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Decision support system for smart urban management: resilience against natural phenomena and aerial environmental assessment

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ABSTRACT

A new concept of Decision Support System (DSS) is presented. It is able to account for and support all phases of the risk analysis process: event forecast, prediction of reliable and accurate damage scenarios, estimate of their impact on Critical Infrastructures (CI), estimate of the possible consequences. It also provides an estimate of the consequences in terms of service degradation and of impact on citizens, on urban area and on production activities, essential for the mitigation of the adverse events. It can be used in two different modes, either in an operational mode (on a 24/7 basis) or in a simulation mode to produce risk analysis, setting up synthetic natural hazards and assessing the resulting chain of events (damages, impacts and consequences). Among the various possible external data sources an aerial, drone based one is presented. The system may capture both thermal and visual images of CI, processing them into 3D models or collect chemical pollutants concentrations for the monitoring of dangerous air quality due to catastrophic events such as volcano eruptions or large fires. The obtained models and the chemical data can be easily displayed within the framework of the DSS.

Keywords:

Decision support systems;
Structure from motion;
Resilience;
Natural hazards;

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1. Introduction

Decision Support Systems (DSS) are complex technological tools, which enable an accurate and complete scenario awareness, by integrating data from both the surrounding environment and the behaviour and functional state of the technological systems, in a way similar to [1]. One of the aims is to produce a scenario analysis and to identify the most efficient strategies to cope with possible crises. In the domain of Critical Infrastructures (CI) protection [2, 3], DSS can be used to support strategy elaboration from CI operators, to improve emergency capabilities and to support preparedness actions [4]. The set of CI constitutes an enabling pillar of societal life in an urban area [5], it guarantees the supply of vital services (e.g. electric distribution, water supply, etc.) thus concurring to citizens well-being. CI are complex technological systems, vulnerable as exposed to natural and anthropic-related events. Physical damages inflicted to CI might produce severe repercussions on their functionality reducing (or even annihilating) it [6]. Moreover, CI outages might produce environmental damages that further worsen the consequences.

DSS could have a critical role in assessing the risk of CI and in enabling asset managers to perform scenario analysis aiming to: i) compare repair/reconstruction strategies; ii) assess risks to mitigate impacts; iii) support the business case for investing into resilience.

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Areti is one of the main Italian electric operators, with about 10 TWh of electricity distributed in Rome, where it manages the electricity grid serving over 1.6 million delivery points. According to our experience and know-how, the applications described in the present paper can be very useful, especially in order to improve the procedures and the processes related to planning and maintenance, and aiming at a prompt and effective risk-based management of the electric network. Moreover, taking into account the increasing demand in terms of service continuity, the applications proposed allow to deal with various issue, such as the stringent requirements arising in complex contexts (e.g. a metropolitan area like Rome). Another added value, compared to similar applications, is the capability to integrate different (interdependent) assets in relationship to the electric system.

Dr. Eng. Silvio Alessandroni, Head of Automation and Innovation Technologies for the Network - Areti (Acea)

The international literature describes several efforts towards the creation of software frameworks for the assessment of risk of CI networks [7, 8]. In most cases the efforts were not directed toward the creation of a user-friendly and ready available DSS to be used by asset managers and local authorities. The American Lifeline Alliance [9] defined guidelines and accompanying commentaries to provide a multilevel process to assess the performance of CI systems in natural hazards and human threat events. In Europe, the EU-funded SYNERG-G project, developed an integrated methodology and a software tool, referred to as OOFIMS Object-Oriented Framework for Infrastructure Modelling and Simulation for the systemic seismic vulnerability and risk assessment of complex systems [10].

One of the main differences with similar applications or platforms, is that the here described DSS has been conceived and developed for a multi-hazard risk analysis (earthquake, flooding, extreme weather, etc.), implementing both a real time operational mode (24/7 monitoring) and a simulation mode (e.g. stress-test analysis). Existing DSS are usually specialised for a single hazard type and/or for a specific operational mode (real time or simulation).

The set-up and implementation of new applications is a crucial initiative. There is an ever-growing belief that prediction and proper preparation to face adverse events can actually produce substantial benefits. This is the spur at the basis of a complex DSS as the CIPCast, here described. A comprehensive worldwide overview of similar approaches, systems and platforms can be found in [11].

The CIPCast is a new concept of DSS [12], which is able to account for and support all phases of the risk analysis process: event forecast, prediction of accurate damage scenarios, estimate of the impact that expected damages could have on CI service and estimate of the possible consequences. A DSS should also support the identification and definition of preparedness and emergency strategies that could be adopted to reduce the impact, speed-up the mitigation and healing procedures, ease the recovery phase, thus reducing the extent, the severity and the duration of the crisis. A preliminary implementation of such issues has been successfully performed, by developing a specific CIPCast tool (RecSIM), which can be used as effective simulator to perform comprehensive *stress tests* [13].

Besides, the use of aerial systems for the collection of thermal, visual and chemical data can be a useful source of knowledge for several aspects of the scenario. The visual and thermal data can be helpful for the monitoring of CI, also through the 3D modeling of the infrastructure [14, 15], before crisis, for early warning, e.g. for the individuation of electrical problems in power substations. The environmental monitoring in terms of chemical pollutants can be valuable for the modeling of chemicals or particulate matter diffusion during crises such as large fires or volcano eruptions.

In section 2 the CIPCast system is described in detail highlighting the capabilities and features of the system, in section 3 the problem of resilience of CI against natural phenomena such as heavy weather is outlined and two operative examples of the use of the system given. In section 4 an example of data collection is described in two possible scenarios, the elaboration of image sequences into 3D models to be stored and displayed in the DSS for the monitoring of CI in normal conditions and the use of chemical data to compute possible scenarios of particulate diffusion, in the last section some conclusions are drawn.

