Funtional Resonance Analysis Method based-Decision Support tool for Urban Transport System Resilience Management

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***Abstract*— Today, managing critical infrastructure resilience in smart city is a challenge that can be talked adopting a new class of smart tools able to integrate the modeling capability with the evidence driven decision support. The Resilience Decision Support tool as presented in this article is an innovative and powerful tool that aims at managing CI resilience through a more complex and expressive Functional Resonance Analysis Method based modeling and through the connection of such a model with a system thinking based decision support tool exploiting smart city data. Thanks to ResilienceDS FRAM model becomes computable and the functional variability that is at the core of the resilience analysis can be quantified. Such quantification allows the decision support tool to compute specific strategies and recommendations for variability dampening at strategic, tactic and operational stage. The solution has been developed in the context of RESOLUTE H2020 project of the European Commission.**

Keywords—smart city, Functional Resonance Analysis Method; Decision Support System; Resilience; Urban Stransport System;

I. INTRODUCTION

Increasing resilience with respect to critical events is a topic of highest political concern in the EU. Regarding the case of transport systems, operations have developed a prominent safety and business critical nature, in view of which current practices have shown evidence of important limitations in terms of resilience management. Enhancing resilience in transport systems is considered imperative for two main reasons: such systems provide critical support to every socio-economic activity and are typically one of the most important economic sectors and secondly, the paths that convey people, goods and information, are the same through which risks are propagated.

Today, traditional risk and efficiency-based approaches in Critical Infrastructures (CI) safety and security management such has UTS (Urban Transport System), are no longer an option for their weakness in addressing widely unknown and uncertain threats [4].

In fact, CIs typically lose essential functionality following adverse events [5], [6] such as climatic extremes that become more intense and frequent. Up to now, there is currently no scientific method available to precisely predict the long-term evolution and spatial distribution of climate changes or man-made critical events, nor are the impacts on society's CI in any way quantified. In order to react and address these unknown elements, building resilience becomes the best decision for large complex systems as UTS [5]. To tackle the challenge of the resilience operationalization in UTS domain, in RESOLUTE[1] EU funded project we have identified three fundamental areas that have been exploited to ground the research and innovation action and creating a sort of stack for resilience assessment and management:

(i) **Complex System Modelling and Understanding** in support of the identification of UTS relevant aspects and related critical functions. The application of tools like Functional Resonance Analysis Method (FRAM) [8]. Resilience Analysis Grid (RAG) [9] and Network analysis/science techniques permit to model, infer, simulate and predict possible events' propagation highlighting interdependencies while preventing/mitigating cascading behaviour in the complex sociotechnical systems. In this case, we have identified that state of the art FRAM models are suitable for resilience modelling but are not expressive enough for modeling large systems, and poorly connected with operational semantics.

(ii) **Evidence Driven Decision Support System (EDDSS)**. A Decision Support System (DSS) [10], [11], [12], [1] is a computer-based information system that supports organizational decision-making activities. The objective of an EDDSS is to use and provide evidences for making decisions for a problem combining human expertise communication, data and knowledge for situation awareness and decision making.

(iii) **(Big) Data Collections**, data analytics, semantic processing and mining for connecting multi-sources data flows to the models. Going beyond the theory and simulations, such a data-driven approach provides the means to assess the levels of criticality at evidence/quantitative level, while seeking to enable the capabilities of the system to take appropriate decision at strategic, tactical and operational level [13].

In this article, we present an innovative tool and solution capable to integrate resilience assessment and modelling

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[1] RESOLUTE EU Funded project www.resolute-eu.org

with the EDDSS in a powerful mean form planning, preparing, absorbing, recovering and adapting in UTS in particular and for CI in general.

The article is structured as follows. In section II, the scientific background about FRAM model is proposed. In section III, the hierarchical extension of the FRAM system modelling and computing are introduced. The extended FRAM model is supported by an innovative development and collaborative tool. Section IV shows the integrated and harmonized collaborative decision support system. Some notes on the early experimental results are reported in Section V. Conclusions are drawn in Section VI.

