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Damage scenario and risk complexity management: use of systemic approaches at different temporal and spatial scales

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Abstract

Nowadays, most of the areas in the world, more or less urbanized, are characterized by a great level of interconnections: physical, economic, social, digital, energetic, etc.. These connections opened, over recent years, new issues in the field of the research about the natural or human disasters, in all the phases of the disaster cycle, from the prevention to the recovery. Focusing in particular on the construction of damage scenarios or risk assessment, there are a lot of questions to be answered regarding different aspects: the mapping of the connections, how to consider the critical infrastructures, the cascading effects, the scales in time and space, the way to measure the effects and what sectors have to be involved, are some of the main issues. Moreover, the complexity of the issues has to be crossed with the effective existence or possibility to develop suitable methodologies to permit the achievement of the fixed objectives. This means that for each kind of connection among the different systems/objects, a sufficiently robust relationship has to be defined, a relationship that can be applied using data, available or obtainable, with a detail level and reliability suitable for the objective and for the scales assumed at the base of the study, to permit to have a significant result, usable by the decision makers to define the consequent actions to mitigate the possible damages. In the paper, the importance of the management of a scenario or risk assessment complexity with systemic approaches and how this can be useful at the different temporal and spatial scales are presented with some examples of real case studies.

Keywords: damage scenario; cascading effects; critical infrastructures; systemic; scales

1. Introduction

As a scientific community, we are witnessing an increasing complexity of disasters worldwide. Such complexity can be attributed to the impact of natural hazards on an increasingly interconnected environment and/or as a consequence of a different approach to the analysis of events. In both cases, new aspects are emerging as relevant in our discussion and require therefore partly new interpretation partly a renewed attention to factors that were perhaps neglected or less investigated until recently.

The way in which disasters are studied has changed as well, moving to a more interdisciplinary work, barriers between disciplines are not useful in areas that are exposed to multiple threats at the same time. This development is reflected in two subchapters of the Disaster Science Report issued in 2017 by the JRC [1] collecting the state of the art according to a rather large and diverse group of experts active in various fields of hazard and risk analysis both natural and man-made. The (2.1) subchapter proposing an innovative perspective on quantitative and qualitative risk assessment and the (2.5) discussing the more recent advancement in multi-hazard/multi-risk perspectives are of particular relevance. As for the former, rather clarifying exposition of the advantages and disadvantages of deterministic and probabilistic methods is provided, pointing at the need to identify the purposes for which one or the other is selected for a given analysis. Considering deterministic scenarios the Authors open the floor for using the wide range of tools available in industrial risk analysis also in other contexts, such as natural hazards: the FMEA (Failure Mode and Effect Analysis) or the "What if" methods can be reasonably used also in developing scenarios where the triggering event is an earthquake or a flood instead of a mechanical failure. The title of the 2.5 sub-chapter: "Where are we with multi-hazard, multi-risks assessments capacities" suggests already that definite and concluding solutions are not available. In that chapter, Zschau quotes the classification provided by Gill and Malamud [2], according to which different types of interconnections can be identified among hazards that co-exist in the same area. The complexity of a quantitative assessment of the probability of occurrence of interconnected or co-occurring events increases significantly respect the evaluation of each single phenomena. Furthermore, once the probability of multi-hazards or multi-events scenario are identified, one needs to establish the risk associated to them, not only in terms of number of deaths or overall economic damage, but also in terms of sequence of different order failures and damages at different scales. In fact, especially economists [3, 4, 5] have shown that damage is not only the direct physical impact due to the stress of the extreme phenomena on a number of exposed assets but also importantly the so called "indirect" damage that actually comprises a number of different types of negative consequences that deserve to be appraised. The latter are key as in some cases second order and long-term damage can be larger than the cost associated to rebuilding and repairing what has been physically harmed (excluding of course the consideration of the victims). In this respect, it is important to account for the unserviceability and malfunctioning of systems, activities and sectors that may be crucial for a community and its economy. In a comprehensive risk assessment, therefore not only the direct physical impact and its equivalent in repair or substitution costs must be considered but also the larger set of indirect and even long-term effects [6].

