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ARTICLE

The Role of the Spatial Network in Urban Disaster Risk Variations: Reimagining the Notion of Spatial Vulnerability at the Urban Scale

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Abstract
The notion of "spatial vulnerability" is present in most disaster studies with a strong geographical connotation and accordingly is adopted at all scales, including the urban. While enabling mapping and visualizing risk patterns at macroscales, this geocentric foundation fails to capture disaster risk dynamics associated with the urban spatial network—an element that plays a significant role in the everyday and emergency functioning of cities, enabling users' movement and interaction. Yet, urban vulnerability assessment overlooks this aspect and thus leaves urban disaster risk mechanisms partially unexplored. This study investigated the role of the network of urban public open spaces (UPOS) in the creation and progression of urban disaster risk in earthquake-prone settlements. Through a multimethod approach that integrates quantitative and qualitative methods and explores spatial configuration, planning policies, and practices of use of UPOS in everyday and emergency scenarios, our study demonstrated that UPOS configuration plays an active role in urban disaster risk. Urban public open spaces impact risk by influencing the exposure of pedestrians and their capacity for self-protection. The study further reconceptualized spatial vulnerability at the urban scale, as the fraction of vulnerability associated to the spatial network, highlighting the interplay of planning policies and spatial practices in its production and progression. Our findings make the notion of spatial vulnerability less ambiguous at the urban scale, by viewing the variable as an imbalance in capacities and exposure that generates spatially unsafe conditions. This refined conceptualization of spatial vulnerability becomes a lens for a more granular approach to urban disaster risk reduction and city planning by identifying and integrating sociospatial considerations.

Keywords Central Italy Earthquakes · Pedestrian evacuation · Space syntax · Spatial vulnerability · Urban disaster risk

1 Introduction

The images captured in earthquake aftermaths and displaying evacuees converging into, and navigating, debris-filled streets show that, when disasters strike, the urban spatial network is both a critical infrastructure enabling evacuation, and a possibly hazardous element endangering its occupants. However, the spatial aspect of urban disaster risk is seldom investigated, with studies prevalently focusing on the distribution of risk across space, rather than the risk generated by, and descending from, it. This study aimed at better understanding the role of space in urban vulnerability studies and broadening the appreciation of disaster risk mechanisms at the urban scale. It does so by presenting novel evidence from research on urban form and disaster risk that redefines the notion of spatial vulnerability in urban contexts. The study overcomes the inherent limitations of the geocentric spatial vulnerability assessments at the urban scale (Cutter et al. 2000) by adopting a configurational approach informed by urban morphology and space syntax knowledge.

Space syntax theory argues that space through its spatial configuration—intended as the simultaneously existing relations among the parts that make up the whole spatial network (Hillier and Vaughan 2007)—is an active formative entity of, and not just a background to, social organization (Hillier and Hanson 1984). Since the 1970s, space syntax research has been developing theoretical concepts and analytical-mathematical tools for the study of spatial configurations. This study looked at spatial vulnerability at the urban scale as a combined effect of spatial configuration, land use, and management of the

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urban fabric, associated with reduced performances of the urban spatial network in an emergency, thus making the whole urban system more sensitive to the impact of specific hazards.

The urban spatial network is a functional element in cities (Hillier and Hanson 1984; Hillier 2005). A growing number of studies has explored its potential in disasters as infrastructure serving the emergency and post-disaster decision making (Marin Maureira and Karimi 2017; Pezzica et al. 2019; Giuliani et al. 2020) with urban morphology tools increasingly informing planning practice (Palaiologou et al. 2021). Yet, little to no attention has been paid to the study of the role of the network as an active element in the (re)production of urban disaster risk.