II. Functional Resonance Analysis Method

For city critical infrastructures, the system analysis and understanding of emergent behaviours of system interdependencies must be traced back to local operational conditions and variability. The Functional Resonance Analysis Method (FRAM) [8], [9] supports the system analysis process, aiming to identify interdependencies and system emergent behaviours potentially relevant for resilience. The approach is essentially a system-modelling tool that focuses on process interdependencies and their dynamics. FRAM is based on four basic principles:

- Success and failure are equivalent in the sense that they both emerge from performance variability.
- Variability as a way for people to adjust tools and procedures to match operating conditions.
- Emergence of either success or failure is not the direct result of variability within a given task or function, but rather to the unexpected combination of variability from multiple functions.
- The unexpected "amplified" effects of interactions between different sources of variability are at the origin of the phenomenon described by functional resonance

FRAM models can be used to investigate potential sources of variability by the modeling and identification of context dependent human, technological and organizational aspects. This approach supports the assessment of system capacities to cope with variability in view of both expected and unexpected variability emerging from system operation.

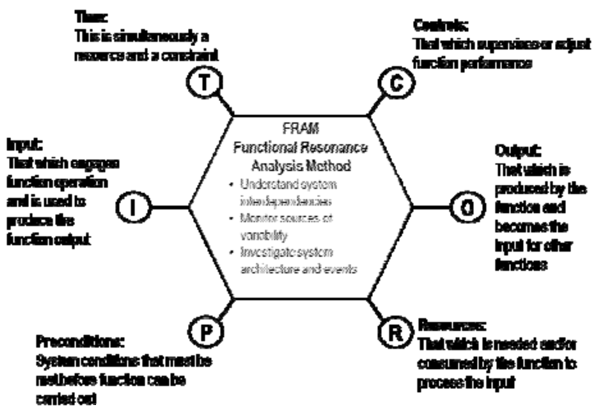

Figure 1 FRAM Function

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The graphical representation of high level function as hexagons becomes useful for the remaining steps of FRAM (**see Figure 1**). Using the six aspects of each function (i.e., time, control, output, resource, precondition and input), system interactions are studied, aiming to identify potential sources of resonance. Thus, the output of a function may be the input, a precondition or even enforce a control aspect of one or model other functions of the system. This process may also lead to the identification of possible dampening sources for undesired variability. As an example, if resources for a given function are rated as "more than necessary", it could indicate the existence of a "spare capacity" that could operate as a damping barrier. The process of investigating possible connections between functions, for the identification of both potential undesired variability sources and barriers, is referred to as an instantiation of FRAM.

III. Funtional Resonance Analysis Method – Decision Support Tool

The **Resilience Decision Support, ResilienceDS** tool is a collaborative tool extending the FRAM model for several aspects and integrating it with a decision support that can be grounded on data and experts assessment. Such tool allows modeling of a sociotechnical system and the generation of formal models for continuously assessing the CI resilience and conditions.

The state of the art of FRAM based tools is well represented by FRAM Model Visualizer (FMV) [7]. FMV is a FRAM editor that supports the FRAM model design. The FMV tool is only focused on realizing pdf documents generating the tables used to provide the descriptions of the functions and the aspects. FMV tool does not support any kind of computations or consistency check, and remain at descriptive level without providing computational aspects. Other tools, as Cambrensis [14], adopt similar approaches by adding some operational aspects with limited capabilities as described in the following.

ResilienceDS tool presents a number of improvements with respect to the classical FRAM model and FMV tool such as:

- Increasing model expressiveness by allowing the hierarchical modeling of FRAM functions, introducing the Macro FRAM Function, MFF (described in the following);
- Introducing a number of rule based formal checks to assess the completeness, consistency and the complexity of Functions, and MFF; They can be used to guide the designer and the experts to create complete and consistent modeling and dedicating more attention to more complex aspects.

- modeling the outputs of a FRAM function as a Bayesian Decision Support process. For example exploiting System Thinking (http://smartds.disit.org).
- Connecting the FRAM function output estimation on the basis of a connection to real data from the smart city and critical infrastructure data (statistical and/or real time data as well).

This set of improvements has transformed the FRAM model to an operational paradigm allowing the operational execution of the model in real time according to the changes occurring in the city on the basis of the events.

A. Smart FRAM features

In Figure 2, the ResilienceDS tool is presented showing the editor for FRAM and Macro FRAM Functions.