2. Complexities unfold across multiple spatial and temporal scales

The complexity of events is due to the fact that combined and enchained effects of what may be perceived as an initial triggering event gain relevance across both spatial and temporal scales. Cascading and domino effects are not necessarily occurring right after the initial triggering event but often manifest along time (days, weeks, months, to years) and may be felt in areas that have not been physically harmed. Agreed upon definitions of cascading and domino are missing in literature. Often, especially in the field of industrial risk analysis, the two terms are used interchangeably or one is used to explain the other. For example, Delvossalle [7], defined domino events as "a cascade of events in which the consequences of a previous accident are increased by following one(s), as well spatially as temporally, leading to a major accident". According to the Centre for Chemical Process Safety as quoted by Kadri et al. [8] domino may be referred "to an accident in which a primary event propagates to nearby equipment (units), triggering one or more secondary events resulting in overall consequences more severe than those of the primary event". Berg [9] suggests that whilst the term domino is more widely used in the industrial risk literature, cascading is more often adopted in natural disaster studies. Pescaroli and Alexander [10] grounding on the results of an extensive review conducted in the context of the EU funded project Fortress proposed the following definition: "Cascading effects are the dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes". The term cascading is also extensively used in the domain of critical infrastructures: it has been defined by Rinaldi et al. [11], in an authoritative article as effects that occur "when a disruption in one infrastructure causes the failure of a component in a second infrastructure, which subsequently causes a disruption in the second infrastructure"; note that such eventuality does not require that the infrastructures are proximal to one another as it may result from functional interrelationships among complex networks. As an example of cascading, typically one may think of power or water outages that are the consequence of the combined effect of physical damage to elements of the network, to the hierarchical relevance of the latter, and to the lack of redundancy of the grid. As an example of domino effect, one may think about the impact that the relocation of services and key businesses may have on the abandonment ratio of a region after a disaster occurrence. In both cases the quality and the timing of response and allocation of resources can modify a damage pattern or sequence. As indirect and longer term damages are hard to measure even after a disaster, there has been a general tendency to underestimate or leave out such considerations certainly from quantitative analyses but often also in qualitative accounts. More recently, improved statistical databases, an improved software and hardware capabilities have permitted to dig more even on longer term damages, being able, albeit with some degree of uncertainty, to clearly detect the impact of disasters on economic activities over longer time frames [6].

Coming back to the multi-hazard events, considering the classification provided by Gill and Malamud [2], a slightly different categorization is proposed here. In particular, it is important to distinguish between interdependent and independent events that may still either occur within a short time delay or still threaten the same geographic area. Under the interdependent hazards, the "triggering relationship", such as a landslide triggered by an earthquake, and the "increased probability relationship", such as landslides increased frequency after wildfires, can be grouped. As for independent hazards, one may consider an earthquake and a storm occurring at the same time, even though not physically related they significantly hamper rescue operations if they happen simultaneously in the same area.

It's also important to notice that some hazards are intrinsically multi-hazards: volcanic eruptions entail a wide range of phenomena occurring simultaneously or within a short time delay (tephra, ballistics, pyroclastic flows, lava flows, gas emission) and may be preceded by seismic events connected to magma activity and followed by events triggered by the previous ones, such as lahars, landslides and tsunami.

Fig. 1 [12] summarizes the framework that is proposed for including in the same scenario assessment the different linkages due to the interaction or co-occurrence of multiple phenomena, the differential sequence of impacts due to the latter and to the ripple effects created by systemic vulnerabilities, response and coping capacity (or lack of) and resilience. The framework is organized so as to show the logic sequence of effects across the time scale from one level to the following one. The stressing factors are always reported on the upper part of the sequence line, whilst the vulnerability and resilience factors are always represented in the lower part. The first order damage is the physical impact resulting from the stress produced by an initial hazard occurrence and the physical vulnerability of exposed assets and people to the event. The first order physical damage scenario can be then modified (worsened) by the occurrence of cascading or co-occurring events combined with the exposed assets and vulnerabilities. The second order damage results from the combination of the first order physical damage, or the modified one, and the systemic vulnerability of complex systems that can be counterbalanced by effective coping capacity of responding organisations and community (or instead magnifying the effect of systemic vulnerabilities). Higher order damage can be identified in larger systems and sectors that depend to different degrees on systems such as lifelines, supply chains and services and that are in their turn interconnected to each other (like for example economic activities that pertain to the same production chain).