2. Methodology and CIPCast in general

The CIPCast was conceived as a combination of free/open source software environments including GIS features (GFOSS) [16, 17]. GIS technologies, among other applications see e.g. [18] in this issue, are suitable for supporting risk assessment and emergency management tasks in case of natural hazardous events [19], multi-source data and GIS analysis provide fundamental information for immediate response [20]. The CIPCast DSS is capable of providing a user-friendly geographical interface, by means of a specific WebGIS application, for querying and analysing data and thematic maps, produce and evaluate scenarios, etc., based on specific GIS and SDI (Spatial Data Infrastructures) architectures, developed using GFOSS packages.

On the basis of the knowledge of the location of the CI elements, CIPCast produces an expected damage scenario by assessing the possible degree of damage, depending on the type of event expected (and its intensity), and the specific vulnerabilities of each individual infrastructure element. In addition it evaluates the impact that the computed damage(s) will cause on the infrastructure as a whole and on other infrastructures functionally linked to the one directly affected (through the so-called "domino effect"). Thus it provides an estimate of the consequences over the urban area, in terms of service degradation [21].

Figure 1 shows the main functional blocks of CIPCast and the relevant components. The platform gets external data from many different sources (e.g. meteo/hydrological models), to establish the current conditions. Then, estimating the expected strength of events, it elaborates a damage scenario, by correlating the strength with the vulnerability of the different CI elements. Expected damages to CI elements are converted into outages of the service. A final step is devoted to inform and support the response, by allowing testing and comparing different strategies for restoring the service by prioritising repairs and deploying physical resources and technical crews [12].

The logical and physical components of the CIPCast architecture, as well as the data workflow, are depicted in the high-level schema reported in Figure 2.

The WebGIS front-end (Figure 3) allows the users to access the available services and the related data through a web browser. In such a way, the user can use thematic maps, charts and other available results (e.g., scenarios).

CIPCast has been designed and implemented to work both in an *operational* mode (on a 24/7 basis, as an alert system) and also in an *off-line* mode by simulating events. In the latter case, the DSS can be exploited as a *stress tester* enabling to set-up synthetic natural hazards (e.g. earthquakes) and assessing the resulting chain of events [22].

Different steps are necessary for estimating induced damage, functional impacts and consequences for infrastructures,:

1. hazard assessment: acquisition, prepocessing and elaboration of input data;

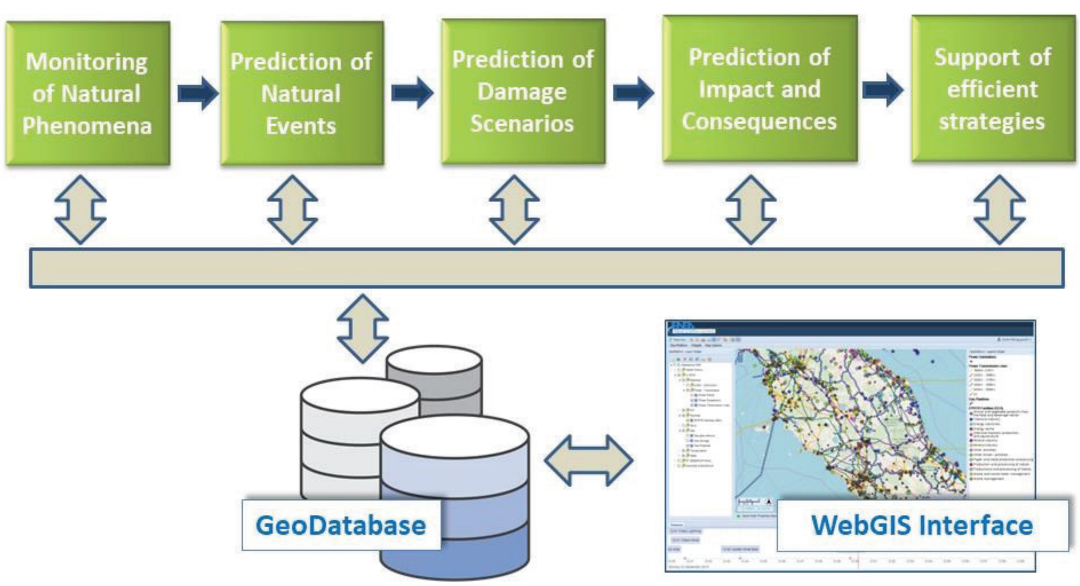

Figure 1: CIPCast workflow and functional blocks [12]