Considering this gap, this research was conducted to investigate the role of the network of urban public open spaces (UPOS) in the creation and progression of urban disaster risk in earthquake-prone urban areas. The study was articulated as a multi-dimensional investigation of spatial configuration, planning policies, and practices of using the UPOS system in the everyday and emergency, in four locations affected by the 2016–2017 Central Italy Earthquakes, to collect evidence of configurational performances and reimagining spatial vulnerability at the urban scale. The reconceptualization of spatial-configurational vulnerability has required two consecutive stages. First, demonstration of the disaster risk potential of the urban spatial network, achieved through configurational analysis and the expression of disaster risk variables through selected space syntax measures. Second, understanding of contextual and systemic mechanisms behind production and replication of spatial disaster risk at the urban scale, achieved through qualitative analysis of planning policies and spatial practices. This article presents the research after discussing the implications of the current, geocentric definition of spatial vulnerability in disaster studies, and illustrating its limitations when applied at the urban scale.

2 Vulnerability Conceptualization in Spatial Terms

In disaster risk terminology, the concept of "spatial vulnerability" is present with a strong geographical connotation, and is accordingly adopted at all scales, from territorial to urban. While enabling mapping and visualizing risk patterns at macroscales, the approach overlooks the microscale of users' experience and fails to capture disaster risk potential linked to the experienced space in cities, consequently affecting the understanding of the associated disaster risk dynamics.

2.1 Geospace in Disaster Studies

Space features in disaster studies as geospace, having the threefold connotations of location (*topos*), spatial relations (*choros*), and topology (*geos*), and serving the purpose to locate, map out, and measure, physical features of a territory and the associated properties (Smirnov 2016). Associated to the notion of "place" used to express a specific locality and unit of analysis, geospace has provided the default lens used in disaster studies to spatially understand, quantify, and analyze risk and its variability between different locations. This has enabled the development of models such as Hazardousness of Place (Hewitt and Burton 1971), Hazard of Place (Cutter and Solecki 1989), and Vulnerability of Places (Cutter et al. 2000) and informed extensive research that, in five decades of contemporary disaster studies, has produced spatial representations of hazard and vulnerability, including exposure, risk, and the associated indicators.

Because of the geodriven approach, the associated notion of "spatial vulnerability" retains a strongly quantitative connotation, enabling the mapping out of geographical patterns of risk and visualizing, quantifying, and analyzing their variations across space in the studied territories (Aubrecht et al. 2012; Roy and Blasche 2015). The mapped information, in turn, provides the starting point for more context-specific investigations into dynamics of vulnerabilization across the studied areas. The trade-offs of the geocentric approach emerge as limitations to a fine-grained investigation of urban disaster risk dynamics, showing the epistemological issues influencing the understanding and conceptualization of space.

2.2 Issues in Disaster Studies: Spatial Vulnerability and the Scale Problem

Spatial vulnerability in this quantitative geographic connotation is functional to displaying how risk variables are distributed on a territory, region, or city, and has supported the understanding of disaster risk dynamics across time and space.

2.2.1 Origins of the Concept

The established notion of spatial vulnerability is rooted in Cutter and Solecki's (1989) studies for the Hazard of Place (HOP) model, building upon Hewitt and Burton's (1971) Hazardousness of Place model and adopted to analyze and map the hazard parameters on the regions affected by airborne toxic release. In further revisitations of the HOP model, social, politic, and economic sources of vulnerability were outlined having explicit spatial outcomes—that

is, outcomes manifesting in, and distributed across, space (Cutter and Solecki 1989). The study assumed GIS-assisted spatial analysis as a necessary method of investigation, consolidating the cartographic approach centered in quantitative geography that is now extensively present in disaster literature. The HOP model introduced the vulnerability assessment in spatial terms by looking at its spatial dimensions and spatial variability (Cutter et al. 2000), with maps showing that the distribution of different vulnerabilities (social, biophysical) on a territory would not necessarily overlap. By rendering the nuanced and multi-layered risk profile of places, the HOP model became an effective diagnostic tool for multi-hazard assessment at territorial scale, consolidating the geographic approach to vulnerability from a spatial perspective. As expressed in Cutter's words: "Physical hazard exposure and social susceptibility to hazards must be understood within a geographic framework, that is, the hazardousness of a specific place. This uniquely geographical concept considers the threat from all hazards in a given place and provides the opportunity to mitigate several hazards concurrently. By harnessing geographic innovations such as GIS, we have the ability to investigate the spatial nature of multiple hazards and the specific subpopulations that are differentially affected" (Cutter et al. 2000, p. 731).

