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Giving life to the map can save more lives. Wildfire scenario with interoperable simulations.

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Abstract: In the Mediterranean region, drier and hotter summers are leading to more likely and severe wildfires. The authors propose an innovative approach for situational awareness by giving life to maps and exploiting interoperable GIS, hazard models, simulations, and interconnection analysis processes aimed to enhance preparedness and strengthen the resilience of responding organizations. The information related to a virtual city and its countryside has been implemented in the terrain of simulation systems. The TIGER wildfire model software has been adapted to a scenario where districts, refugee camps and critical infrastructures can be impacted by a fire and has been linked to a smoke dispersion model, and associated impacts to the electricity network and roads. The transfer of computed fire propagation and combustion data to the AI-powered SWORD simulation enable more accurate computing of damage and loss. In SWORD, civil protection, military assets and humanitarian actions can be performed for training and operation preparation. The simulation data about fire and assets' deployments can feed a web app map or a command and control system, thus providing situational awareness for optimal decision-making, and analysis about people in danger, network interconnections and potential service disruption. Disaster managers and commanders can interact with simulated assets performing their chosen courses of action and analyse the outcomes.

In conclusion, tests in a wildfire case study demonstrated a high level of interoperability among those systems and the possibility to provide updated situational awareness leading to better emergency preparedness and critical infrastructure resilience building, finally contributing to save more lives.

Keywords: GIS, wildfire, modelling, simulation, decision-making

1. Introduction

In general terms, regions that are more affected by natural hazards are also those most conflict prone; in fact, when natural hazards strike an area the reduction of food could lead to subsequent conflicts (Lana, 2015) and migration (Platt et al., 2012). Since 2008 more than one half of the world population lives in cities (UN, 2014) and megacities that are increasingly under pressure and are also targeted by hybrid threats including terrorism and organized crime (David et al., 2017).

The optimal decision-making in crisis and disasters requires information exchange, coordination and updated situational awareness. This is a critical element to increase system's resilience under pressures, such as population growth and climate change.

Furthermore, vital services produced by critical infrastructures, such as energy, transport, health, etc. are also affected by natural hazards and climate change (see Table 1).

According to recent studies and based upon future climate projections the following impacts are expected (David et al., 2018):

- changing nature of hazards (faster, more frequent, extended, higher magnitude); this could result in change of design thresholds or require adaptation to changing hazards;
- faster degradation of performance (e.g. higher temperatures on pavements), different requirements for predictive maintenance;
- change in supply and demand profiles (higher energy demand in more warmer days);
- increased vulnerability of infrastructures to physical damages due to extreme events, impact on humans (e.g. heatwaves) and changes in operational profiles of the infrastructures.

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	Research	Space	Chemical	Transport	Financial Health	Food	Water	ICT	Nuclear	Energy
High winds		Yellow				Yellow		Red		Yellow
Extreme convection			Yellow	Yellow		Yellow		Red		Red
Extreme precipitation				Red		Yellow	Yellow	Yellow		Yellow
Ice storms			Yellow			Red		Yellow		Red
Hurricanes	Yellow	Red	Red	Red	Yellow	Yellow	Red	Red	Yellow	Red
Flood-inducing storms			Yellow	Red	Yellow	Yellow	Red	Yellow	Yellow	Yellow
Fire weather				Yellow		Yellow	Yellow	Yellow	Yellow	Yellow
Cold snaps						Red	Yellow			Red
Heat waves						Red	Yellow			Red
Drought						Red	Red		Yellow	Yellow
Climate change						Red	Red			Red

(Yellow: Low impact; Red: High Impact)

Table 1: Critical Infrastructures and threats (source: EU Circle)

According to the recently published IPCC AR5 report, climate change-related risks to infrastructures are increasing with widespread negative impacts on local and national economies and ecosystems (IPCC, 2018). As Critical Infrastructures (CI) are important components to the normal functioning of modern societies, their resilience encompasses the operational component in addition to its structural integrity and its capacity to maximize business output under climate stressors (CEN, 2002; Dimova et al., 2015). On the other hand, the increasingly dependent, interdependent and interconnected nature of critical infrastructures exposes previously unseen risks, new vulnerabilities and opportunities for disruption across the CI networks (Hokstad, Utne & Vatn, 2012).