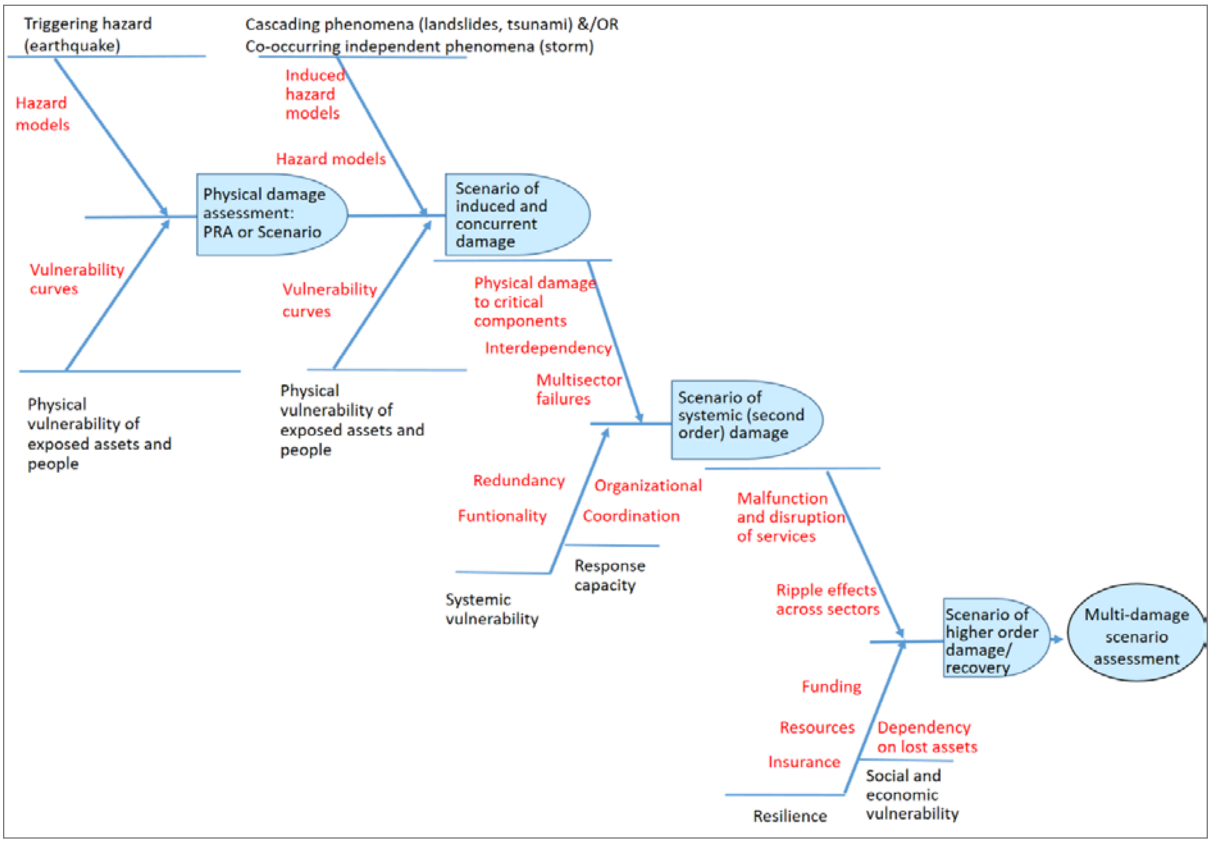

Fig. 1 - Sequence of multiple hazards and consequences [12]

3 Examples of multi-hazards events and damages in the Central Italy seismic swarm 2016-2017

The Central Italy swarm constitutes an interesting example of event that defeat the traditional understanding of the phases following a disaster due to fast onset natural hazards such as earthquake. Such a traditional sequence implies an impact, a first emergency, an early recovery, reconstruction and advanced reconstruction. A swarm however is bringing back the system to the emergency phase even when recovery and even first reconstruction is ongoing, creating a significant stress on the population and also on in intervening agencies and governments (regional and national). Also in terms of spatial scales the event was not limited to the villages that were particularly devasted but created significant functional and systemic damage in a large territorial system comprising four regions, non-redundant road connections between the Adriatic and the Tirrenian coasts, displacing and reconfiguring the life of communities displaced from the mountain areas to the shoreline. In the article we will provide as examples two cases of multi-hazard events [12]: the landslides triggered by the numerous ground shakes that cut many roads, and two co-occurring independent events: the 5.5 magnitude shake that occurred on the 18th of January 2017 and the snowstorm that affected the Central-Eastern part of Italy in the days comprised between the 15th and the 24th of January.

3.1 The effects of the landslides triggered by earthquakes on the road system

The evolution of the seismic crisis in the months between August 2016 and January 2017 caused a continuous evolution of the landsides activations and displacements. After the 24th August event, the triggered landslides were very numerous and spread in the territory, but, in most of the cases, characterized by limited dimensions, with the exception of the well-known case of Pescara del Tronto. The situation though worsened significantly after the October events both in terms of number and dimension [13].

Phenomena such as rock-falls, debris-falls on the roads, or cracks/failures of the roadways impacted severely the road system interrupting and/or reducing its functionality over a large area. These criticalities had to be added to the numerous direct damages caused by the earthquakes (e.g.: to bridges and retaining walls).

Due to the complexity of the problem, the national government decided to design Anas (National Autonomous Roads Corporation) as unique subject in charge of analyzing, coordinating and managing the damages and the consequent interventions in collaboration with the local administrations and Civil Protection (D.L. n. 205/2016). To understand the dimension of the problem and the weight of the landslides effects in the total amount of criticalities, it's possible to download the data from the interactive map published in the devoted website (updated to May 3, 2018, Fig. 2) [14]: overall 541 interventions are reported, 65% of which regard landslides.