The evaluation of vulnerability in spatial terms adopting cartographic methods and quantitative geography serves large-scale assessments with large areas of units but is not equally effective and applicable at smaller scales, such as the urban, which would require a more granular approach (Cutter et al. 2000). Conscious of the scale limitation, Cutter et al. (2000) expressed the need for additional research on spatial vulnerability of urban areas to be performed with reduced units of analysis—that is, micro-mapping. This reference to spatial vulnerability used for both territories and cities, without discriminating between the two dimensions, informed one school of thought in disaster studies, which indeed retained a vague differentiation between the macro- and microscale, and, consequently, the inexact understanding of disaster risk dynamics in urban contexts.

2.2.2 Influences

In disaster studies, references to spatial vulnerability are frequent in large-scale multi-hazard assessments in relation to local exposure, sensitivity, and capacity, mapped over time within a given region (Rashed and Weeks 2003; Simpson and Human 2008; Fang et al. 2016). Among recent examples are works assessing the geography of poverty, studies mapping out and visualizing the distribution of indicators of social vulnerability across different regions (Contreras et al. 2011; Fekete 2012; Frigerio and De Amicis 2016; Frigerio et al. 2016; Carnelli and Frigerio 2017) and defining the hazard profile of a territory to inform urban and regional planning (Li et al. 2016; Bevacqua et al. 2018). Large-scale, multi-hazard social vulnerability assessments map out spatial patterns of risk areas informing operational assessment tools (De Sherbinin 2014; Raduszynski and Numada 2023).

Even when mobilized at the urban scale, the notion of spatial vulnerability retains this geographic connotation and either refers to location and width of hazard-exposed areas in urban or peri-urban context (Sritart et al. 2020), or it is used to express local and global impact of a specific disruption on a spatial network (Hu et al. 2019). Hazardous conditions in cities are generally mapped by means of spatial vulnerability indicators (Contreras et al. 2011, 2017), consisting of variables exogenous to the spatial network and distributed across space rather than endogenous and descending from it. While performing the urban micro-mapping recommended by Cutter et al. (2000) these studies fail to engage with the backbone, and mutated concept, of space in cities—that is, the urban spatial network intended as active configurational component, influencing the functioning of the physical and social city (Hillier and Vaughan 2007). The existing studies mobilizing the concept of spatial vulnerability at the urban scale are not looking at space per se, but are using it as an ancillary entity, either the canvas upon which to project and visualize other variables, or as a passive element that is affected by, but not actively generating, hazardous conditions.

Outside the domain of disaster studies, attempts at approaching spatial vulnerability from a socio-spatial perspective mobilize critical spatial theory and urban geography, to reflect on the dynamics of creating consumers' vulnerability within social space (Saatcioglu and Corus 2016). Although rooted in marketing and apparently removed from the disaster risk reduction (DRR) remit, the study outlines some of the links between public space, users' agency, and variations in "socio-spatial disadvantages" (Saatcioglu and Corus 2016) that highlight the links between power, socio-cultural, and economic values, and production and use of space in cities.

3 Issues in Epistemologies: Fallacies in the Discourse on Space

The geoconnotation of spatial vulnerability is underpinned by, and contributes to consolidating and reproducing, a narrow understanding of space and its relational properties (Heesen et al. 2014; Bergmann 2016). This, in turn, undermines the understanding and interpretation of dynamics of risk and vulnerability associated to space at the urban scale. The narrow understanding of space is rooted in the deeper question of its definition and representation, anchored to broad, vague, or imprecise meanings (Thrift 2006) and common to the domains of both physical and social sciences. In

fact, "The definition of space was caught up in the dialogue between natural and human sciences. That was one of the encounters through which space became sedimented into a particular chain of meanings" (Massey 2005, p. 31).

The currently adopted concepts of space a-critically reflect these established meanings, acquired through commonly accepted positions rooted in epistemological fallacies: space as opposed and subordinated to time, space as a geometric entity, the physical space of experience separated from the abstract space of the mind, space as a background to human activity (Lefebvre 1991; Massey 2005). The neglect of spaces' inherent features—namely, its being relational (product and generator of interrelations), in its containing heterogeneity, and its being dynamic, always under construction, never finished (becoming)—spreads beyond geography, impacting other disciplines that deal with the spatial dimension.