1.1 Research Aim, Objectives, and Rationale

Geographic Information Systems (GIS) and simulation systems can be exploited to model highly complex and interconnected systems like urban areas and infrastructures. The authors' vision is to support, with interoperable systems and tools, the analysis, preparedness training, and decision-making in disaster management and countering asymmetric warfare scenarios.

A decision-making process is required at every step of the problem solving process (FEMA, 2005) and it allows the choice among different courses of actions in a set of alternatives (Wang and Ruhe, 2007). In a crisis, it is essential to assess the situation, to estimate available resources and make decisions (Menoni and Pugliano, 2013). A decision-making model like the famous Observe Orient Decide Act (OODA) loop allows iterative deliberate change and adaptation of planning to the evolution of situation. Decision-making in a complex context requires a combination of human judgment and technology. In responding organizations, a fast 'lessons learning' mechanism can supplement technology tools.

In an optimal situation, we can provide decision-makers with a menu of possible courses of action that can be pre-loaded and anticipated, like in the inventory management (the inventory can include all required assets like people, resources, supplies, goods, etc.).

Models and simulations are also an effective way to learn and acquire actionable knowledge regarding disasters and challenges in crisis management (Menoni, 2017).

This paper focuses on the development of a technical platform for exploiting geospatial information, simulation technologies and knowledge supporting decision-making in disaster management, response analysis, preparatory training and exercises. We need to combine highly detailed cartographic data, social media and sensors' data, disaster models, repository of procedures and triggers, *constructive* simulations and Command and Control (C2) systems. By integrating these aspects, emergency agencies and military would better prepare for disaster and support community and responding organizations' resilience.

The authors' research questions included the following:

- What are the cutting-edge training technology and architectures considering modern crisis, disaster and emergency management cooperative scenarios?
- How it is possible to acquire actionable knowledge to support resilience?
- Is it possible to exploit the capabilities of existing disaster, simulation and command and control tools and to fill the gap between the civilian and the military simulations' domains?

1.2 Methodological Approach

In the context of disasters affecting complex systems, due to the stochastic nature of factors and variables involved and their mutual interactions, a single simulation tool cannot cover all aspects (Bruzzone et al., 2014). It is necessary to create a simulation environment by integrating tools, models, simulations with the use of standards, such as the High Level Architecture (HLA) for simulations federation (IEEE, 1516-2010), the Military Scenario Definition Language MSDL (SISO, 2008) and the Coalition Battle Management Language C-BML (SISO, 2017).

The authors reviewed models and simulations in NATO, EU and United Nations, and conducted meetings and workshops with experts from the industry and academia communities.

The dual-use of hazard predictive tools and interoperable (military) constructive simulation systems has been exploited in order to fill the gap between (mainly civilian) hazard expert tools and (mainly military) simulation model. Such a solution has the potential to strengthen the coping capacity and resilience of organizations and in addition, support humanitarian action with Foreign Military Assets (FMA) when appropriate (UNOHA, 2007).

The research used a virtual megacity GIS model (David at al., 2018), hazards predictive tools and an end-to-end collaborative modeling environment, to potentially able to provide resilience monitoring and support cost-efficient adaptation.

As a proof of concept, a wildfire scenario has been chosen. The software of the TIGER predictive wildfire simulation of the University of Naples, currently used for training forest firefighters and fire prevention, has been modified and adapted to a civil protection/asymmetric warfare scenario where residential districts, refugee camps and lifeline infrastructures (e.g. power networks, roads) can be impacted by fire and smoke.

The development of the research technical platform required also the following processes:

- generation of terrain by an AI-powered constructive simulation system;
- scenario preparation on the constructive simulation system;
- simulation of a urban/peri-urban environment,
- standardization of data and information exchange;
- integration of simulations with decision support and command and control systems, and
- HLA standard simulation federation of predictive disaster models and other (including military) simulation systems.

Testing and Experimentation have been used to validate the concept.

2. The Wildfire scenario and TIGER

In the Mediterranean region (but not only here) due to climate change, drier and hotter summers are leading to more likely and severe wildfires. Industrial accidents and criminal actions also are frequent causes of fires, but in the Middle East, incendiary balloons and kites are also deployed as asymmetric warfare weapons, targeting crops and infrastructures with devastating effects.

