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A Theoretical Framework to Investigate Interdependency in the Assessment of Fire Resilience

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Abstract: Communities and ecosystems may be particularly vulnerable to fire hazard. In addition, modern societies are connected with interdependent infrastructures, and the assessment of their resilience to fire may be extremely challenging. In this regard, fire resilience may be described as the ability to maintain the functionality of infrastructures to deliver services during and after hazard events. This paper considers several typologies of interdependency in order to propose several models that may quantify fire resilience. These models are based on the previous literature and the applications recently proposed for earthquakes. Fire resilience is herein calculated by considering a multi-dimensional formulation of the repair function that depends on time and the different components of the systems. The formulations that are described may be applied for preliminary studies aimed at pre- and post-fire assessments. Many stakeholders may take advantages of such formulations to consider the interconnections between the different infrastructures, their components, and subcomponents subjected to fire hazard.

Keywords: interdependency; fire hazard; resilience

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1. Introduction

Fire hazard has become the object of attention in recent years due to the impacts of changing climatic conditions, as described extensively in the literature [1–4]. Among the various natural hazards, fires are probably the most challenging to be modelled in relation to simultaneous impacts on systems. The structure of the paper consists of this first section that introduces the various parts of the topic: the research gap, the definition of resilience and the focus of the paper. Then, in Section 2 the concept of resilience is described. The methodology is then developed in Section 3. Section 4 focuses on the definition of the interdependency, while Section 5 proposes the extension to multiple dimensions.

1.1. Research Gap

Interdependencies are fundamental to be considered in the assessment of fire resilience. In this regard, some contributions [5–15] considered the role of cascading effects on the calculation of resilience. In particular, Ref. [6] applied drop-link analysis to assess the interconnectivity of road infrastructures by considering three typologies of infrastructure services (water, power and people) and concentrating on the role of cascade effects. Moreover, Ref. [7] considered two interconnected systems (a power grid and a telecommunications network). A mathematical approach was presented by [5,8–11] that proposed interdependency matrices to assess the propagation of attacks between two networks. Ref. [12] developed a methodology to study service-oriented interdependencies in interconnected networks. Cascading failures were analyzed in [13–15] with particular focus on consequences to the structure connectivity due to interdependence. In particular, Ref. [15] investigated the impacts of recursive cascade effects on interdependent networks. Recent assessments of fire hazards were proposed in reference to resilience and several classifications have been developed. For example, Refs. [16,17] considered soil moisture and temperature regimes provided by NRCS soil surveys. In particular, the latter aimed to consider modifications in soil temperature and moisture regimes due to climate change in western North American dryland ecosystems, including sagebrush steppe and shrublands. However, research on the role of interdependency in the assessment of fire resilience is still lacking in the literature and this paper aims to cover this gap.

1.2. Resilience: Historical Background

Historically, a concept that was proposed by Bruneau et al. [18,19] in structural engineering. Another method was proposed by Chang and Shinozuka that considered the relationships between expected losses and selected performance objectives of the community [20]. Moreover, Miles and Chang considered a recovery model that accounts for different aspects of the community, such as lifeline network, households and business [21,22]. In Rose [23], seismic resilience was defined on the basis of the behavior of different actors, such as individuals, markets and the regional macroeconomy. A quantification of seismic resilience for health care buildings was proposed by Cimellaro [24,25]. Ouyang et al. [26] defined a multi-stage methodology that assesses the resilience of infrastructures by considering several improvement strategies for each stage. In Burton et al. [27], a novel framework assesses the seismic resilience of a community by considering the performance limit states for buildings. Hosseini and Barker proposed to assess resilience by considering Bayesian networks [28], while Nozhati et al. [29] developed a decision-making methodology for post-event resilience actions. Goldbeck [30] proposed a method to include dynamic modelling and simulation by considering network and asset representations of infrastructure systems.

1.3. Focus on Fire Resilience

Even if resilience was the object of extensive research, few studies considered the role of interdependency. One of these methods was proposed by Zebel and Khansa [31] to assess the resilience to several hazards acting simultaneously. Interdependence was also considered by Ouyang and Wang [32] that concentrated on the interaction of the various restoration processes. In this regard, Ref. [33] proposed a multidimensional definition of resilience to include the various variables that may describe the interconnections. The aim of the paper consists of extending such methodology with a specific focus of fire resilience. In particular, recent contributions focused on fire resilience of a single building [34,35] by applying the multi-layer zone (MLZ) model [36] to represent the fire behavior inside single rooms. This paper proposes a theorical framework that investigates the role of interdependency in fire resilience.

