M, F_1) = 0.28$	$d_2(M, F_2) = 0.155$

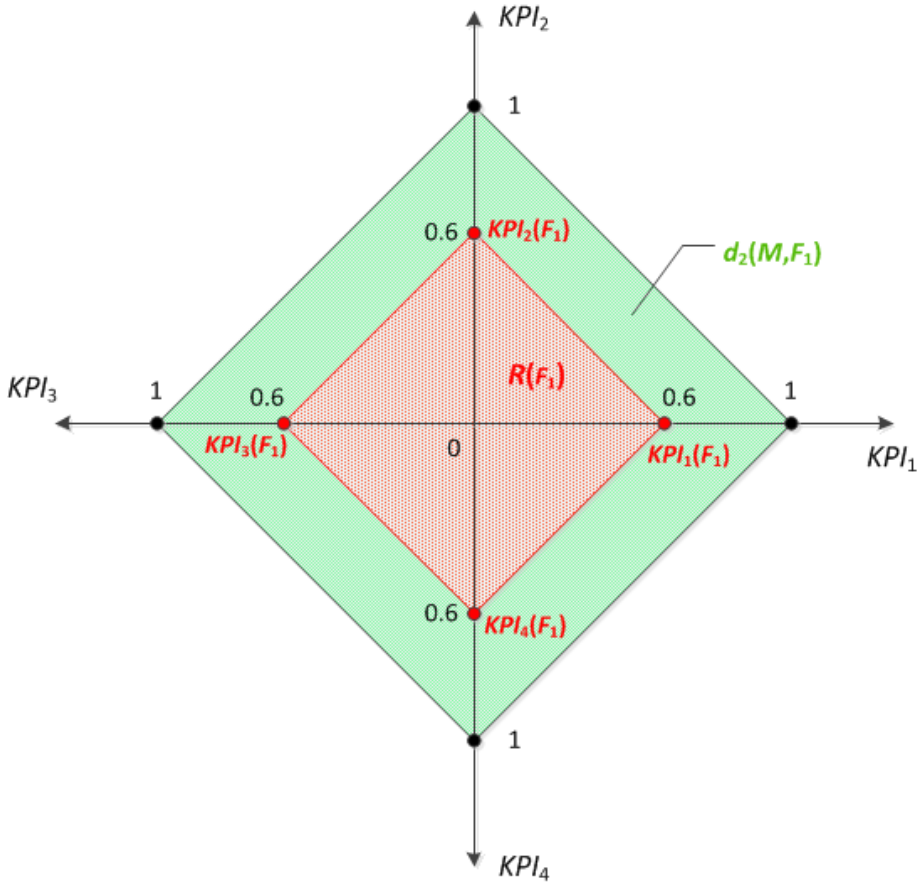
It holds that:

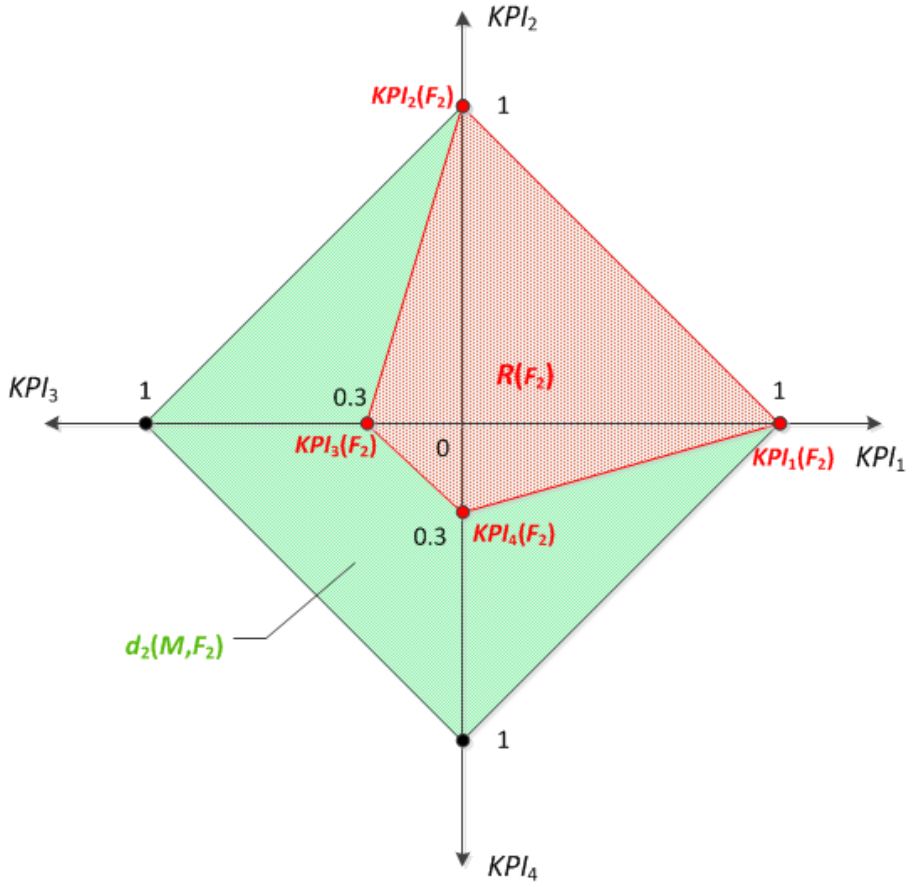
$$d_1(\mathrm{M}, F_1) < d_1(\mathrm{M}, F_2) \text{ and } d_2(\mathrm{M}, F_1) > d_2(\mathrm{M}, F_2)$$

The distance d_1 will select the alternative flow F_1 instead the distance d_2 will select the alternative flow F_2.

1. It seems that d_2 «explore» larger set of «solutions» (flows) than d_1
2. The distance d_1 focuses on flows with fewer differences

Considerations about Distances (2)





Questions

1. Which are the useful considerations to formulate a “good” distance function? For instance, referring to the previous example, is d_1 better than d_2? Always? Only in special cases?

2. Should we take into account a combination of more than one distance function?

3. Can we propose a new distance function that represents a more intuitive concept of resilience?

4. Is it true that a KPA can be more important than others? If yes, does it make sense to assign a weight to each KPA in the proposed distance definitions?

5. Is it reasonable to think that the KPI of a KPA cannot be less than a threshold? For instance, think at the Safety area. In this case, a natural choice could be the pruning of the alternative flows that do not satisfy these constraints before the selection of the “best” alternative flow.

Thank you for your attention

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