2.1 The TIGER model

TIGER is a set of wildfire simulation models which are being applied for Mediterranean area fire training and investigation work. It evolved from work carried out under the EU-sponsored Fire Paradox project (2006-2010) to develop a spatial wildfire simulation framework. It is maintained by the University of Naples and World in a Box company. TIGER is developed using a modular modelling approach (Figure 1) which allows the integration of different sub-models (combustion, convection/diffusion, irradiation, wind flow, insolation, fire spotting). The philosophy is that complex systems can be described by simple processes, with complexity arising as an emergent property of their integration. The models are designed to simulate fire propagation in various conditions of fuel heterogeneity and include wind/fire interactions.

A variety of technologies can be combined in TIGER:

- WASP Engineering flow model for wind simulation, www.wasp.dk;
- a fire propagation rule set based on the USDA BEHAVE model;
- MATLAB for convection/diffusion processes (PDE), www.mathworks.com;
- Simile for combustion model and other “pixel” processes (ODE) www.simulistics.com;
- C++ for the insolation sub-model;
- Visual Studio .NET for GUI and model integration;
- the user interface is a Windows Forms application developed with Microsoft Visual Studio and using Bing maps visualisation facilities.

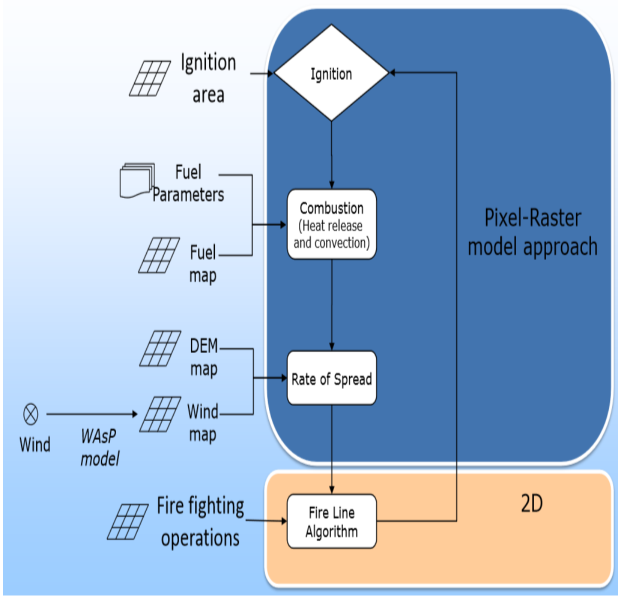

Figure 1. Key geospatial inputs and parameters to the TIGER model.

2.2 TIGER maps and data

TIGER input data comprise the fuel map of the region, digital elevation model (DEM), wind data, and the ignition/burned area. Wind data can be updated in real time from deployed sensors using mobile devices. The output data comprise fire lines and polygons (in .kml format), MS Word and Excel reports while Google Earth is used for visualization.

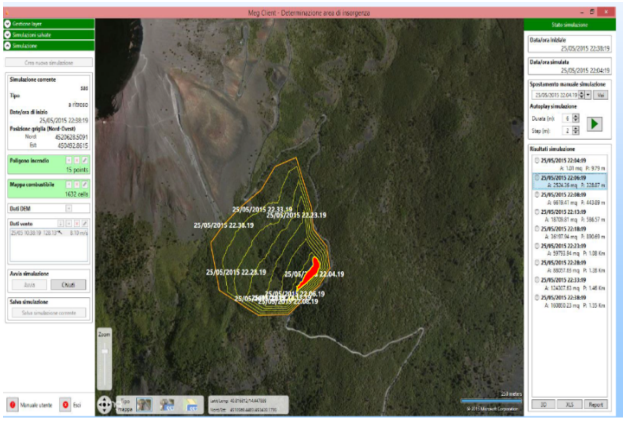

Figure 2. Fuel map and other input data in TIGER.