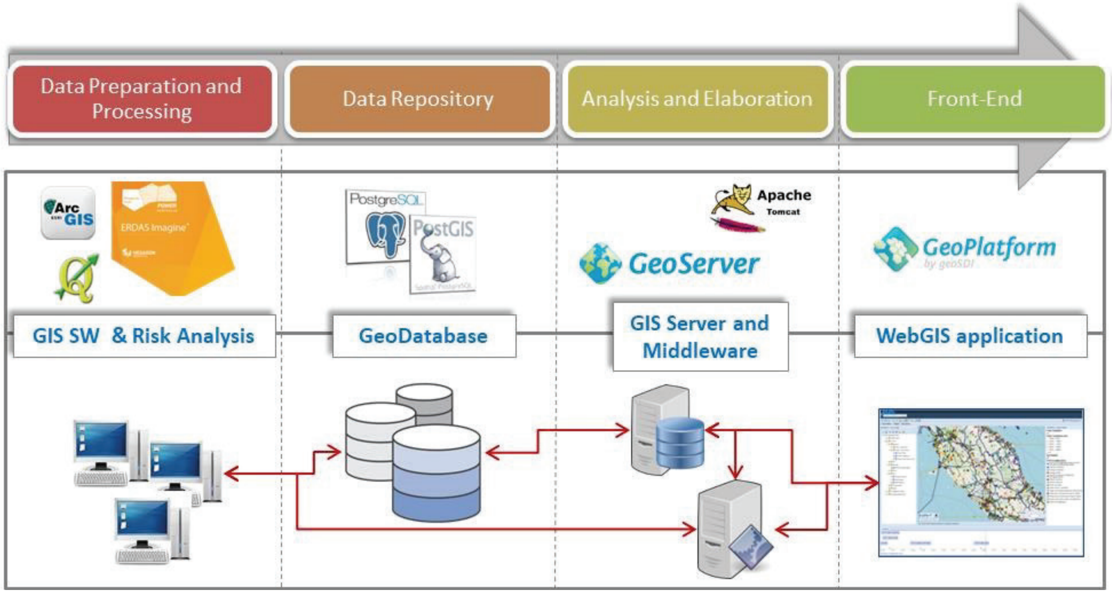

Figure 2: CIPCast architecture high-level schema

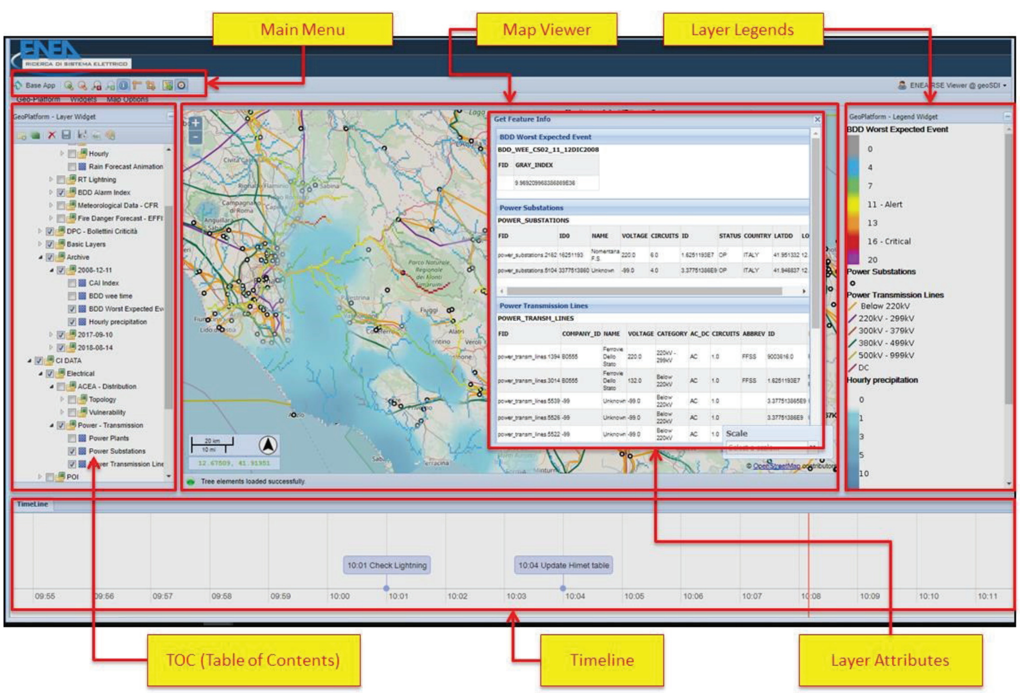

Figure 3: CIPCast WebGIS interface: example of layout

2. classification of infrastructure components;
3. physical damage and functional impact metrics;
4. damage assessment (appropriate hazard-damage relationships);
5. system performance assessment: residual performance of the whole infrastructure;
6. service restoration assessment: repair and service restoration timeframe.

3. Hydrological forecast applied to urban resilience

The Hydrological warning system discussed in this paper is based on the activities carried out with Cetemps Hydrological Model (CHyM). This model has been developed since 2002 in the Cetemps Centre of Excellence of University of L'Aquila with the aim to provide a suitable and adaptable operational tool for flood alert mapping. CHyM is a physical-based model, all the physical processes contributing to the hydrological cycle are explicitly parametrized. All the variables needed for the hydrological forecast are defined on a regular grid; the typical horizontal resolution for applications over the Italian peninsula ranges from few hundreds of meters to few kilometres. The model has been used in the last years for hydrological simulations both at meteorological [23, 24] and climatic [24] time scale.

Two main features of the model makes it very fitting for the application discussed in this paper: the possibility to run hydrological simulations in any geographical domain with any spatial resolution and the implementation of a native algorithm [26] allowing to ingest and merge on a regular grid, different sets of precipitation data.

A very critical aspect for flood alerting deals with establishing a discharge threshold above which severe hydrological event is expected; of course such threshold level also depends on the specific geomorphological characteristics of each segment of the drainage network. In order to find an efficient numerical approach, a large number of case studies has been simulated and analysed leading to the definition of two different flood alert indexes to map the segment of drainage network where severe hydrological events are expected.

A first index, CHyM Alarm Index (CAI), is an empirical index obtained by the comparison between the total precipitation available for runoff drained by each elementary cell and the cross section of the river channel for the selected cell; the latter quantity being considered a linear function of the total drained area. CAI index is therefore calculated as the ratio between the total drained precipitation and the total drained area; the precipitation is considered in a time interval of n hours, being n the average runoff time for the considered upstream basin.