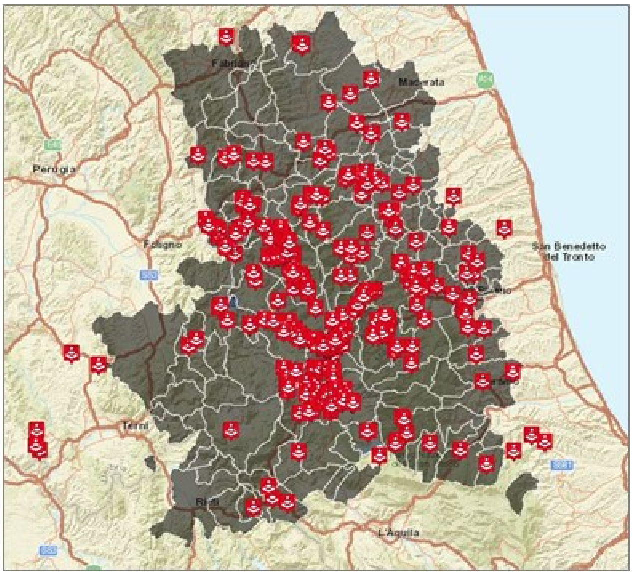

Fig. 2- Anas interventions updated to May 3, 2018 [14]

The functional second order damage, in terms of interruptions or limited accessibility before and during the interventions, varied depending, besides on the type of problem, on the type and relevance of roads. As example, intervening on a series of rockfall threatening a road, required several subsequent interventions to retrofit large portions of slopes. This implied to close and reopen the same road tract more than once to permit the access and the works in safe conditions. In the following, two examples of functional second order damage, at different scales, will be described in more detail.

The first case regards the provincial road number 209 (Valnerina), an important connection between Umbria and Marche regions, that, during the 2016 seismic crisis was affected by a large number of landslides, in most of the cases rockfalls. Fig. 3 shows the impressive rockfall provoked by the 30th October 2016 earthquake near Visso (km 65.8) that fall down in the narrow valley where the sp 209 road runs parallel to the Nera River. The road and the river were buried by a large amount of deposits and the riverbed diverted flooding the road, following the sequence represented in the scenario diagram in Fig. 4.

In this case, the road interruption was a concatenation of criticalities: the large rockfall and the flood. So, a series of complex interventions were planned by Anas: to retrofit the slope, to remove the deposits and the repositioning of the river in the original riverbed, besides the repair of a bridge and of another part of the road near this point damaged by other rockfalls [14]. A temporary re-opening with limitations was possible in October 2017 and the road was completely accessible since the 1st February 2018 (in Fig. 5 the situation in July 2018, after the interventions).

The described situation put in evidence the many vulnerabilities of the sp 209 road in that site: an intrinsic physical and morphological condition (a narrow valley), the river near the road, the presence of numerous landslides with high possibility to fall down, especially in case of earthquake.

Fig. 3 - The rockfall triggered by the 30 October 2016 earthquake on the sp 209 and Nera River [15]

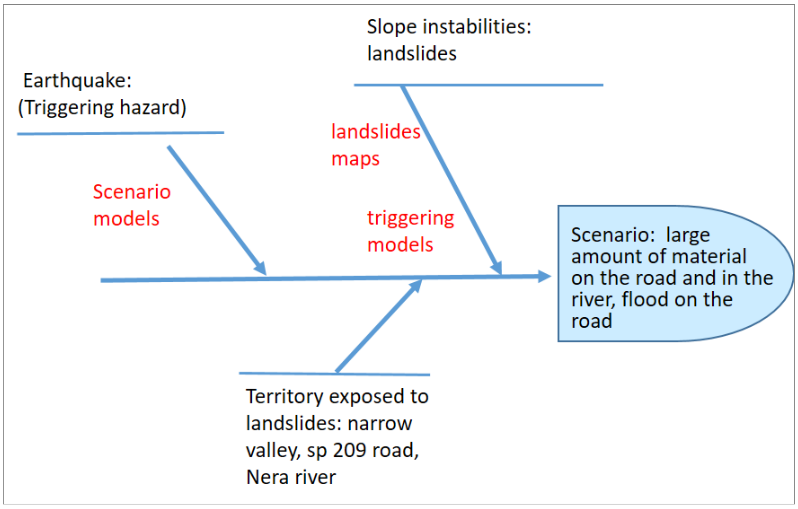

Fig. 4 - Cascading effects concerning the 30 October 2016 earthquake and the sp 209 near Visso [12]

Fig. 5 - The sp 209 near Visso after the interventions (July 2018) [12]

The second case refers to the access roads to the Castelluccio di Norcia Plan (PG). All four roads leading to the Castelluccio Plan were affected by the 30th October 2016 shake. Different causes produced damages and/or obstructions: roads structural failure, landslides and debris of collapsed buildings [14]. After the event, it was quite impossible to access the Plan, with significant repercussions not only in terms of mobility for the inhabitants of the hamlet of Castelluccio, but also for the local economy based on the lentils cultivation (very particular and appreciated variety) and on tourism, especially in summer during the "Plan Flowering", when a carpet of coloured flowers covers the Plan and it seems like a paint. The sequence of second and higher order damage is represented in Fig. 6.