2. Definition of Resilience

In this section, the concept of resilience has been analyzed by considering its historical definitions. In 1988, Wildavsky [37] considered resilience as "the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back." These definitions described two base principles: (1) prevention and (2) learning from the paper for future events. A decade later, Hoiling et al. [38] developed a definition that in many aspects may be considered wiser. Resilience was described as "the buffer capacity or the ability to a system to absorb perturbation, or magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables." In the same year, Ref. [39] extended the concept of resilience to "individuals, group and organizations, and systems." In 1998, Mallak [40] proposed to apply resilience to health care systems and defined it as "the ability of an individual or organization to expeditiously design and implement positive adaptive behaviors matched to the immediate situation, while enduring minimal stress." It is worth noting that this is the first time that the concept of recovery was included in the definition of resilience. In 1999 [41], included a more important aspect in such definition: the possibility of an "amount of assistance from outside the community." This approach was original because of two main reasons: (1) the possibility to have some help from the outside of the community and therefore (2) the extension of the principle of resilience from the narrow system-scale to the wider community-scale. In the same year, Ref. [42] improved the concept by considering resilience as "the capacity to adapt existing resources and skills to new systems and operating conditions," stressing two important points: capacity and adaptation to external events. Therefore, resilience may be considered the adaptability of a system or a community to external events. In 2000, Ref. [43] defined resilience "an active process of self-righting, learned resourcefulness and growth—the ability to function psychologically at a level far greater than expected given the individual's capabilities and previous experiences." This last definition may be regarded as modern since it is considered that (1) resilience is a process, (2) psychology contributes to resilience and (3) individuals have an active role.

A significant step forward, a more holistic approach, was proposed by [44–46] that considered the interaction of several aspects: technical, organizational, social and economic. In particular, they considered several dimensions to evaluate the resilience of systems together with the various dimensions of communities. Finally, perhaps the most comprehensive proposal for defying resilience was developed by the Hyogo Framework [47]. In such an approach, resilience was considered "the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures." In this definition, many contributions were put together: social dimension of resilience, the importance of learning from the past, the community exposure, the possibility to change, the need to define some levels of performance and the importance of future protection actions. Moving from this background, the next section aims to describe the fire resilience.

In this context, fire resilience (FR) may be defined as the process of recovering from the impact of fire and it needs to consider the role of interdependency between the various systems. In particular, the recovering process is based on the interaction between several aspects, such as the community preparedness, human resources, technical knowledge and skills, availability of fundings, level of organization, quality of management and political decisions.

3. Methodology

In this section the general approach described in the previous section has been applied to the assessment of fire resilience by proposing a novel methodology that is herein described. As introduced, fire resilience (FR) needs to account for interdependencies and thus a multidimensional formulation needs to be considered. The calculation of resilience needs the application of the Loss Model and the Recovery Model.

(1) The Loss Model describes the reduction of the functionality due to the initial impact of an event on a system. The quantification of the losses that is at the base of this model may be a challenging issue, since several typologies of losses need to be considered, such as direct and indirect losses, as described in [48].
(2) The Recovery Model aims to assess the ability of the system to recover from the impact by considering the process of recovering that is generally represented with an analytical formulation. Such formulation needs to describe several variables that are challenging to be defined and generally depend on the preparedness of a community, the level of technological know-how and the distribution of economic funds for the recovery process.

In this context, what is described in [33] is extended herein to assess the resilience to fire hazard. FR is formulated on the basis of the recovery function $Q_N(t)$ that describes the recovery process to return an estimated level of functionality:

$$Q = Q(t, Q_1, \ldots, Q_N) \tag{1}$$

that is defined in the R^N space and is function of time (t) and all the various dimensions Q_i of the problem/system. Consequently, fire resilience can be computed by following [24] as

$$FR = \int_{t0F}^{t0F+RT} \frac{Q(t, Q_1, \ldots, Q_N)}{RT} dt \tag{2}$$

where

t0F is the time of occurrence of the fire F,

RT is the repair time (RT) necessary to recover the original functionality.

It is worth noting that this formulation has the same shape of that proposed by [24] and it expresses the dependency of FR not only on time, but also on the N dimensions with which the system may be described.

Graphically, Equation (2) represents the normalized volume underneath the recovery function QN(t) and the plane t = RT (Figure 1). It is worth noting that in Figure 1, the values of RT could be different for the various dimensions.