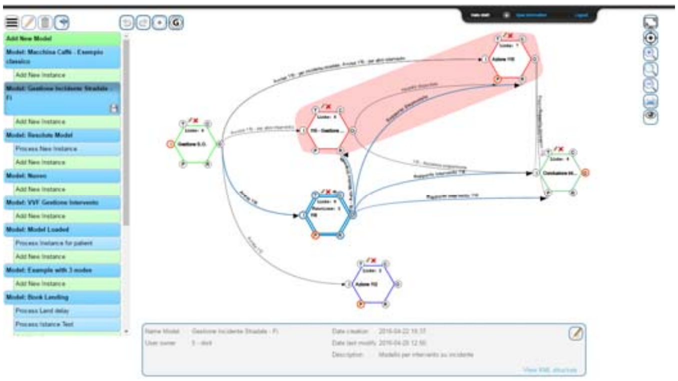

Figure 2 ResilienceDS: FRAM and Macro FRAM Function tool editor

ResilienceDS allows creating FRAM Model providing:

- a name and a description, and
- a combination of
  - (a) FRAM **Functions** as **hexagons**;
  - (b) MACRO FRAM Functions, **MFF**, as hexagons with double line border (modeling internally subgraphs of FRAM Functions as hexagons). Each Functions as hexagons presents 6 **Aspects**: P, I, O, T, C, R;
- a set of links connecting vertex of the hexagons

According to the FRAM model:

- Function Type: who makes the function, it can be a person ('Human'), a group of persons ('Organization') or otherwise a 'Technological' part.
- Potential Output variability with regard to Time: the possible values are 'Too Early', 'In Time', 'To Late' or even 'Not at All' when it's not sure that the function can complete in the expected time.
- Potential Output variability with regard to Precision, which can be: 'Precise', 'Acceptable' or 'Imprecise'. Several Outputs can be defined, and can be produced by a FRAM Function.

When an instance is created is always possible to change the model, without loss of information, except for the function eventually deleted.

Thus, ResilienceDS allows creating a hierarchical FRAM model. An ResilienceDS hexagon (Function or Macro Function) has attributes, like: the name, a description and color. Once created, the user can delete or edit it (with the pencil icon or by double clicking the function). The links can be created on the editing panel of a function or by dragging the link from the circle that corresponds to the aspect selected, to the entryway of another function. The Aspects are visualized in the screen and reported in the function's edit page, where is also possible to modify or delete them. In FRAM, each link has always a source and a target Function aspect. The only links that may provide a missing terminal are those that have to be closed with the external information. Naturally is not possible to create connection between two inputs (Like from a Precondition to a Resource) but only from an Output to one input, or vice versa. Therefor is possible that a function's Output goes into different functions or in the same but in various entries.

The ResilienceDS tool controls the model's completeness and consistency, and avoids user's distractions or other wrong behaviors, like duplication of aspects. Each function has a different identifier; also the aspects have an ID. This, fact is a major difference with respect to FMV where the links are univocally identified by their names. In our case, a link is identified by a unique number, and considering that the same link can be shared among many Functions (and Aspect), in the visualization is managed with the quadruple: {ID, source Function, target Functions, and target Aspect}. The last one is the entryway's type (Aspect) of the Function. FRAM Function vertex Output is the only source for any other five Function's inputs (Aspects) of other hexagons. So is not discriminant for linking (the source Function is always the Output Aspect).

In order to improve FRAM modeling expressivity and capability of managing complexity by using FRAM graphs, a Macro FRAM Function, MFF, concept has been created. The MFF is used to reorganize connected Functions, for example those that interest the same C.I., or which are addressed by the same organization. The Functions can be added just dragging and dropping them into the group. A MFF is like a mini-model or a macro-function that can be split in sub components. Only constraint for maintain consistency in the model is that this object doesn't have its own aspects. So when we try to add a new aspect the tool asks to choose a component of the group.

It is possible to add links between the functions included into a MFF. Those are only internally displayed. Whereas aspects that come from a function outside to another one inside the group are grouped by the Aspect selected, and shown like entering the MFF/group, though the groups don't have its own aspects. Once created the user can edit and delete MFFs.

The attributes of MFF are: *name*, *description* and *color*. Inside a MFF it is possible to have functions but also other MFF as well. This implements a **multi level hierarchy** in the model. As a constraint, an MFF can belong to at most one other MFF and it can't be inside two different on the same level. The result is a simplified view, but at any time is possible to show the functions inside a MFF/group without deleting it, just clicking on the eye icon over the relative hexagon. The models created are saved on the server and can be edited by the creator and shared among the users.