The model is able to represent the mass dynamics due to the fire consumption of different types of fuel (leaves and wood), the moisture evaporation and the temperature balances for the following state variables:

gas mass (G), gas temperature (TG), leaf mass (L), leaf moisture (ML), leaf temperature (TL), leaf moisture temperature (TML), diametric wood classes (W), wood

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moisture (MW), wood temperature (TW) and wood moisture temperature (TMW).

In particular, the Leaf and Wood temperature balance

$$\frac{dT_i}{dt}\cdot cs_i\cdot i=\sum_{i=L,W}\left[A_i\cdot(T_G-T_i)\cdot(h_{i\_wind}+h_{i\_no\_wind})\right]+\frac{di}{dt}\cdot H_i$$
$$-\sum_{i=L,W}\frac{dMi}{dt}\cdot\lambda_{i\_vap}-S_i\cdot\varepsilon_i\cdot\sigma\cdot(T_i^4-T_\infty^4) \quad (1)$$

where i=L, W and cs_i are the weighted average of specific leaf and wood heats, H_i are the leaf and wood heat content and the gas temperature balance:

$$\frac{dT_G}{dt}\cdot cs_G\cdot G=\sum_{i=L,W}A_i\cdot(h_{i\_wind}+h_{i\_no\_wind})\cdot(T_i-T_G)+$$
$$+\sum_{i=L,W}S_i\cdot\varepsilon_i\cdot\sigma\cdot(T_i^4-T_\infty^4)+\sum_{i=L,W}\frac{dMi}{dt}\cdot\lambda_{i\_vap} \quad (2)$$

where:

- cs_G is the gas specific heat; A_i are the heat transfer surface areas;
- h_{i_wind} are heat transfer coefficients under windy conditions;
- $h_{i\_no\_wind}$ are the heat transfer coefficients under non-windy conditions;
- S_i are the irradiation surfaces;
- ε_i are the leaf and wood emissivity;
- is the Stephan Boltzaman constant;
- T_∞ is the environmental temperature (~300K);
- λ_{i_vap} are the leaf and wood heat of evaporation.

TIGER combustion/convection/diffusion processes are described by the formula:

$$\frac{\partial T}{\partial t}=-\nabla\cdot(v(P,t)T)+\nabla\cdot(\chi(P)\nabla T)-h(T)(T-T_\infty)+f(t,T) \quad (3)$$

where the quantities:

- *T(P,t)* is the temperature scalar field;
- v(P,t) is the wind vector field, function of space and time;
- $\chi(P)=\frac{kV}{m(P)c}$

where k is the air conductivity, V is the volume of the cell, *m(P)* is the air mass in the cell, c is the specific heat of the air.

$$h(T)=\frac{\bar{h}\cdot V}{m(P)c}(T-T_\infty)^{1/3} \quad (4)$$

is the vertical convection heat transfer coefficient, being the T_∞ ambient temperature

f(t,T) is the heat source due to combustion in the cell.

TIGER models produce results as time series of standard GIS outputs such as mapable data and kml, which can be displayed in the software user interface using Google Earth technology for visualisation.

For the present research, the TIGER model was extended to provide a new output: the maximum heat per unit area (kJ/m^2).

3. GIS and M&S for analysis, planning and training

3.1 Geographic Information System

Spatial and network analysis can be integrated with historical data sets, disaster models and simulations (David et al., 2017).In addition, availability of data on the distribution of population, during the night (using available census data) and during work time (considering the commuters' flows to reach work places) can provide the ability to support quantitative analysis of disaster's effects on people.

The GIS provides a central infrastructure for crisis management in terms of a geospatial database, analytical models and visualization tools, addressing the three dimensions: *immediacy*, *relevancy*, and *sharing* (Cai et al,. 2006) but it is coupled with the dynamic simulation provided by the interoperable simulation systems (David et al., 2018).

The disaster damage is usually measured in physical units (e.g., square meters of housing, kilometers of roads, victims, number of homeless, etc.) and describes the destruction of physical assets, the disruption of services and damages to livelihood's sources (UNSDR, 2017). The authors performed tests on a virtual megacity (David et al., 2018) where geo data include resident population, public informative territorial system data, digital elevation model DTED level 2, Open Street Map data, GPS points of interest, etc., comprising more than two hundred data layers describing the city and its political, military, economic, social, information and infrastructure information (David et al., 2018). The Specific built in Damage/Networks Analysis tool permits the analisys of interconnected networks (electricity, water, gas, etc.) and the damage on a network by specifying the point of service disruption. The results from the hazard impact on buildings and infrastructures can be overlaid as raster and vector files, and integrated into a 2D and 3D web map where the Common Operational Picture can be accessed from pc and mobile devices.