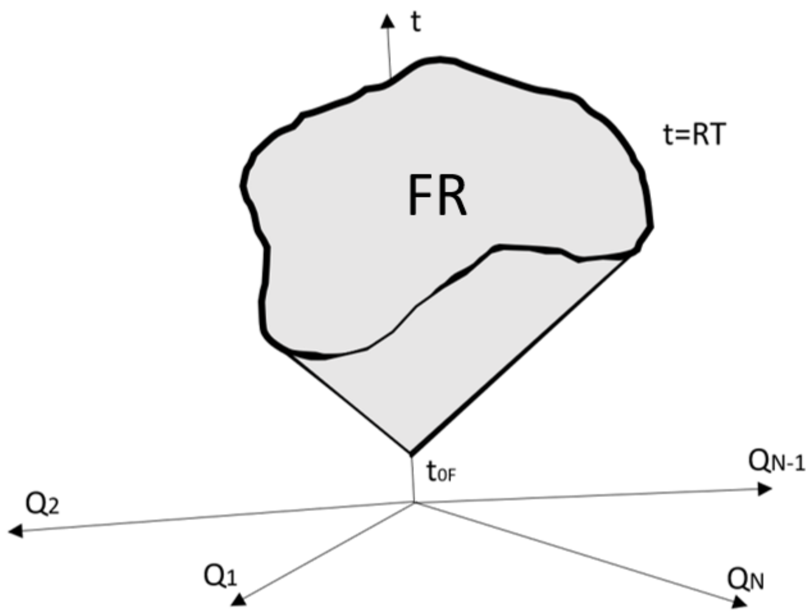

Figure 1. Multidimensional formulation of FR.

It is worth noting that for every time t = k, with k < RT, is possible to consider the plane:

$$Q(t = k, Q_1, \ldots, Q_N) \tag{3}$$

that represents a plain surface connecting the points on the recovery function corresponding to t = k for all variables Qi. In other words, Equation (3) describes the section of the cone whose perimeter represent the sum of the functionalities Qi reached by the total system at the selected time t = k. Figure 2 shows the contour lines (lines joining points at the same time t = k_i).

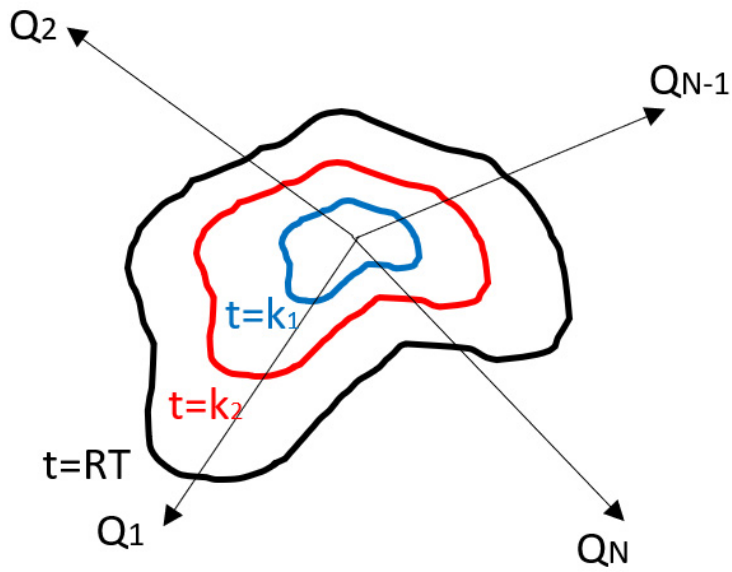

Figure 2. Contour lines of the functionality $Q_N(t)$.

Following [24], in the present paper, the simplification of the linear repair function is considered to be realistic when there is insufficient information regarding the preparedness of the community or the consistency of the resources [49]. Therefore, the solid assumes a conical shape with different angles with the t-axis, depending on the coefficient ci:

$$\mathrm{ci} = \frac{Q_{F,i}}{RT_i} \tag{4}$$

where $Q_{F,i}$ is the value of the functionality after the complete recovery of the system i. Such a value may vary from 1% to 100% with respect to the original functionality, but may be also bigger than 100% when the repair function allows improvements of the original functionality [50]. As shown in [33], herein the case in which the loss due to the fire are 100% was considered, meaning that the value of the functionality at $t0_F$ is 0. It is worth noting that this hypothesis means that the solid has a common vertex in V ($t0_F$, 0, ... 0). These assumptions have been discussed in [33] for the case of earthquakes, while for fire, they need be reconsidered due to the role of interdependencies, as explained in the following sections.