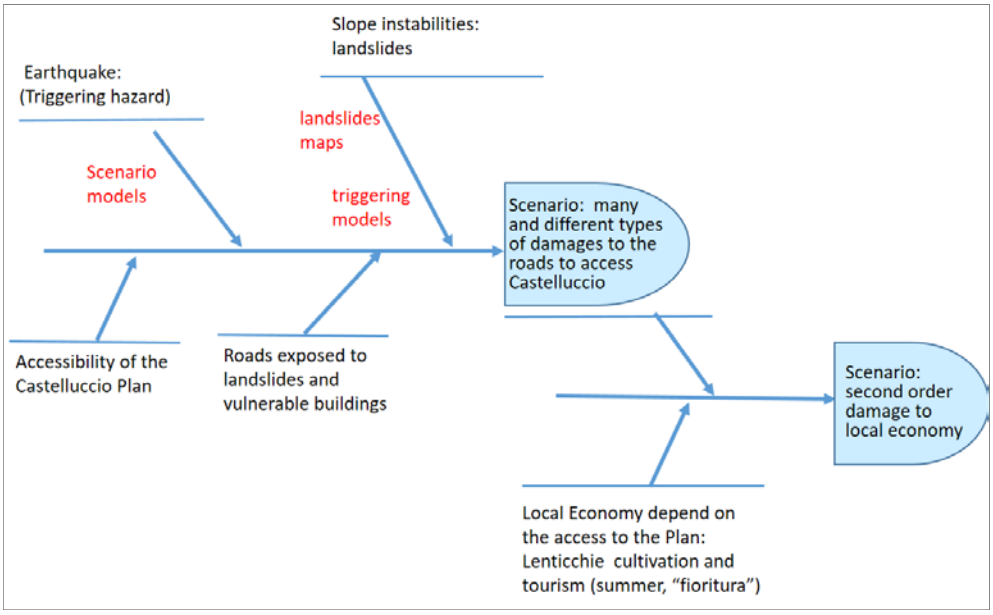

Fig. 6 - Second order damages due to the 30 October 2016 earthquake in Castelluccio di Norcia Plan [12]

Given the multiple causes of the roads damage, several interventions were programmed and realized, setting as a primary goal to permit at least limited access to allow the lentils production and the presence of tourists during summer. On the 3rd of April 2017 it was made possible for the farmers to reach the Plan for the lentils sowing with the tractors and other agricultural vehicles. Farmers were guided by Army personnel along two pre-defined itineraries, after some interventions to guarantee a minimal level of safety [16]. During the summer, instead, some roads were temporarily reopened in the weekends for touristic activities. Such program of interventions followed a systemic approach considering, beyond physical/technical aspects of road recovery also social and economic needs. Such an approach required the coordination among many actors: the local administrations, Anas, the Civil Protection, the population/associations. An unusual and complex way of working together had to be achieved: albeit difficult and imperfect, it permitted to obtain some relevant shared results.

3.2 The snowstorm and the power outages in January 2017

In the days between the 5th to the 24th January 2017, an exceptional prolonged snowfall associated with strong winds affected Central Italy. The storm occurred mainly along the Apennines but to some extent also along lower areas up to 300m, affecting the same regions already hit by the August and October shakes.

According to the recording that were made available by Terna and Enel (the companies responsible respectively for the network and for the provision of power) in their official website open to the public, after the 15th of January, two phases can be distinguished: the first between the 15th January in the afternoon and the 19th January, when both mountain and plain areas as low as 200m above sea level were covered by snow; the second phase between the 20 and the 24th January mainly in the mountain areas. Focusing on the Abruzzo region, in the first period the two provinces of Pescara and Teramo witnessed a continuous increase in the amount of accumulated snow precipitation, whilst the two other provinces of L'Aquila and Chieti recorded a more constant level. In the second period, and differently from the forecasts of those days, the amount of accumulation increased steadily in all provinces, as can be seen in Fig. 7.