3.2 MASA SWORD Simulation

An innovative, Artificial Intelligent (AI) powered constructive simulation platform MASA SWORD, has been chosen, with the ability to be populated by emergency and military assets and show in real-time the impact when a disaster strikes. The propagation of the disaster information is one of the most important aspects and SWORD can work with external disaster propagation models. Since the propagation of the disaster very much depends on the geography, to make its output as accurate as possible, SWORD needs as much as precise geospatial data as possible for generating the simulator's terrain. The "de facto standard" ESRI shapefiles can be imported to represent basic types of terrain. The SWORD terrain generation process regroups vector data layers and delimitation of terrain area and builds the land use (forest, urban, farms, etc.). Many other geospatial data useful to the simulation engine can be imported during the scenario preparation process as xml objects, extracting useful (for the simulation engine) information from shapefiles whenever possible. With the AI incorporated in the simulation, SWORD agents implement doctrinal behaviours specific to their class (population, civil security, police, etc.) in response to the disaster used. Overall the use of the constructive simulation provides a realistic environment which can then be incorporated in the 2D/3D GIS environment used as a decision support system, and in CBML/MSDL standards compliant (SISO, 2008, 2017) command and control systems if available.

4. Testing and Results

The research group has defined a specific hazard scenario. In this research, test trials have been conducted to actually federate existing disaster models with simulations. The capability of the simulation systems to collaborate was explored. There was also a successful assessment and evaluation of their capabilities to interact with other systems, predictive tools and command and control systems.

Changes of the TIGER wildfire model software by University of Naples and World in a Box allowed the successful transfer of TIGER computed data into SWORD whose damage model has the ability to use those data for calculating damage and loss. SWORD output can feed the common operational picture of a web map or a command and control system.

In fact, from its side, the GIS will support the analysis, for example, by provide the visualisation of those city districts that will be affected by a disruption caused by a wildfire crossing the high voltage power lines.

In order to visualize the propagation of wildfire on a web map (ESRI environment) used as a decision support tool, TIGER wildfires area files (in kml form) have been imported into a virtual city map via a Java gateway that constantly monitors the presence of new kml files from TIGER and convert them for the ESRI environment. The city GIS has been connected in HLA standard (IEEE, 2010) through a gateway that intercepts data (for examples units and assets simulated in JCATS, another connected simulation systems) from an HLA federation of simulation systems through a Pitch Google Earth Adapter.

In SWORD database, a TIGER Wild Fire "Disaster" has been created and the fire temperature thresholds have been associated to colors: 400 °C –yellow, 5000 °C – orange, 10000 °C –red.

"TIGER Wild Fire" polygon object has been created in SWORD and the TIGER output in terms of temperature values as .asc grid files have been imported into SWORD. The fire propagation was observed on the web map. The contour of fire dispersion can be observed on its entire evolution according to the defined time steps/window. The area of fire dispersion can be seen in SWORD. The observed location and shape of the object in SWORD and in the web map are the same.

The fire propagation can be observed at different speeds both in the map and in SWORD.

The simulated SWORD entities are affected by the fire with an appropriate damage.

The entities of the other connected (via HLA) military simulation system JCATS, in SWORD have been affected by the fire but the calculated effect (damage model) has been injected with a detonation that was initiated by SWORD damage model. This is due to the fact that JCATS has an explosion model but not a fire damage model.

Within EU-CIRCLE, the resilience of interconnected critical infrastructures to climate change has been defined as multi-dimensional components, incorporating risks and capacities. EU-CIRCLE has created a dataset of virtual data allowing for stakeholders and the Critical Infrastructures (CI) community to validate resilience and risk concepts under conditions of strong winds, prolonged high temperatures and low relative humidity values. These conditions resulted to low fuel moisture content and intense fire regime. The CI assets affected by the fire event and the released smoke are defined using spatial overlay analyses functions.