An example, observable from philosophy to architecture, is the misunderstanding of, and antagonism between, the dimensions of intellectual space and lived or intuitive space. In his critical reading of Levi Strauss' approach to culture, Fabian (2014) argued that the philosopher built the argument on space and time that favors misinterpretation: he initially presented space of experience and social interaction, then reduced it to a taxonomic space, the tabula where to plot "any and all cultural isolates"—in fact, a map. Following this misconstruction, the experienced space is confused with its representation due to a combination of omissions and assumptions that consolidate its conceptualization, bouncing between philosophy (Fabian 2014), social theory (Massey 2005), and urban theory (Lefebvre 1991). The resulting ambiguity impacts the imagination of that space and the disciplines building upon it. The established notion of spatial vulnerability as a map of vulnerabilities is a clear example of this operation, showing how the inexact conceptualization of urban space has trickled down into cognate disciplines in physical geography and social sciences, being then persistently replicated. In architectural and urban design, consequences of this overlap manifest in the conflict between the abstract space intellectualized by the designer-planner against the experienced space of the users—pedestrians (Hillier 2008) also expressed as the "authored" space of superimposed planning versus the "authorless" space of urban informality (Psarra 2018).

4 Issues at the Urban Scale: The Lack of a Configurational Perspective

The geoconnotation of spatial vulnerability assumes space as canvas for the cartographer, playing no active role for disaster risk: disaster risk variables change in/across space but not due to/because of space. This assumption works at the macrolevel, where cities can be treated as homogenous spatial units from a territorial perspective (Lees 2002). To understand spatial vulnerability at the urban scale, a more granular approach, compared to the geocentric one, is needed; one that accounts for the network of UPOS—that is, all publicly accessible pedestrianized streets and squares—and its fundamental function as relational space of human interaction (Hillier 1986, 2005; Harvey 1988; Lefebvre 1991; Massey 2005). The non-quantitative notion of urban scale herein adopted builds upon Hiller's socio-spatial characterization of "urban" (1989) and is applied to all built-up areas showing a spatial culture, that is, a distinct way of ordering space, so as to "produce and reproduce social relations" (Hillier 1989, p. 6). In contemporary city planning, the production and organization of space, intended as material environment (Simonsen 1996), is operated through land partition and zoning and driven by real estate values. Hence, space production becomes both a manifestation and an exercise of power (and interests), carrying different values and relevance (Lefebvre 1991; Saatcioglu and Corus 2016; Buckhardt et al. 2019). The absence of socio-spatial sensitivity in planning emerges among the consequences of the approach to urban planning consolidated by the 4th International Congresses of Modern Architecture (CIAM) in 1933, informed by functionalist principles, disproportionately centered on dwelling (that is, the physical city), and devoid of the sociological intentions that the modern movement promoted in its theory (Gold 1998; Mumford 2019). Consequently, the network of UPOS is shaped and dimensioned based on quantitative standards, prevalently subordinated to buildable spaces, and often treated as a residual element. Emergency planning has replicated both in content and structure the flaws of everyday planning, contemplating space only as provision of "square meters per capita" when defining size and distribution of gathering areas and muster points for evacuation, or as a selection of routes connecting critical infrastructures. Once again, the widespread spatial network, and its effects, are disregarded.

The a-spatial approach of urban and emergency planning has practical implications for urban disaster risk assessment and mitigation, starting from urban vulnerability assessment, where the threefold separation between physical, social, and spatial dimension of cities is not replicated. So, if physical vulnerability at the urban scale is the fragility descending from buildings and artifacts, and social vulnerability derives from the activities of everyday urban life and transformations (Hewitt 1997), no spatial counterpart is currently considered that informs about the rate of vulnerability associated to the urban spatial network and endangering its occupants. This is problematic in the case of specific hazards, such as earthquakes, because overlooking the spatial network means failing to notice the

first informal infrastructure activated in the emergency and used, simultaneously, by all citizens.