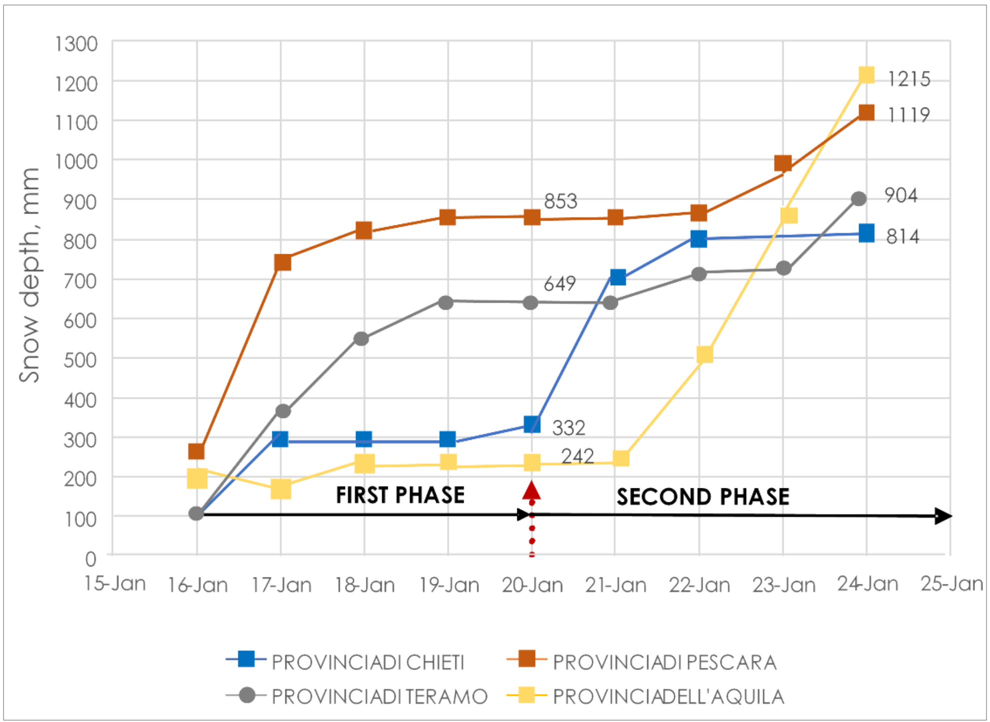

Fig. 7 - Snow depth as recorded by Enel and Terna [17] in Abruzzo region

The snow created problems to lifelines, in particular to the road network and to the power system. As for the latter, the accumulation of wet snow sleeves damaged power overheads while trees fell on both high voltage and medium to low lines. A number of transformation rooms in substations were disconnected as a result of disturbances along the lines resulting in a large number of outages across the four provinces of Abruzzo. The long lasting precipitation worsened the operational conditions of the workers of the Enel and Terna companies in charge of repair and of providing mobile generators to restore energy in multiple places. In Fig. 8 the effectiveness of the restoration operations can be appreciated as the red lines shows the peak number of customers suffering power outages in each day, whilst the blue line represents the same parameter at the end of each day. The difference between the two lines is the actual number of customers experiencing recovered service. For example, on the 17th of January as many as 159.000 customers suffered a blackout; at the end of the same day this number had diminished to 87.000, meaning that energy had been restored for 72.000. A steady decrease of unserved customers can be appreciated in the graph, even though after a week there were still 15.000 customers deprived of energy.

Fig. 9 provides information regarding the geographic distribution of the outages along the entire disturbance period. The provinces of L'Aquila and Pescara experienced a less severe blackout in terms of unserved customers; the maximum number of outages were felt in the Chieti province, but diminished rather fast in the next days. The province of Teramo is the one that experienced the second highest peak of outages and for a longer period of time compared to the other provinces. A number of factors may explain this result. Some cannot be verified without a more refined and exact information regarding in which areas the most severe physical damage occurred and also the geographic distribution of customers served by the physically damaged lines and by the disconnected sub-stations. However, some systemic vulnerability factors can be certainly appreciated. As the snowstorm affected severely also the road system, a number of localities became inaccessible to rescue services and to the teams in charge of restoring energy.

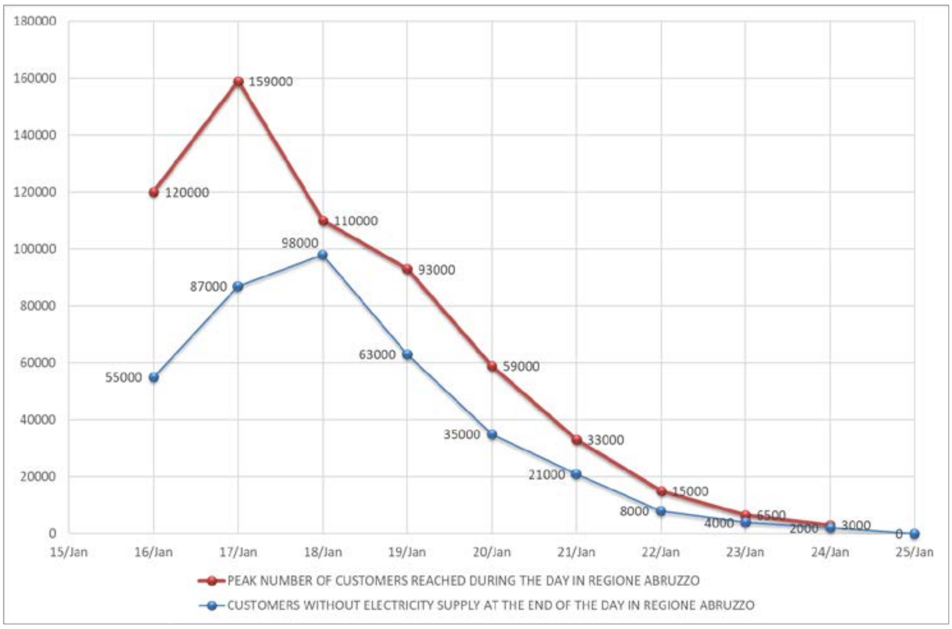

Fig. 8 - Outages (peaks and at the end of the day) at each day in Abruzzo Region [17]