4. The Role of Interdependencies on Fire Resilience

As introduced, for fire hazards, the role of interdependencies is fundamental to consider the simultaneous impacts on systems. Interdependencies may be defined as the mutual interactions between several systems (i.e., energy, transportation, communication and water networks) that may be affected by the same event [33], in this case the fire. Interdependencies may cause significant consequences and thus the assessment of FR may be severely underestimated when they are neglected [51–55]. In particular, Ref. [51] proposed an object-oriented approach for generalized network-system analysis in order to model interdependent infrastructures. Ouyang et al. [52] suggested to assess the resilience of interdependent infrastructure systems by focusing on joint restoration modeling and analysis. Another interesting approach considered the community resilience-driven restoration model for interdependent infrastructure networks [53]. Urban interdependency under earthquakes was studied in [54], which developed a methodology to quantify seismic resilience. The most severe contribution of interdependencies is that when a fire occurs, the lifelines whose role is to deliver services become ways to distribute the consequences of the fire itself, because they may be responsible for interconnected failures. These mutual interactions may spread in many areas and cause the collapses of several systems. There are essentially two different typologies of interdependencies that can occur, as discussed in [33]. In the case of fire hazard, due to the extreme uncertainties regarding its diffusion, these two may occur at the same time with the possibility of having both of them during the same fire event. The next sections focus on these typologies of interdependencies, developing the formulation proposed in the previous section for the three cases.

Overall, interdependencies needs to be considered by several stakeholders (e.g., public- and private- administrators, designers, technicians). In particular, these actors must consider the importance of accounting the mechanisms of interdependencies in order to investigate pre- or post-event responses, establish recovery strategies, define solutions and organize emergency procedures. It is worth noting that the assessment of interdependency may result in the difference between a well-managed disaster and catastrophic events because of proper planning and management.

4.1. Typology 1: Common Cause

This is the classic (and easiest-to-model) kind of interdependency among the infrastructures, since it consists of a cause that simultaneously affects various infrastructures. In particular, this assumption may be considered acceptable to describe an earthquake, while in the case of fire hazard, only the first seconds may be strictly represented by this model. However, for this case, the time of occurrence t0F of the fire F may be considered the same of all the infrastructures and the previous formulation (Equations (2) and (4)) may be used simultaneously to describe the mechanisms of the various infrastructures. Therefore, FR may be calculated as

$$FR = \sum_{i=0}^{N} \int_{t0F}^{t0F+RT} \frac{Q(t, Q_1, \ldots, Q_N)}{RT} dt \quad (5)$$

where N is the number of infrastructures that are considered interconnected in parallel (with the same t_{0F}). It is worth noting that Rt may be not the same for all the interconnected infrastructures. However, RT may be considered the maximum between the RTs of the various infrastructures. Figure 3 shows this typology of interdependency that may represent the case of a series of lifelines that deliver products or services that are damaged, degraded or interrupted by the single event of a fire (F).

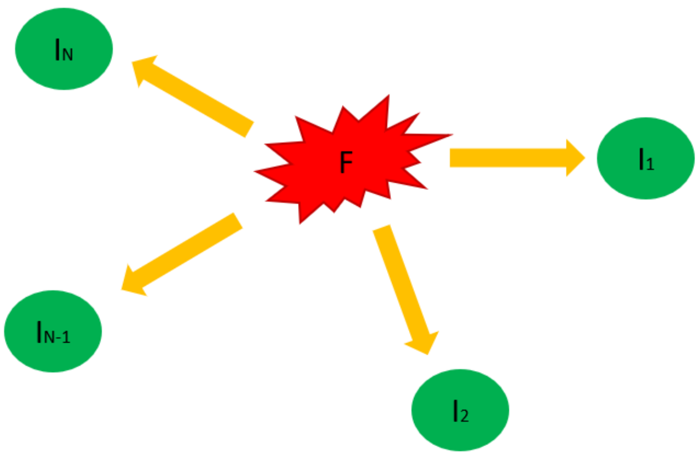

Figure 3. Common cause (F: Fire, Ii: Infrastructures, N: number of interdependent infrastructures).