A further more deterministic alarm index, based on the predicted discharge, is the Best Discharge-based Drainage (BDD). It is defined, for each grid point of the simulated domain, as the ratio between the maximum value of expected discharge in a given time interval and squared of hydraulic radius for the channel contained in the elementary cell; the latter quantity being an estimation of the river cross section in the selected cell.

These indexes have been validated and calibrated during a long operational activity for flood alert mapping carried out for the whole Italy in the last ten years, establishing threshold levels for BDD and CAI above which hydrological stress has to be expected. The final product is a graphical mapping of the drainage network where the segments of the network for which the alarm indexes are above the alarm level are highlighted; see the central panel of Figure 4.

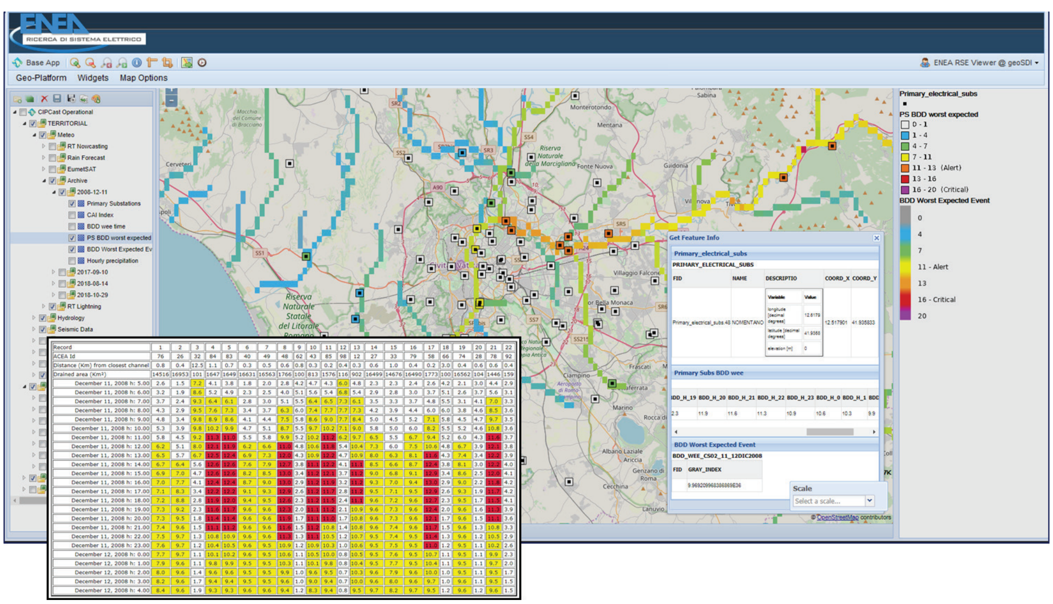

Figure 4: CIPCast WebGIS interface: example of visualization of meteorological forecast (rainfall and flood hazard) overlaid to Electric Distribution Network Primary Substations

For the application described in this paper, the alarm indexes are also specialized to highlight possible critical hydrological stress for each CI element. Basically it is assumed that, for each CI, the main hazard source is represented by the closest channel point within the CHyM grid; the CAI and BDD for that cell are then considered an estimation of stress for that asset. The output consists in a table where, for each CI element, the predicted time series of stress index is given. An example of such tables is reported in the lower panel of Figure 4.

In order to provide to CI operators an objective validation of the proposed alarm system, the operational output has been reproduced for several case studies characterized by severe meteorological events affecting the Tiber basin and the surrounding area in the last years, with different meteorological situations and occurring in different seasons. A summary of these events, for what concerns the total accumulated precipitation, is reported in Figure 5, while the complete list and all the results obtained for each case study are available starting from the URL: http://cetemps.aquila.infn.it/chym/rse/cs.html.

Concerning the daily operational activities, CIPCast gathers external data about rain precipitation forecast in a specific area within a specified interval. CHyM model runs simulations every day at about 2 a.m., and makes available all the numerical and graphical outputs in the early morning hours. These simulations cover a period of time that goes from 96 hours before the start of the simulation, up to the following 24 hours. The results are produced both in graphical (NetCDF) and numerical format (data sources, precipitation rates and evolution, hydrological alarm indices, etc.). Data about forecast precipitation are provided as a sequence of 24 maps covering, with hourly time resolution, the whole *current* day starting from midnight. All files with rainfall data and hydrological indices are then automatically acquired by CIPCast to be exploited by the DSS processes and to be usable through WebGIS interface.

In particular, meteo/hydrological indices are useful to early assess flooding hazard where CI elements are located (Figure 4). Thus, in case of possible hazardous event, the DSS evaluates the damage that the assets (e.g. CI specific elements) are likely to undergo. CIPCast provides an initial damages scenario describing the affected CI components and the damage extent. Estimates can be done either by using historical data or a vulnerability assessment. In such a way, CIPCast, by a tight collaboration with CI operators, can provide impacts on their infrastructures. In addition and in perspective, CIPCast can support all the players involved in the operations, from CI operators to Civil Protection, in order to allow them to have a coherent set on information on which they could properly elaborate mitigation or maintenance strategies and, whenever the case, emergency plans.

As an example of DSS usage, two different applicative cases are described below.