For each ResilienceDS model is possible to create one or more **Instances** by providing real values and parameters. An instance is a real implementation of the model where is possible to figure out behaviors, errors and analyze resonance among the functions. Each function can be edited for set the type of variability.

According to the ResilienceDS model, extending the FRAM classical model, each Output process can be operationally computed on the basis of a computed function on the basis of the Function inputs. In Cambrensis tool, a FRAM model is proposed with structurally predefined Bayesian model imposed [http://www.cambrensis.org] [14] thus limiting the expressivity of the possible output kinds. In ResilienceDS, each process is modeled by means of SmartDS.disit.org process, that adopt an extended System Thinking Approach [1].

The ResilienceDS tool provides the options for: view in full screen the graph, center the model at the origin, zoom in, out and reset the visualization (this is also possible scrolling the mouse's wheel), print the current model and show/hide the aspects for focus only over the functions. In the bottom menu are reported the model's information: name, description, user owner, creation and last modify date. From there is possible to edit the model info and view the XML structure (The information sent from the server to the client when the model is requested). When a model is request to be shown, from the top menu is possible to: edit the model, delete the model and import a new FMV model to modify or test. While editing a model, appear a top menu that allows the user to undo and forward the basic operations (Precisely: add and remove of functions, add, remove and modify aspects, add and remove a group, and add and remove functions in groups). Whereas over the functions there are the options for editing, deleting and, for the group, show the elements in. Finally, there are also mouse triggers to speed up the user modeling experience, like: focus a function connection with mouse over, focus the extreme of an aspect with mouse over the label, edit functions and groups with double click and creating aspect with just the drag from the hexagon vertices. The tool provides the management of multiple users. For that is possible to register new users, login/logout with the own account, or access as a guest for view available models.

IV. EVIDENCE DRIVEN DECISION SUPPORT SYSTEM TOOL: MODEL & IMPLEMENTATION

The SmartDS is an EDDSS component has been designed [1] and integrated with the aim of assisting decisional processes in a light collaborative environment for decision makers.

The two main functional entities the system operates with are called *models* and *instances*. The term "model" identifies the set of decisional criteria, defined by decision makers according to the System Thinking paradigm, focusing on the *Analytical Hierarchical Process* (AHP), which models the problem to be solved as a hierarchical decision tree composed by different levels (with the root identifying the Goal to be achieved). The AHP paradigm has been integrated with the *Italian Flag* (IF) representation structure. The IF representation is a three-values logic used to measure uncertainties, and it has been considered to be an appropriate integration to the proposed solution, since the system can receive input data from different sources, including feedbacks and opinions from users, citizens and experts (which may often deal with uncertain responses, not clear opinions etc.). Defined in this way, a model represents only the hierarchical decisional structure with no data assigned to nodes or arcs.

On the other hand, the term "instance" identifies a model filled with data (represented by IF values and priority weights defined for each decisional criterion, as better described in the following), which are required to calculate the final decision result. The tool provides two main ways to define instance values: decision makers can manually fill statistical values derived from users' interviews, opinions, rates, feedbacks etc.; in addition, the tool allows to estimate statistical data by querying external relational databases, as well as semantic knowledge bases, such as Smart City ontologies and Linked Open Data (in order to better react to real-time events and dynamically adapt to different contexts).

The tool offers a collaborative solution, with the possibility to share, reuse, clone and modify models, as well as creating different instances of the same model.

A. Modified AHP Model – Italian Flag

The first step in the decisional process development is the definition of the model by decision makers. As mentioned in the previous subsection, the model is represented as a hierarchical tree composed by different levels. At the top of the hierarchy there is the Goal, which is the root of the decision tree. The nodes belonging to the first level under the Goal represent the decisional criteria which have been defined to achieve the goal. Lower level nodes can describe sub-criteria, as well as properties of corresponding upper level criteria. All the decisional criteria and their inner hierarchy are defined by decision makers.

The next step is the assignment of weights to each node. Such weights are defined as priority values (their sum, calculated for all criteria belonging to a same level, yields 1). In order to estimate priority weights, a set of pairwise comparison matrices is built, one for each level. For every single level, its decisional criteria are compared in pairs using the Saaty's scale [2]. This rating scale assigns integer values from 1 to 9, according to the relative importance between the compared elements. The procedure of pairwise comparison matrix generation, oriented to priority weights calculation, is described in more detail in Section D.