A shift is needed, that moves from looking into the "spatial distribution of vulnerability" to considering "distribution of spatial vulnerability" when the scale of the inquiry changes. This would require moving away from the consolidated geo-centered approach. Instead, first adopt a configurational perspective that considers the simultaneously existing relations between points in the spatial system, influencing the city's functioning (Hillier et al. 1993; Vaughan et al. 2005). Second, define how the spatial network influences variation of exposure and capacity, hence vulnerability creation (Watts and Bohle 1993; Bohle 2001). The concept of space as a functional element in cities is explored in the internalist studies in urban morphology (Gauthier and Gilliland 2005) that consider the intrinsic relational nature of the urban spatial network and its role in the functioning of the urban systems.

Space syntax—the active role of space in cities: Space syntax argues that urban space should be understood as a spatial system whose network of public spaces (streets, squares, parks, and so on) is made up of destinations and passing through routes (Hillier and Hanson 1984; Hillier 2006; Hillier and Vaughan 2007). It then suggests that the mathematical qualities of that network, expressing how accessible and well connected these destinations and passing through routes are, account for the probability of users (that is, pedestrians) visiting/using certain parts of the network more than others—all other decision-making variables being equal (that is, not considering individual preferences/intentions such as wanting to avoid crowds, take a sheltered route, looking for a niche shop, and so on) (Hillier et al. 1993). Namely, space syntax suggests and has proven through empirical research that movement patterns, and by extension human encounter, have a fundamental connection to the way urban space, specifically the street network, is configured (Hillier et al. 1993). Moreover, the allocation of land uses—particularly, commercial/retail uses—has been found to relate to the spatial configuration, whereby well-integrated in the network streets are found to be occupied by public-facing uses (Hillier 1996). It follows that when spatial configuration is not accounted for in planning and decision making, spatial layouts designed to perform specific functions might fail to do so, predisposing to crime, social injustice, and social vulnerability (Hillier 1986; Vaughan et al. 2005; Vaughan and Geddes 2009)—up to disaster risk (Cutini 2013; Marin Maureira and Karimi 2017; Giuliani et al. 2020).

5 Urban Form and Disaster Risk

Departing from the spatial vulnerability gap at the urban scale, a study on urban form and disaster risk was conducted focusing on the spatial network's role in urban disaster risk dynamics.

5.1 Recontextualization of Knowledge

By adopting a critical realist ontology, this study reframed the understanding of space through the lens of risk, by combining social and spatial theories, questioning existing interpretations and reviewing the enforced paradigms in urban and disaster studies (Næss 2015; Danermark 2019; Albris et al. 2020). The critical realist ontology supported a multimethod approach encompassing (1) thematic analysis of planning policies and spatial practices (qualitative); (2) spatial analysis of the urban spatial network (quantitative); (3) translation of selected spatial properties into relevant disaster variables of the broadened Disaster Risk Mnemonics $DR = H \times [(V/C) - M]$, with H = Hazard (and exposure to secondary hazard), V = Vulnerability, C = Individual capacity of self-protection, M = External protection provided by the state (Wisner et al. 2011) (recontextualization); and (4) interpretation of results through the vulnerability framework using the Pressure and Release model (Blaikie et al. 1994). This strategy enabled connecting spatial components of cities to specific outcomes in disaster contexts, producing evidence-based knowledge redefining the established notions of disaster risk variables at the urban scale—namely, exposure and capacity of self-protection, and, through their interplay, vulnerability (Watts and Bohle 1993; Bohle 2001). In line with the interpretive approach, space syntax theory and methods were used for their hermeneutic and explanatory potential (Griffiths 2012).