In the first case, an a-posteriori simulation of an extreme weather event striking the electric distribution network was carried out, in order to produce an expected damage scenario and check it against the actual event outcome. This has also allowed to calibrate the hydrological alarm indices (CAI and BDD) and properly define the thresholds. To this end, the CAI and BDD

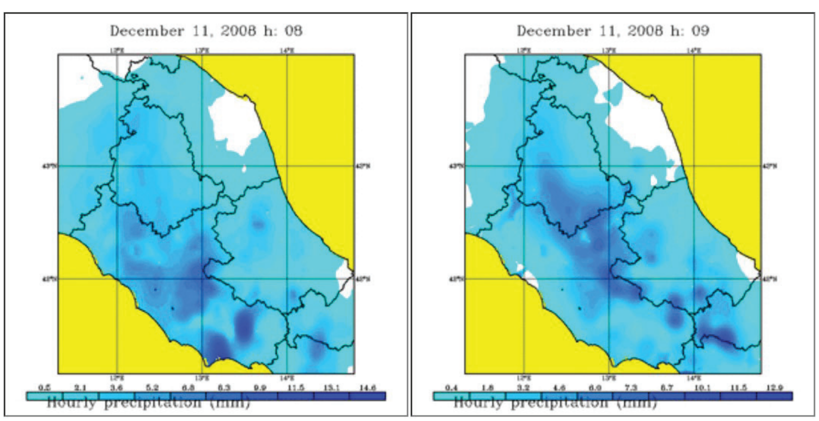

Figure 5: Summary of the total accumulated precipitation for the case studies of December 11, 2008 (left), and December 11–12, 2008 (right)

have been specialised to a set of specific sites that Areti (the branch of ACEA Spa holding, which manages the electric distribution network in the area of Rome) considers as relevant and strategic for the robustness of the electric grid and the services continuity. The alert levels and thresholds were calibrated and validated by simulating a severe event, selected from those that in recent years (2008–2014) affected the area of interest. Hydrological alarm indices were spatially correlated to the location of specific Areti assets (e.g. Primary Substations, PS, of Medium Voltage, MT, network, Figure 4), which are critical elements as they represent the interface between transmission and distribution grids. Possible expected alerts, are highlighted in the table of Figure 4, in yellow or red colour, indicating when CAI/BDD thresholds are expected to be exceeded, impacting the PS monitored (represented with black dots in the DSS GIS interface).

The second applicative case is related to the exploitation of the DSS in real time operational mode, during a different extreme weather event, occurred in fall 2018, when the DSS was actually running. The DSS capability to manage the scenario elaboration and the alarm dispatching towards the CI operator (i.e. Areti) was tested. From the post-analysis, has emerged how the approach was effective for real time operational purposes. In particular, BDD and CAI indices have exceeded their thresholds (indicating a potential critical situation) in correspondence of areas where hydrological criticality actually occurred.

In both cases, the results obtained has shown how the DSS has been able to predict the expected scenario, providing early alerts and highlighting the segments of the drainage network that may represent situations of possible hydrological or hydraulic risk on specific electric grid elements.

4. Data collection

As described in section 1, the DSS can be easily interfaced with several genres of data producers e.g. weather forecasts, infrastructure locations, etc.. In the following, as an example, is presented an aerial monitoring data producer. This system can perform two different tasks: either the thermal and image assessment of buildings, or the measurement of the levels of some air pollutants. From the point of view of the DSS, the first activity may be useful for the monitoring of CI for early warning, while the second can yield measurements for the modeling of chemicals or particulate matter in fires or volcano eruptions.

The aerial system is conceived as a portable and easily deployed one used for local monitoring, the locality of the produced data is a direct consequence of the legal aspects subtended to the use of remotely piloted aerial systems (RPAS) [27]. The pilot is obliged to have the drone in line of sight, prohibiting any kind of vehicle autonomy and limiting *de facto* the geographical extension of the collected data.

The heterogeneous data collected by the RPAS are to be furnished to the DSS in order to have it easily available for the user. The amount of data in the first case is quite large being composed of thermal and HD images and videos, thus a data processing pipe has been set up to reduce the data to a more compact description. The resulting representations are two 3D models, fusing the images in a single entity: a visible spectrum 3D model for the structural analysis of the building and a infrared one to check for itsthermal signature. On the side of the chemical monitoring the data are not processed being a series of records arranged in a limited number of real values and their georeferentiation.

Structure from motion

The algorithms of the structure from motion (SFM) family belong to the photogrammetry science, which performs measurements from images, typically from airborne cameras [28]. SFM is a technique used to estimate 3D structures from a sequence of 2D images either collected by a single moving camera or by a set of cameras from different points of view. The key point of these algorithms is the triangulation of corresponding points across different images. This approach is computing intensive and has found a recent success with the introduction of powerful processing units such as the graphical ones (GPUs).

A paramount importance resides in the algorithm used to extract candidate points from images, the method mostly used is the scale invariant feature transform (SIFT). It uses a vector of image features which are invariant to translation, rotation and scaling and partially invariant to illumination changes, which are then matched against those coming from the other images in terms of Euclidean distance [29, 30].

Once that the correspondences are found, it is possible to compute the so-called fundamental matrix, i.e. the transformation from the point of view of the camera in one image to the one in a different image and thus the

3D content of the scene. If there are more than two images, the subsequent images are iteratively aligned to the already computed set. This cloud of 3D points is then input to the bundle adjustment algorithm [31]. This is an optimisation operating on a very large number of parameters at the same time, i.e. the camera and 3D point positions, repeated over time in the SFM algorithms. It tries to minimise the total reprojection error.

At the end of the optimisation we end up with a cloud of 3D locations representing the features location; an interpolation is then performed in order to obtain a smooth, hole free surface, usually using Poisson surfaces [32]. The last step is represented by the meshing, i.e. the geometrical description of the surface by use of small triangles and finally its texturisation with the color information of the original images.

At the end of the procedure a model in the form of a PLY file (PoLYgon file format) is obtained. This kind of file can be visualized using most of the 3D visualisation software.