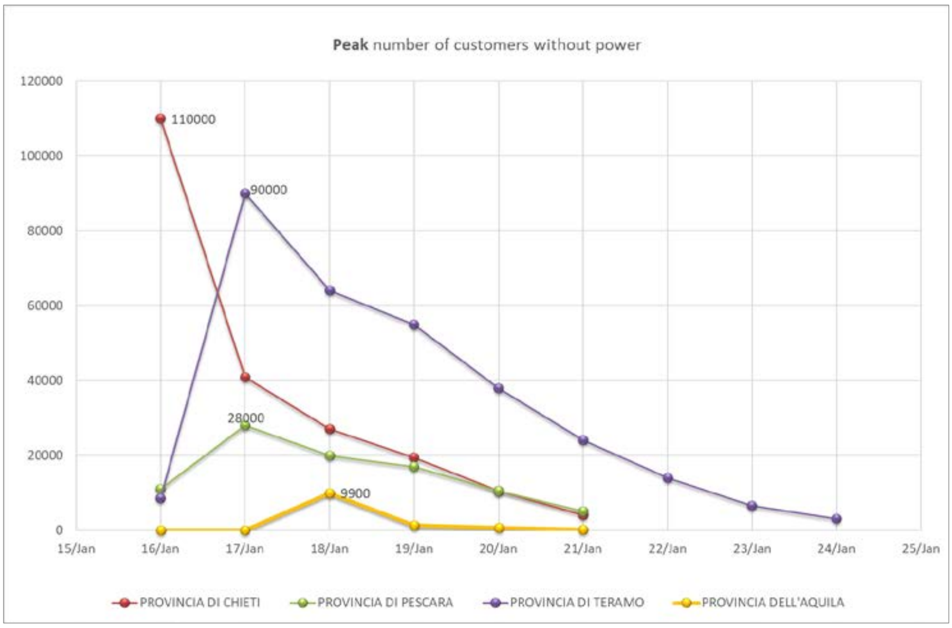

Fig. 9 - Power outages in the four provinces of Abruzzo Region [17]

The map in Fig. 10 [12] shows the overlapping of the towns that experienced the longest duration of power cuts and the roads closed for one, or more days, between the 20th and the 23rd of January. In fact, it can be easily seen that those towns are mainly in mountain areas, and were difficult to access those days.

The example illustrated above displays a number of features that characterize a multi-hazard event in a complex setting. The chain of failures and resulting damage scenarios are displayed in the fishbone diagram in Fig. 11 [12]. In fact, two independent events, the snowstorm and the rather strong earthquake co-occurring at the same time created additional challenges to a territory that had been already significantly affected by the seismic swarm of the preceding months. The snow, exceptional both for its duration and intensity in terms of accumulation provoked damage to physical components of the power system. The mountain setting of the area made some places unreachable for the combined effect of the snow on the road system, made of narrow lanes with many curves and high inclination in some parts; small towns and hamlets dispersed over a wide region, partially isolated also in less severe circumstances where a declining old population lives without means and resources such as local generators and snow cats.

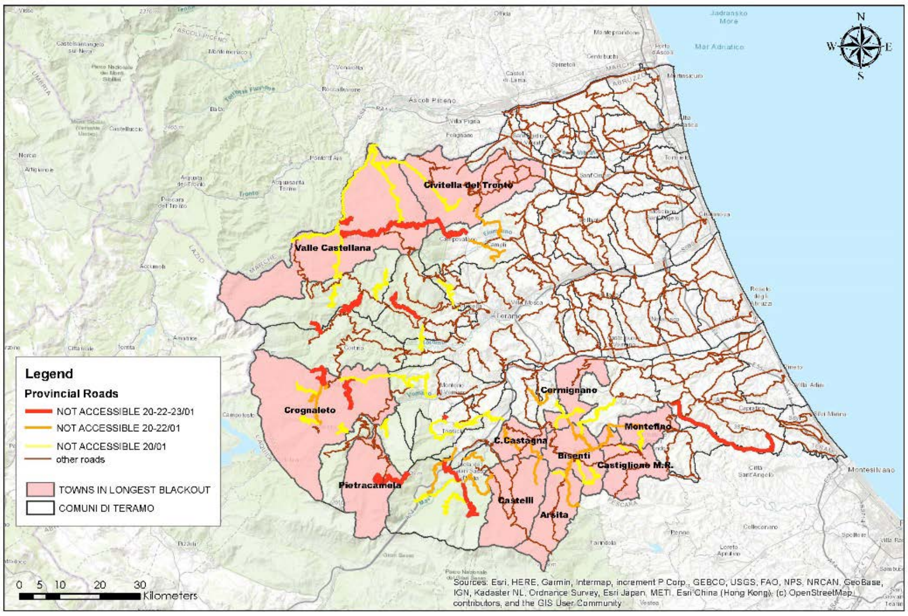

Fig. 10 - Maps overlapping road interruption and the towns experiencing the longest power cuts [12]