As earlier mentioned, the IF representation is a three-values logic which extends the concept of the traditional two-values logic by providing also a measure of uncertainty, as often encountered in users' rates, surveys and interviews [3]. In such contexts, the belief that an event may occur or not, or that a generic proposition may be true or false, can be only partial, so that some level of confidence is assigned to an uncertain state. By this way, given a generic proposition or event *E*, its occurrence probability *P*(*E*), and the probability against its occurrence *P*(*not*(*E*)), we can define the measure of uncertainty as 1 – *P*(*E*) – *P*(*not*(*E*)). IF is a graphical representation of the above defined triple form [*P*(*E*), 1 – *P*(*E*) – *P*(*not*(*E*)), *P*(*not*(*E*))], where *P*(*E*), 1 – *P*(*E*) – *P*(*not*(*E*)) and *P*(*not*(*E*)) are depicted as green, white and red bars respectively, as illustrated in Fig. 3. A compact way to represent the IF record is to indicate explicitly the interval [*P*(*E*), 1 – *P*(*not*(*E*))]. In the following, we will use the notation: $g = P(E)$, $r = P(not(E))$ and, consequently, $w = 1 - (g + r)$ to define the green, red and white probability values, respectively.

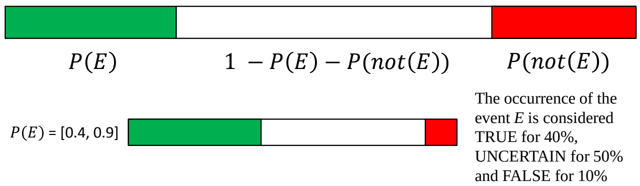

Figure 3 Three-value logic IF representation for a generic proposition or event E with some examples explained

A general schema for the modified AHP model, including the IF representation, is shown in Fig. 4.

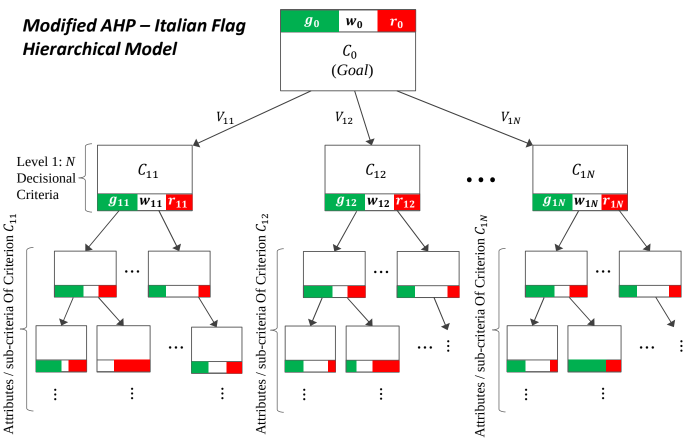

Figure 4 General schema of the modified AHP hierarchical model integrated with IF representation

B. Generation of Model Instances

Once the modified AHP-IF model is created, decision makers can create an instance of a defined model, by filling the nodes with IF values that can be gathered from the following different sources:

1) Data from external semantic or relational database interrogation: in this case, the system allows to represent the conditation of a generic decisional criterion as a query to an external RDF semantic repository (by providing valid SPARQL endpoint URLs in a proper field of the user interface), as well as to a generic SQL relational database. As an example, decision makers and critical infrastructure managers could be possibly interested in taking decisions based on static and real-time data provided by public administrations, (such as traffic flow, number of available parking lots, and many other kinds of data gathered from sensors etc.), organized in a semantic knowledge base which can be accessed and queried by the proposed DSS tool. Each query yields numerical results, and the decision makers can logically combine up to two queries for eahc single node, whose results are numerically compared to threshold values defined by decision makers.

2) Data coming from opinions and feedbacks gathered by interviewing selected stakeholders, critical infrastructure managers, public administrations or citizens groups. Opinions are directly mapped into IF values, assigning to the green value the percentage of opinions in favor of the considered criterion, to the white value the percentage of uncertainty opinions (as well as answers not provided), and to the red value the percentage of opinions against the condition.

3) Manual entry data: this kind of data is usually represented by manually filled IF values, on the basis of decision maker's personal experience and expertise.