There are several different available SFM softwares that can be used, they can be coarsely divided into commercially available and open source ones. The open source solutions come from academic institutions and are usually difficult to use, but, at the same time, open. The market solutions also come from the academic world but through small spinoff companies, they are usually expensive since are targeted to professional use and are closed. There are several scientific papers comparing the two, e.g. [33], whose conclusions are that the results obtainable both with the academic or the commercial solutions are similar, depending on the single application. Naturally the commercial software is much easier to cope with and furnishes a customer support, but often the academic one is more advanced on the technological side but with a more complex interaction. A note: at least in one case it has been checked that the names of the temporary files produced by a commercial software are almost indistinguishable from those of an open source one, testifying that the professional solution makes use of the open source one, at least partially.

In this work the chosen open source solutions are represented by MicMac [34] and Colmap [35]. The first has been developed by the ENGS (Ecole Nationale des Sciences Geographiques) and the ING (Institut National dell'information Geographique et forestiere), both French and the second by the ETH (Eidgenössische Technische Hochschule, Zürich) and the University of North Carolina (Chapel Hill). In a nutshell MicMac is more powerful but more difficult to interact with, while colmap is window based and more friendly; the results are more geometrically precise on the MicMac side but at the price of sparseness, while Colmap produces smoother surfaces with less holes, see Figure 6. The software has been uses "as is" except for a mild pre processing of thermal images in order to enhance image sharpness and dynamics for a better effectiveness of the matching.

Display

In the DSS the user should be able to display the resulting 3D models with ease. To this end it has been implemented a HTML web page to visualize the models, that can be invoked directly from the DSS. It is based on three.js [36] a JavaScript library that can work in several browser, able to create and animate 3D graphics in a web page without the use of browser plugins, but only using WebGL a JavaScript API for graphical rendering, working directly in hardware on the client side.

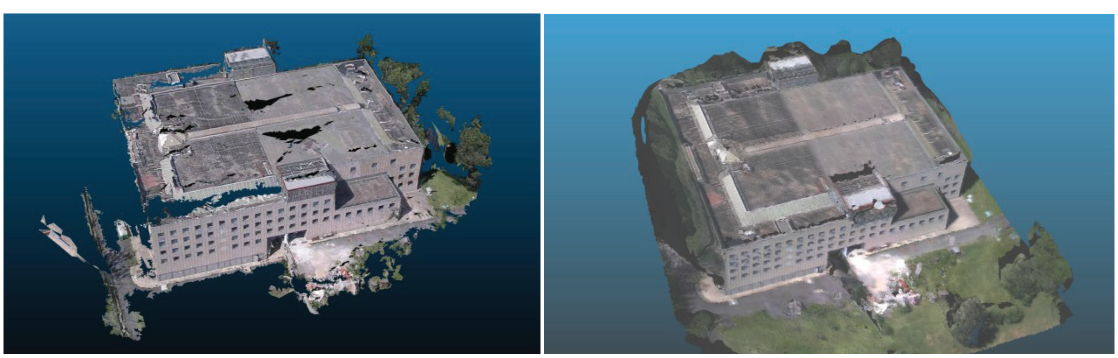

Figure 6: A comparison of MicMac on the left and Colmap on the right

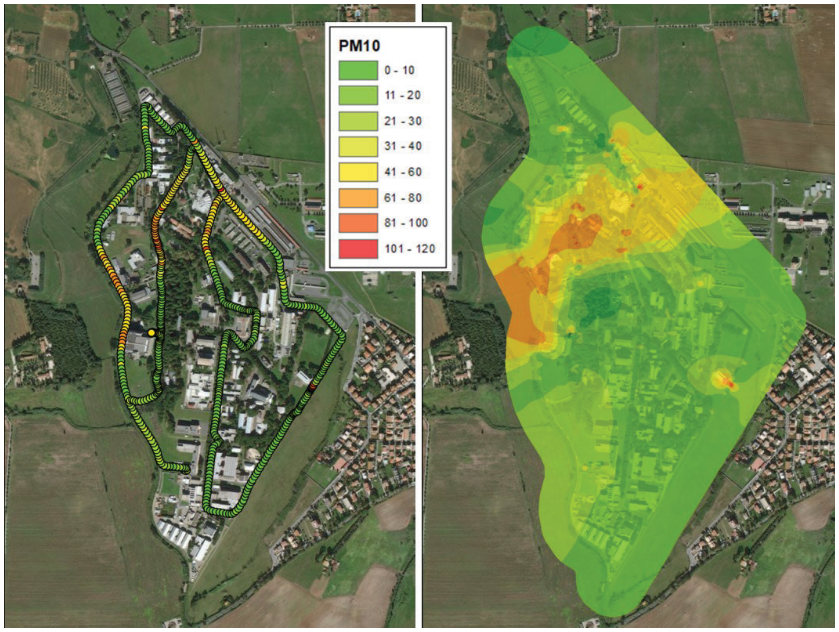

Figure 7: The interpolation of particulate content data (left) by the DSS into a diffusion map (right)

From the side of the chemical measurement, in Figure 7 is shown an example of interplay between the aerial system and the DSS. It can be seen how on the basis of the values of particulate matter (PM10) measured by the system, the DSS may interpolate them to offer a prediction of diffusion in space useful for issuing warnings in the area. Specifically the source of pollution was a bonfire of garden waste and the measurements are the coloured dots on the map.

5. Conclusions

To achieve the goal of creating a user-friendly and ready available DSS to be used by CI asset managers, local authorities and civil protection departments, ENEA has designed and developed (in the frame of EU/Italian-funded projects) a specific DSS platform, namely CIPCast, which enables to operationally perform risk assessment on CI for different kind of natural hazards, allowing to receive external data and to integrate applications enabling data analysis and decision making actions [37]. As an example of external data collection a procedure for the elaboration of image sequences into 3D models and of the processing of chemical pollutant data have been presented. The obtained models can be displayed within the framework of the DSS and exploit the DSS capabilities for data elaboration.