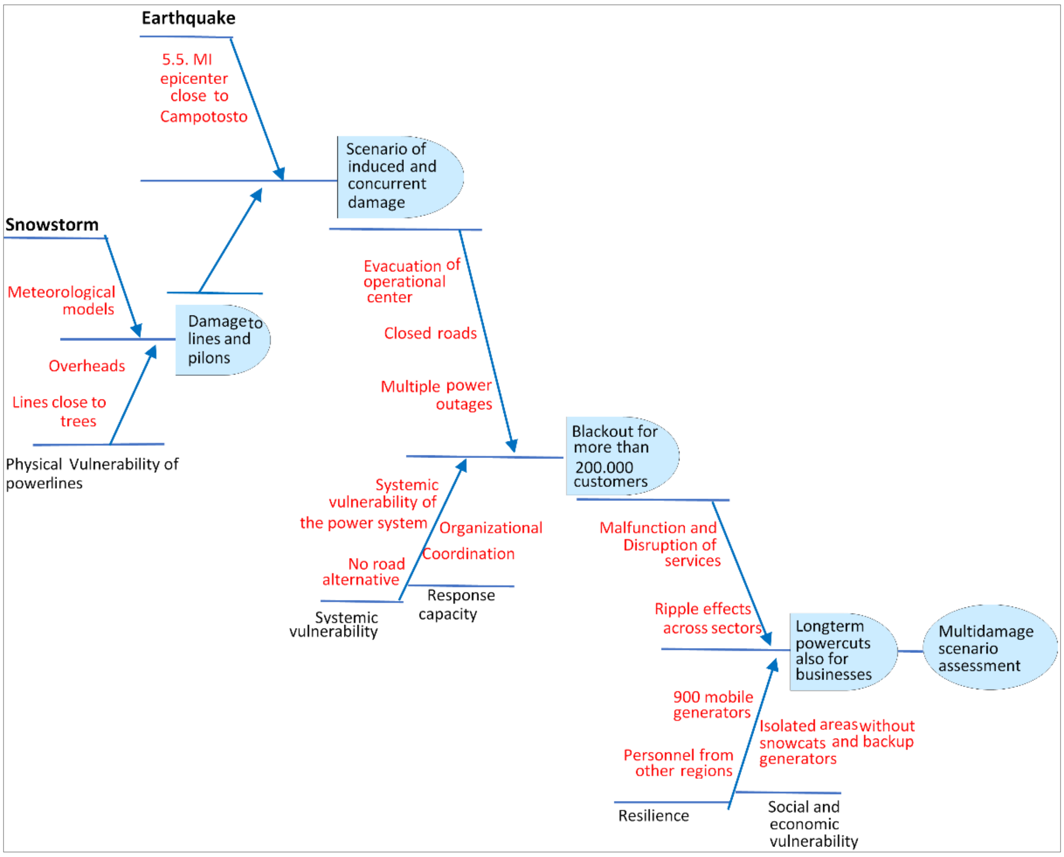

Fig. 11 - Sequence of damages in January 2017 in Central Italy due to the combined effect of the snowstorm and the earthquake [12]

4. Discussion and conclusion

The analysis of the two cases, using the conceptual framework that has been provided in section 2, highlights the importance of collecting and appraising damage and failure data in a systematic way, addressing not only the direct impact that is usually recorded but also more systemic effects. It has been shown how the environmental context matters, not only in shaping the potential for multiple, enchained or not, phenomena, but also what we have defined elsewhere as systemic vulnerability [18]. The latter refers to those weaknesses and fragilities that arise at systems' level, depending on interconnections and interdependency among systems and systems' components [11], and on the lack of redundancy and transferability [19] of crucial functions and services. Systemic vulnerability is one important cause of the disruption of services, businesses and societal sectors often independently from the magnitude and the extent of the physically damaged components, due to amplification effects that derive from lifelines and other critical infrastructure complexity. In the case of Central Italy, both the landslides triggered by the shakes and the snowstorm in January 2017 represent a typical multi-site event as defined in Menoni and Margottini [20] that stressed a rather wide area that was systemically vulnerable due to the dispersed territorial pattern made of small towns and hamlets located in the mountain, often with few alternatives, difficult to drive because of their configuration and sometimes closed due to the lack of organizational and technical resources needed to clean them from the snow.

The effort that the European Commission, international organizations such as Irdr, Unisdr, and scientific associations are carrying out to improve the modality of damage data collection and reporting is justified also by the need to enlarge the pool of data from which more robust analysis of second order damage, cascading and enchained effects can be derived. Recent disasters have unveiled a complexity that was unexpected due to a number of causes: some related to the hazards, other to the characteristics of exposed assets and the vulnerability of the latter and of systems. Being able to comprehend, model and assess such complexities in order to better prepare and prevent risks, requires a better understanding of the multiple relationships that the diagrams that we have used to represent the conceptual framework suggest. A better understanding that can be achieved by continuous comparison and cross validation of indicators and parameters that have been already identified by past research but need to be empirically verified in real events. Therefore what has been proposed in this paper is just a first step that opens though a trajectory for future studies in order to substantiate both the conceptual framework and the indicators that have been already propose and to indicate new ones that appear to be relevant in the course of the analysis.

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