5.2 Methodology Overview

This study adopted a mixed-method approach to multiple case studies, in a multi-dimensional investigation examining planning, use, and configuration of the spatial network of earthquake-prone settlements, in the everyday and emergency scenarios (Fig. 1). Data collection methods included desk-based research and six weeks of fieldwork in the case study locations between April and May 2019, to perform interviews and retrieve documents and maps not available online. Data preparation encompassed spatial modeling of segment maps in the ArcGIS environment, and transcription of interview recordings. Data analysis encompassed spatial analysis of the refined maps, and thematic analysis of policy documents and interviews. The broadened disaster risk mnemonic (Wisner et al. 2011) was used to define spatial disaster risk variables from configurational measures in spatial analysis, whereas results were interpreted through the Pressure and Release (PAR) model (Blaikie et al. 1994) (Fig. 1). The limitations associated to the PAR model's breadth in time—specifically, the drop of evidence for causal connection between consecutive stages of analysis—were mitigated by narrowing the timeframe of the study and designing an analytic strategy supporting explanation building. The analysis

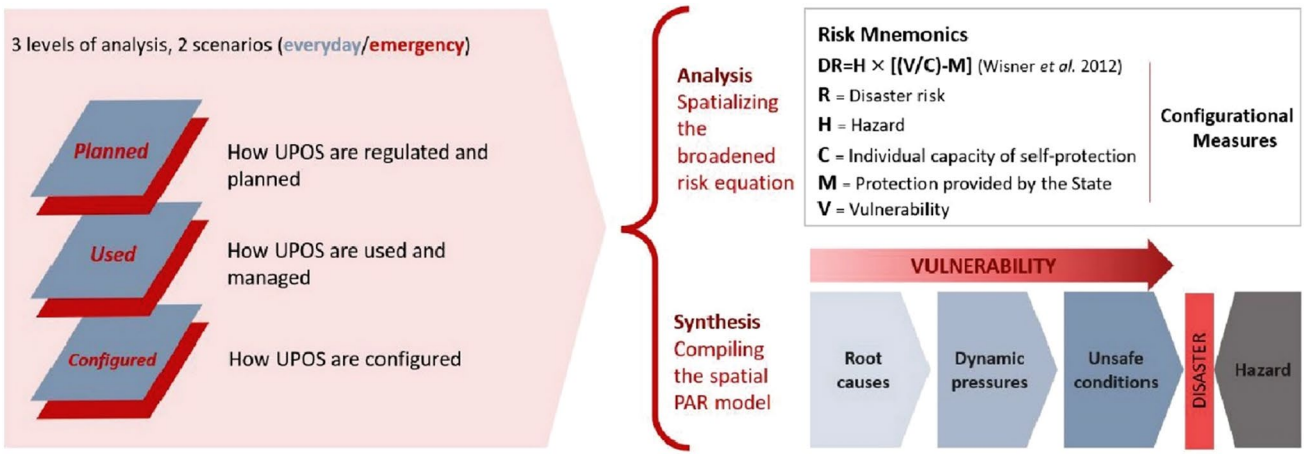

Fig. 1 Overview of the multidimensional investigation performed in the study towards spatial vulnerability reconceptualization. *UPOS* urban public open spaces, *PAR* pressure and release model