CI operators and managers can take advantage from such new concept of DSS, capable to account for and support all phases of the risk analysis process: event forecast (when applicable/predictable), prediction of reliable and accurate damage scenarios, estimate of the impact that expected damages could have on CI service (service reduction or loss), estimate of the possible consequences [38].

In perspective, such a kind of DSS will also support the identification and definition of preparedness and emergency strategies that, taking into account the different phases of the expected crisis (event, damage, impact and consequence), could be adopted to reduce the impact, speed-up mitigation and healing procedures, ease the recovery phase, thus reducing as much as possible the extent, the severity and the duration of the crisis.

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References

[1] Heinisch V, Göransson L, Odenberger M, Johannson F. A city optimisation model for investigating energy system flexibility. Int J Sustain Energy Plan Manag 2019;24. http://doi.org/10.5278/ijsepm.3328

[2] CIPedia© - Wikipedia-like online community service focusing on Critical Infrastructure Protection (CIP) and Critical Infrastructure Resilience (CIR)-related issues http://www.cipedia.eu

[3] Council Directive 2008/114/EC of 8 December 2008, http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32008L0114

[4] Rosato, V., Di Pietro, A., La Porta, L., Pollino, M., Tofani, A., Marti, J.R., Romani, C.: A Decision Support System for Emergency Management of Critical Infrastructures Subjected to Natural Hazards. In: Critical Information Infrastructures Security: 9th International Conference, CRITIS 2014, Limassol, Cyprus, October 13-15, 2014. pp. 362–367. Springer, Cham (2016), https://doi.org/10.1007/978-3-319-31664-2_37

[5] Zio, E. Reliability engineering: Old problems and new challenges. Reliab. Eng. Syst. Saf. 2009, 94, 125–141, https://doi.org/10.1016/j.ress.2008.06.002

[6] Panteli, M., & Mancarella, P. (2017, Sept). Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. IEEE Systems Journal, 11 (3), 1733-1742, https://doi.org/10.1109/jsyst.2015.2389272

[7] Pitilakis, K., Franchin, P., Khazai, B., Wenzel, H. (Eds.): SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities. Springer Netherlands, 2014, ISBN 978-94-017-8835-9

[8] GFDRR: Understanding Risk - Review of Open Source and Open Access Software Packages Available to Quantify Risk from Natural Hazards. (2015)

[9] A.L.A. - American Lifelines Alliance: Guideline for assessing the performance of Electric Power System in Natural Hazard and Human Threat Events. (2005)

[10] OOFIMS - Object-Oriented Framework for Infrastructure Modelling and Simulation, https://sites.google.com/a/uniroma1.it/oofims/, last access 27/06/19

[11] Setola R., Luiijf E., Theocharidou M. (2016) Critical Infrastructures, Protection and Resilience. In: Setola R., Rosato V., Kyriakides E., Rome E. (eds) Managing the Complexity of Critical Infrastructures. Studies in Systems, Decision and Control, vol 90. Springer, Cham, https://doi.org/10.1007/978-3-319-51043-9_1

[12] Di Pietro A., Lavalle L., La Porta L., Pollino M., Tofani A., Rosato V.: Design of DSS for Supporting Preparedness to and Management of Anomalous Situations in Complex Scenarios. In: Setola, R., Rosato, V., Kyriakides, E., and Rome, E. (eds.) Managing the Complexity of Critical Infrastructures: A Modelling and Simulation Approach. pp. 195–232. Springer International Publishing, Cham (2016), https://doi.org/10.1007/978-3-319-51043-9_9

[13] Di Pietro A., LaPorta L., Lavalle L., Pollino M., Rosato V., Tofani A. (2017) Simulation of Cascading Outages in (Inter)-Dependent Services and Estimate of Their Societal Consequences. In: Havarneanu G., Setola R., Nassopoulos H., Wolthusen S. (eds), https://doi.org/10.1007/978-3-319-71368-7_30

[14] Urquizo J., Calderon C., Philips J. (2019). Modelling the spatial energy diversity in sub-city areas using remote sensors. Published in International Journal of Sustainable Energy Planning and Management (Vol.22) https://doi.org/10.5278/ijsepm.3324

[15] Kuriyan K., Shah N. (2019). A combined spatial and technological model for the planning of district energy systems. Published in International Journal of Sustainable Energy Planning and Management (Vol.21), URL: http://dx.doi.org/10.5278/ijsepm.2019.21.8

[16] Steiniger S., Hunter A.J.S., Free and Open Source GIS Software for Building a Spatial Data Infrastructure. In: Bocher E. and Neteler M. (eds.) Geospatial Free and Open Source Software in the 21st Century. pp. 247–261. Springer Berlin (2011), https://doi.org/10.1007/978-3-642-10595-1_15

[17] Pollino M., Modica G.: Free Web Mapping Tools to Characterise Landscape Dynamics and to Favour e-Participation. In: Murgante, B. et al. (ed.) Computational Science and Its Applications. ICCSA 2013, Part III, LNCS 7973. pp. 566–581. Springer Berlin (2013), https://doi.org/10.1007/978-3-642-39646-5_41

[18] Miguel FJ, Hernández-Moral G, Serna-González VI. Supporting tool for multi-scale energetic plan through procedures of data enrichment. Int J Sustain Energy Plan Manag 2019;24. http://doi.org/10.5278/ijsepm.3345