Initially, the generated data from the wildfire spreading model and ancillary data were fed into the Fire Emission Production Simulator Model FEPS v.2.0 of the US Forest Service (www.fs.fed.us/pnw/fera/feps). The return from the model was the estimate of fuel consumption, smoke emission – PM2.5, and heat release characteristics. The output was set on an hourly basis. Then the hourly geolocated emissions – PM2.5 data were fed into an atmosphere dispersion model that was used in EU-CIRCLE and produced as outputs: 1) air concentrations (in $\mu g/m^3$) of the pollutant and 2) ground deposition values ($\mu g/m^3$). The data are available on hourly time steps and can be integrated for longer periods. These data were then used to estimate the impacts of the wildfire on the electricity and transport network.

In fact, impacts to the Electricity Network come from:

- direct fire crossing with the high voltage – steel - transmission lines. As a pre-cautionary measure and depending on the operational procedures of the electricity network operator the power of the line was cut;
- wooden pylon burn outs when the wildfire intersects with their location;
- dense smoke over a certain concentration (> 500 $\mu g/m^3$) causing flashovers in air gaps. Furthermore, substations should be checked for electricity shortcuts caused by deposited smoke (usually represented as fine particulate matter PM2.5).

5. Results' Discussion

Outcomes from external disaster models like TIGER have been successfully transferred into a constructive militaryfocused simulator were the commanders' decisions will be translated into orders.

The creation of the terrain within a simulation system enables the direct interaction of decision-makers with planned tactical actions performed by deployed civil and military units. Such interoperability has been achieved through standardization of data exchange.

The outcomes of simulation (responding units' people in need location, posture, behavior, supply and status, and wildfire data) can be visualized on an interactive web app map where it is possible to perform analysis about number of resident population in the area (useful information for evacuation planning) or disruption to lifeline and other critical infrastructures networks as for example its impact of viability for assets deployment and logistic supply. In addition, the same data can be transferred to real command and control or operational systems.

The results of the simulation from SWORD, in **Military** Scenario Definition Language MSDL (SISO, 2008) standard, enable the creation of scenarios that can be shared and reused between a variety of simulation systems, between simulation and Command and Control (C2) systems, and between C2 systems.

Contribution to knowledge include the effort to fill the gap between specialized disaster models and military simulations and their applications to urban and per-urban complex populated environments and their critical infrastructures.

6. Conclusions, Lessons Learned and Way Forward

In this paper an example of application disaster simulation within a complete GIS environment has been presented. We introduced a set of complementary software tools for computationally intense modelling of cities, infrastructures and their interconnections.

This research represents an innovative approach for assessing disasters impacting the human dimension of urban and peri-urban areas, by exploiting interoperable

urban high resolution GIS and web map, historical datasets, hazard and climate models, simulations, risk assessment, HLA (IEEE,2010), MSDL (SISO, 2008) standards, *ad hoc* interfaces and interconnection analysis processes.