C. Pairwise Comparison Matrix and Priority Weigths

At this stage, the weights associated to each criterion of the decisional tree, $C_{\tilde{l}1}, \dots, C_{\tilde{l}N}$ have to be estimated. This is done by using the evaluation matrix, whose single elements are obtained by pairwise comparisons of the decisional criteria. Considering a generic level $\tilde{l}$ of the hierarchy, composed of *N* criteria , the pairwise comparison matrix is defined as:

$$P_{\tilde{l}} = \begin{bmatrix} p_{11}^{\tilde{l}} & \cdots & p_{1N}^{\tilde{l}} \\ \vdots & \ddots & \vdots \\ p_{N1}^{\tilde{l}} & \cdots & p_{NN}^{\tilde{l}} \end{bmatrix}$$

where elements p_{ij} are the Saaty's scale values for comparison between criteria. Among the properties of the pairwise comparison matrix *P*, its symmetrical elements stand in a reciprocal relationship (which is in agreement with the Saaty's rating scale):

$$p_{ij}^{\tilde{l}} = \frac{1}{p_{ji}^{\tilde{l}}}, \qquad 1 \leq i, j \leq N$$

Subsequently, a normalization by column is made over *P*, thus obtaining the $P_{\tilde{l}}$matrix. Keeping the assumption to have *N* nodes at level $\tilde{l}$, the $\hat{P}$ matrix is defined as:

$$\hat{P}_{\tilde{l}} = \begin{bmatrix} \hat{p}_{11}^{\tilde{l}} & \cdots & \hat{p}_{1N}^{\tilde{l}} \\ \vdots & \ddots & \vdots \\ \hat{p}_{N1}^{\tilde{l}} & \cdots & \hat{p}_{NN}^{\tilde{l}} \end{bmatrix} = \begin{bmatrix} \frac{p_{11}^{\tilde{l}}}{\sigma_1} & \cdots & \frac{p_{1N}^{\tilde{l}}}{\sigma_N} \\ \vdots & \ddots & \vdots \\ \frac{p_{N1}^{\tilde{l}}}{\sigma_1} & \cdots & \frac{p_{NN}^{\tilde{l}}}{\sigma_N} \end{bmatrix}$$

where:

$$\sigma_1 = \sum_{k=1}^{N} p_{k1}^{\tilde{l}}, \ldots, \sigma_N = \sum_{k=1}^{N} p_{kN}^{\tilde{l}}$$

$$V_{\tilde{l}1}, \cdots, V_{\tilde{l}N}$$

Priority weighs are finally obtained by computing the arithmetic mean over the rows of the normalized matrix: $\hat{P}$

V. EXPERIMENTAL RESULTS

The approach proposed of adopting ResilienceDS has been experimented on the data related to the smart city of Florence. As a first step, according to the RESOLUTE H2020 EC project, the FRAM model for implementing the European Resilience Management Guidelines for Urban Transport System have been modeled and declined in Florence conditions. The model can be accessed from Http://www.disit.org/fram using "guest, guest" as username and password. The second step has been to implement some of the decision supports as SmartDS processes [1] (similar user name and password on http://smartds.disit.org). Some of those processes depend from their computability from the data accessible on Km4City platform as well as on the open data and real time data in Florence. The *Km4City* [13] ontology, designed and developed at our DISIT Lab is used for gathering Smart City data. The system may query different repositories for each process/criterion. As a first result, it has been possible to monitor the trend of relevant data and function on the Firenze Dashboard on which also the SmartDS processes are modeled (http://www.disit.org/dash).

VI. CONCLUSIONS

The combination of an extended FRAM builder tool and SmartDS into a unique integrated tool as ResilienceDS represents a powerful and the all-in-one solution for managing resilience of Critical Infrastructure as UTS. Such a new tool allows modeling, monitoring and suggestions for actions at the same time. In fact ResilienceDS allows the function variability analysis exploiting the data driven decision process of Smart DS. ResilienceDS adopts a highly synergic approach towards the definition of a resilience model for the next-generation of collaborative emergency services and decision making process. Within this framework, it can be stated that the pursuit of RESOLUTE H2020 objectives faces the challenge of relating dynamic and emergent system features, to a wide diversity of human, technical and organisational elements that at each time and place, generate equally diversified operational needs.

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