[19] Pollino M., Fattoruso G., Della Rocca A.B., La Porta L., Curzio S. Lo, Arolchi A., James V., Pascale C.: An open source GIS system for earthquake early warning and post-event emergency management. In: Lecture Notes in Computer Science. pp. 376–391. Springer, Berlin (2011), https://doi.org/10.1007/978-3-642-21887-3_30

[20] Pollino M., Fattoruso G., La Porta L., Della Rocca A.B., James V.: Collaborative Open Source Geospatial Tools and Maps

Supporting the Response Planning to Disastrous Earthquake Events. Futur. Internet. 4, 451–468 (2012), https://doi.org/10.3390/fi4020451

[21] S. Giovinazzi, M. Pollino, I. Kongar, T. Rossetto, E. Caiaffa, A. Di Pietro, L. La Porta, V. Rosato, A. Tofani: "Towards a decision support tool for assessing, managing and mitigating seismic risk of electric power networks". ICCSA 2017. Lecture Notes in Computer Science, vol 10406. Springer, Cham, 2017, https://doi.org/10.1007/978-3-319-62398-6_28

[22] L. Matassoni, S. Giovinazzi, M. Pollino, A. Fiaschi, L. La Porta, V. Rosato: "A Geospatial Decision Support Tool for Seismic Risk Management: Florence (Italy) Case Study". ICCSA 2017. LNCS, vol 10405. Springer, Cham, 2017, https://doi.org/10.1007/978-3-319-62395-5_20

[23] Tomassetti B., E. Coppola, M. Verdecchia, and G. Visconti, Coupling a distributed grid based hydrological model and MM5 meteorological model for flooding alert mapping, Adv. Geosci., 2, pp. 59–63, 2005, https://www.adv-geosci.net/2/59/2005/adgeo-2-59-2005.pdf

[24] Verdecchia M., E. Coppola, C. Faccani, R. Ferretti, A. Memmo, M. Montopoli, G. Rivolta, T. Paolucci, E. Picciotti, A. Santacasa, B. Tomassetti, G. Visconti and F. S. Marzano, Flood forecast in complex orography coupling distributed hydrometeorological models and in-situ and remote sensing data, Meteorol. Atmos. Phys., 101, pp. 267-285, 2008, https://doi.org/10.1007/s00703-007-0278-z

[25] Coppola E., M. Verdecchia, F. Giorgi, V. Colaiuda, B. Tomassetti, A. Lombardi, Changing hydrological conditions in the Po basin under global warming, Sci. Total Environ., **493**, pp. 1183–1196, 2014, https://doi.org/10.1016/j.scitotenv.2014.03.003

[26] Coppola E., B. Tomassetti, L. Mariotti, M. Verdecchia and G. Visconti, Cellular automata algorithms for drainage network extraction and rainfall data assimilation, Hydrol. Sci. J., 52(3), pp. 579-592, 2007, https://doi.org/10.1623/hysj.52.3.579

[27] https://www.enac.gov.it/ContentManagement/information/N122671512/Regolamento_APR_ed2_em2.pdf, last access 27/06/19.

[28] https://en.wikipedia.org/wiki/Structure_from_motion, last access 27/06/19.

[29] Lowe D, Object recognition from local scale-invariant features, in Proceedings of the International Conference on Computer Vision, 1999, https://doi.org/10.1109/ICCV.1999.790410

[30] Lowe D, Distinctive image features from scale-invariant keypoints, International Journal of Computer Vision, vol. 60, n. 2, 2004, https://doi.org/10.1023/B:VISI.0000029664.99615.94

[31] Triggs B, McLauchlan PF, Hartley RI, Fitzgibbon AW, "Bundle Adjustment - A Modern Synthesis", Vision Algorithms '99, LNCS 1883, pp. 298–372, 2000, Springer, Berlin, https://doi.org/10.1007/3-540-44480-7_21

[32] Kazhdan M, Bolitho M, Hoppe H, Poisson surface reconstruction, in Proc of the 4th Eurographics Symp. on Geometry Processing, 2006, http://dl.acm.org/citation.cfm?id=1281957.1281965

[33] Chiabrando F, Donadio E, Rinaudo F, SfM for orthophoto generation: a winning approach for cultural heritage knowledge, in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 25th Intl CIPA Symp 2015, Taipei, Taiwan, 2015, https://doi.org/10.5194/isprsarchives-XL-5-W7-91-2015

[34] Rupnik E, Daakir M, Pierrot-Deseilligny M, MicMac – a free open-source solution for photogrammetry, Open Geospatial Data, Software and Standards, vol. 2, n. 14, 2017 https://doi.org/10.1186/s40965-017-0027-2

[35] Colmap Structure-from-Motion and Multi-View-Stereo, [Online]. Available: http://demuc.de/colmap/, last access 31/05/19.

[36] three.js - Javascript 3D library, http://threejs.org, last access 27/06/19.

[37] Tofani A, Di Pietro A, Lavalle L, Pollino M, R. V: Supporting decision makers in crisis management involving interdependent critical infrastructures. In: The International Emergency Management Society (TIEMS) 2015. TIEMS, Rome (2015)

[38] Tofani A. et al.: Operational Resilience Metrics for a Complex Electrical Network. In: D'Agostino G., Scala A. (eds) Critical Information Infrastructures Security. CRITIS 2017. LNCS, vol 10707. Springer, Cham (2018), https://doi.org/10.1007/978-3-319-99843-5_6

[39] Østergaard PA, Maestoso PC. Tools, technologies and systems integration for the Smart and Sustainable Cities to come. Int J Sustain Energy Plan Manag 2019;24. http://doi.org/10.5278/ijsepm.3450.