4.2. Typology 2: Cascading Effects

Another typology may occur when the consequences of a fire on the first lifeline propagate on a second infrastructure and then, from there, to a third, and so on. This case may be representative of the case of failure due to fire of the electric distribution network which shuts the delivery of services in a factory and thus the distribution of the services to the linked infrastructures. The cascading effects have been described in several contributions, such as [55,56]. In particular, Ref. [57] considered the effects of multiple flood hazards by proposing an integrated framework based on a comprehensive investigation of local infrastructure systems and their interrelationships. Another approach was proposed by [58] that developed a methodology for the identification of infrastructure interdependencies by modeling uncertainties simultaneously. Figure 4 represents a chain of infrastructures that are affected by the same fire event, and they are connected in series. Operatively, it is not possible to consider that the various infrastructures have the same time of occurrence, and also that the various infrastructures have different RT. Therefore, FR may be calculated as

$$FR = \sum_{i=0}^{N} \int_{t0Fi}^{t0Fi+RTi} \frac{Q(t, Q_1, \ldots, Q_N)}{RTi} dt \quad (6)$$

where N is the number of the infrastructures that are considered interconnected in series.

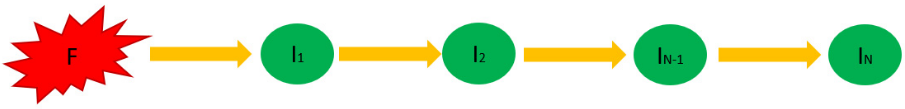

Figure 4. Cascading effect (F: Fire, Ii: Infrastructures, N: number of interdependent infrastructures).

4.3. Typology 3: Mixed Effects

This is the most complex typology that may occur with fire, and it consists of a combination of the first two. Herein, the complexity increases because the time at which the failures occur, and the repair time are different for (1) the various chains and at the same time (2) for the various infrastructure inside the same chain. Figure 5 represents N chains of Mk infrastructures for each. All these systems are affected by the same fire event (F) and they are connected in series (typology 2, cascading effect) and in parallel (typology 1, common cause) at the same time. This case may be representative of the case of failure due to fire of the electric distribution network which shuts the delivery of services contemporary to several factories that at the same time cause failures to the distribution of the services to the correspondent linked infrastructures. Therefore, FR may be calculated as

$$FR = \sum_{i=0}^{N} \sum_{j=0}^{Mk} \int_{t0Fj}^{t0Fj+RTj} \frac{Q(t, Q_1, \ldots, Q_N)}{RTj} dt \quad (7)$$

where N is the number of the chain interconnected in parallel and Mk is the number of infrastructures connected in series for each chain.

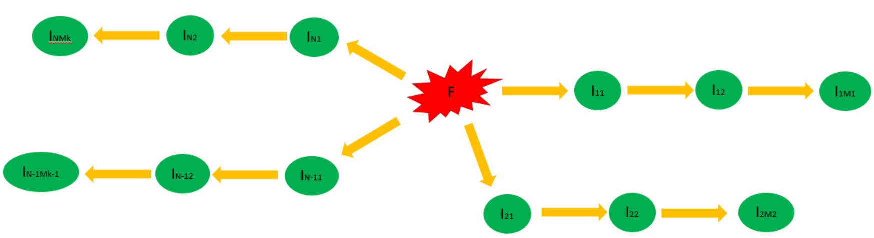

Figure 5. Mixed typology (F: Fire, Ii: Infrastructures, N: number of interdependent chains, Mk: number of interdependent infrastructures per each chain).

5. Conclusions

This paper investigates the role of interdependencies in the assessment of fire resilience by considering the approach proposed by [24] and its extension in [33]. Resilience has been assessed by considering a Loss Model and a Recovery Model. The former allows the assessment of the losses occurring at the various infrastructures, while the latter is applied to quantify the repair time (RT). The formulation proposed herein is simplified with linear functions that may be considered realistic because insufficient information is generally available due to the extreme uncertainties of fire events. In particular, this kind of data regards the preparedness of the community or the consistency of the resources. The interconnections between the different infrastructures, their components and subcomponents have been modeled with interdependencies that must be considered for systems that are subject to fire hazard. The formulation proposed herein considers the different dimensions with which fire hazard may be described by proposing a simplified (but realistic) formulation of fire resilience. Such an approach may be considered a first attempt to spot extremely challenging issues, such as the assessment of the fire resilience of interconnected infrastructures. In particular, the presented approach may be implemented in emergency procedures and recovery decision making assessments in order to select the best strategies to reduce the damage due to fire hazards. However, the present methodology may be considered a theorical framework that investigates the role of interdependency in fire resilience without exploring its applications that will be object of future work.

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