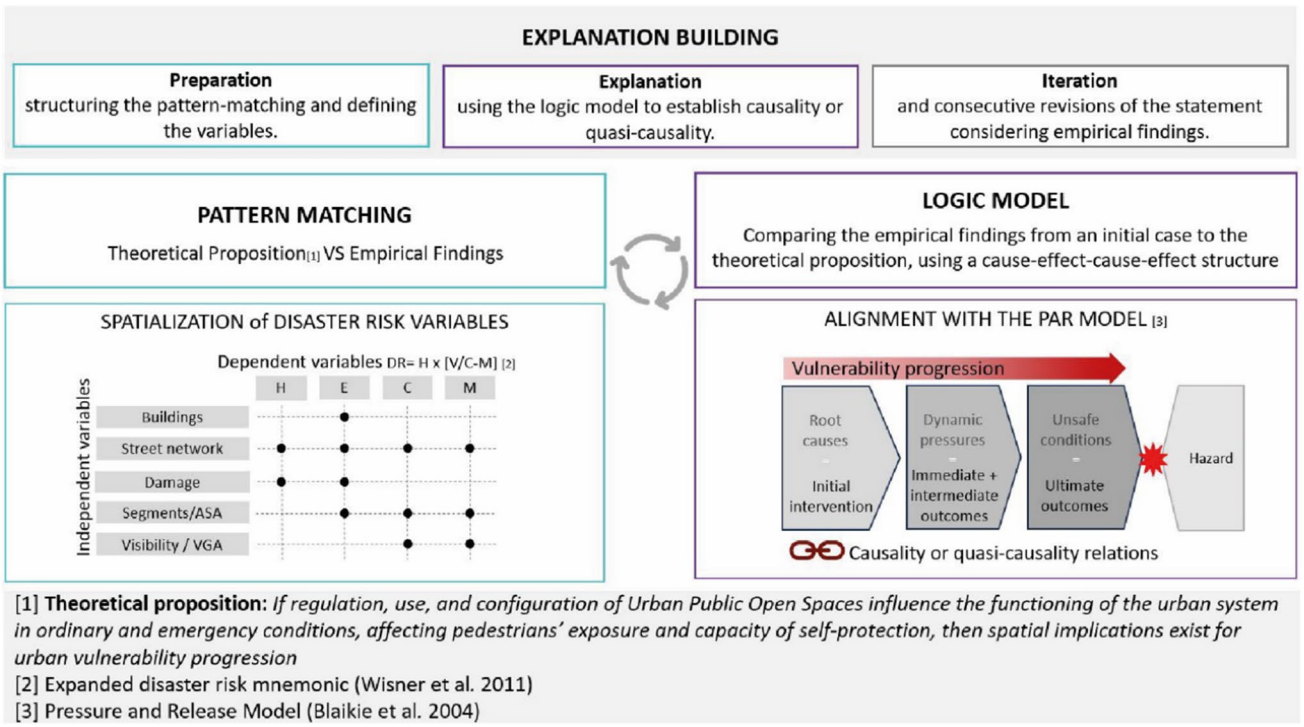

Fig. 2 Analytic framework designed for the case study analysis towards the reconceptualization of spatial vulnerability. *ASA* angular segment analysis, *VGA* visibility graph analysis. *Source* Author elaboration on Yin (2014)

focused on the period 1942–2019 to trace influences on spatial planning of the processes prompted by the 1942 Italian Planning Law, which aligned the Italian town planning to supranational trends in spatial planning, land partition, and governance (Piccinato 2010). The analytic strategy, integrating pattern matching and logic model (Fig. 2) enabled to trace cause-effect-cause-effect patterns and populate the PAR. The goal was not to prove causality but to unfold the implicit connections between planning policies, urban form features, formal and informal spatial practices, and vulnerability manifestations in spatial terms.

5.3 Research Design: Case Study

Four case study locations were selected, one from each region hit by the 2016–2017 Central Italy Earthquakes, defining a single-hazard and multi-location scenario. The investigation was treated as a multiple, embedded case study,