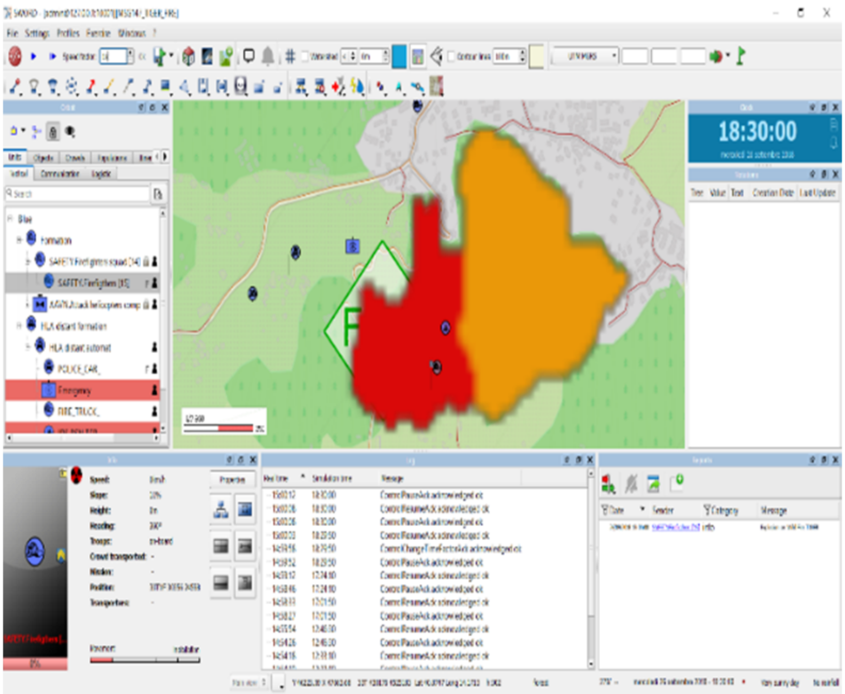

Figure 3. SWORD damage simulation after import of TIGER wildfire data.

Moreover, within this paper another type of simulation and risk/impact analysis is presented, showing the capabilities of such simulators to assess and analyze critical infrastructures networks towards climate change. A Critical Infrastructure Resilience Platform (CIRP) solution within EU-CIRCLE has been developed and supported the establishment of climate resilient infrastructure by ensuring that an asset is located, designed, built and operated with both the current and future climate. conditions and incorporates resilience to the impacts of climate change over the lifetime of that asset. In this direction EU-CIRCLE, provided a coherent baseline for moving from sector-based climate resilience infrastructure frameworks, into holistic resilience plans for entire regions, introducing the interdependencies of heterogeneous infrastructures in the implementation process.

This architecture model has the ability to support applications for emergency management simulation in a comprehensive innovative framework implementing virtual command and control capabilities to support an agile emergency management approach. In fact, it would be possible to train disaster managers, military commanders and other decision-makers remotely in a virtual Emergency Operations Centre. (David, 2016).

Those remote users would be able to actively participate and interact with the simulated assets within a common synthetic environment.

Due to the evolving nature of a disaster and the different outcome of performed actions and reaction and behavior of people to the hazard and to the responders' actions, in the affected area, the information must be continuously updated from ground and aerial sources including unmanned systems' sensors, in order to support re-planning. The updated information about damage could be provided also by volunteers and virtual communities, exploiting crowd-mapping platforms and social media applications (Mejri et al., 2017) thus supplementing available satellite imagery and other official mapping data.

In fact, Twitter can provide fast, real-time information about a large-scale disaster as it unfolds. In particular very useful information to find the people in need or plan and re-planning for safe evacuation routes.

In conclusion, tests performed in a wildfire case scenario demonstrated a high level of interoperability among the involved systems and the possibility to provide better situational awareness leading to optimal emergency operational and logistics planning, critical infrastructure resilience building, finally contributing to save more lives.

For short term, analysis and preparedness training, high resolution GIS, interoperable and federated simulators, and C2 systems, were tested. This solution could support training and analysis of_damages, impacts on population and decisions, estimation of the preparedness level, evaluation of the mission concept, simulation of deployment and logistics, by interaction of players with their tactical actions.

For long term analysis, virtual data of a coastal city has been generated and exposed to climate hazards (e.g. forest fire and smoke) related to extensive disruption to interconnected critical infrastructure operation.

The effects of alternative decisions including population behaviour as reaction to disaster and countermeasures can be tested (e.g., effectiveness in performing water bombing intervention using aerial assets during wildfire spreading near a refugee camp or electricity network infrastructures).

It is therefore recommended to complement the platform with:

- a repository of procedures in order to compare simulation outcomes from the disaster impact and the courses of actions chosen by the decision-makersith expected outcomes from procedure's compliance thus building knowledge and lessons learned;
- near real-time information provided by sensors and social media feeds, for updated situation awareness.

Future plans include linking the two approaches conceptually moving to:

- a *real time* disaster prediction and management system focusing on the interconnectivity between societal functions;
- highly resolved and detailed scenario building accounting for extreme events under climate change, e.g. optimal deployment of emergency and military assets and maintaining a supply chain of needed response equipment and first aid material;
- new governance models focusing on the dual use of military capabilities in disasters (e.g. the *"multi-purpose by design*" concept of main military equipment to be designed from the beginning to be used also for civil protection);
- introduction of new hazard simulations models for flooding, forest fires, extreme climate events.

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