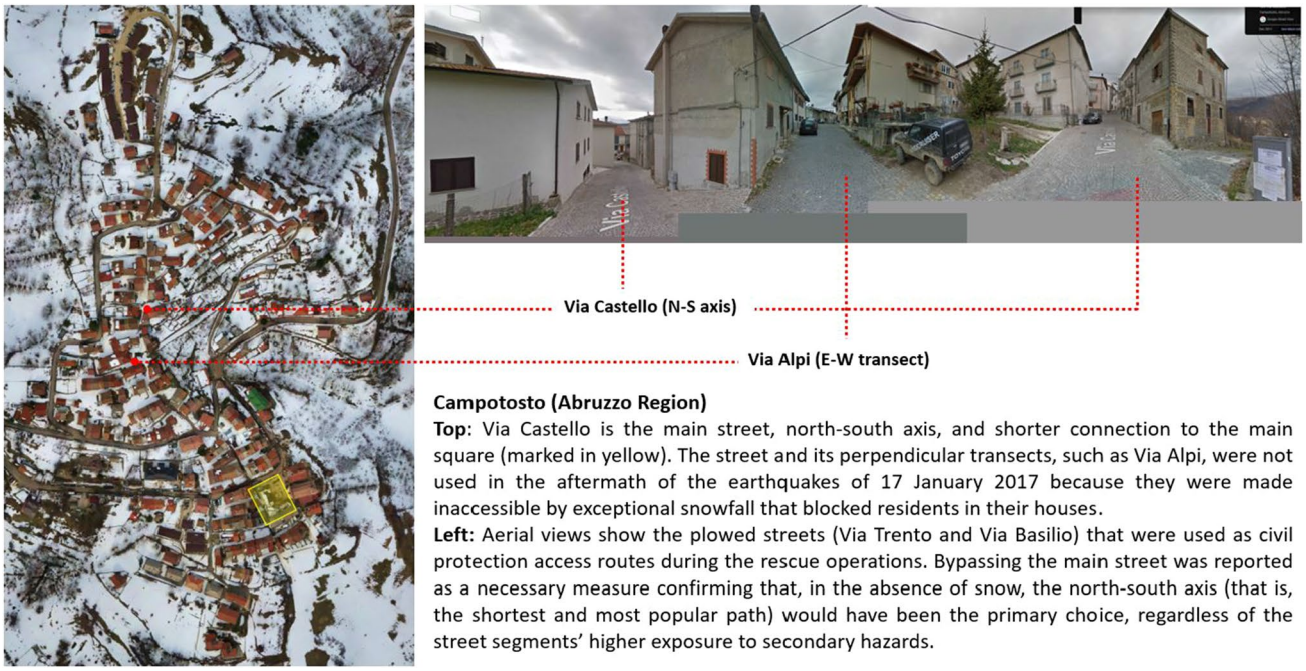

Fig. 3 Aerial view and street view composition of Campotosto, case study from the Abruzzo Region and epicenter of the 17 January 2017 earthquake. *Image sources* Author elaboration on Google Street View; aerial view courtesy of Norcia Fire Brigades

with each case presenting multiple units of analysis (Yin 2014) namely planned, used, and configured space (Fig. 1). Based on criteria of relevance, layout features, and data availability, the selected locations were Amatrice (Lazio Region) epicenter of the first mainshock of 24 August 2016; Visso (Marche Region) and Norcia (Umbria Region) respectively epicenters of the consecutive shocks of 26 and 30 October 2016, and Campotosto (Abruzzo Region) in the epicenter of the fourth shock of 17 January 2017. The analytic framework ideated for the study integrated the strategies of pattern matching and logic model to build explanation of the studied phenomenon (Fig. 2). Spatial and thematic analyses were performed in parallel, although with alternate predominance, mutually informing their intermediate outcomes—in line with the iterative character of the analytic framework.

5.4 Data Collection

The desk-based research retrieved online policy documents and archival records from Italian/EU institutional websites (municipalities, regional and central governments, civil protection, European Union, Eurostat, and Istat), and the raw data for spatial analysis, including damage maps of the building stock in the four settlements produced by municipalities and fire brigades, and Road Centre Lines (RCL) of the urban networks extracted from OpenStreetMap (OSM) using OSMnx Python package (Boeing 2017). The fieldwork was used to gather the cartographic data and documents not available online (such as Municipal Civil Protection Plans) and perform field surveys (Fig. 3) and semistructured interviews, in Italian, with local participants recruited with the support of local gatekeepers. Interviewees were selected based on their active role in planning and emergency operations before and during the 2016–2017 earthquakes, to inform about planning, management, and use of UPOS in everyday and emergency. The pool consisted of local civil protection volunteers, regional civil protection coordinators, firefighters from within and outside the regions, local planning officers, local councillors and mayors—later organized into the macro-categories of policymakers, rescuers, and technicians. Interview questions received ethical approval from Loughborough University with Risk Assessment no. DT8190.

5.5 Data Analysis

Thematic analysis was performed on a total of 69 policy and planning documents released between 1945 and 2019, and 24 interviews. To minimize information loss intrinsic in translation (Edwards-Jones 2014), all documents and interviews were analyzed in the original language (Italian). The analysis adopted a hybrid coding framework, combining inductive and deductive approaches (Braun and Clarke 2006; Braun et al. 2012). The clusters of strong themes (urban form, use, planning, risk, heritage, attitudes) and associated subthemes defined cross-case recurring patterns, which

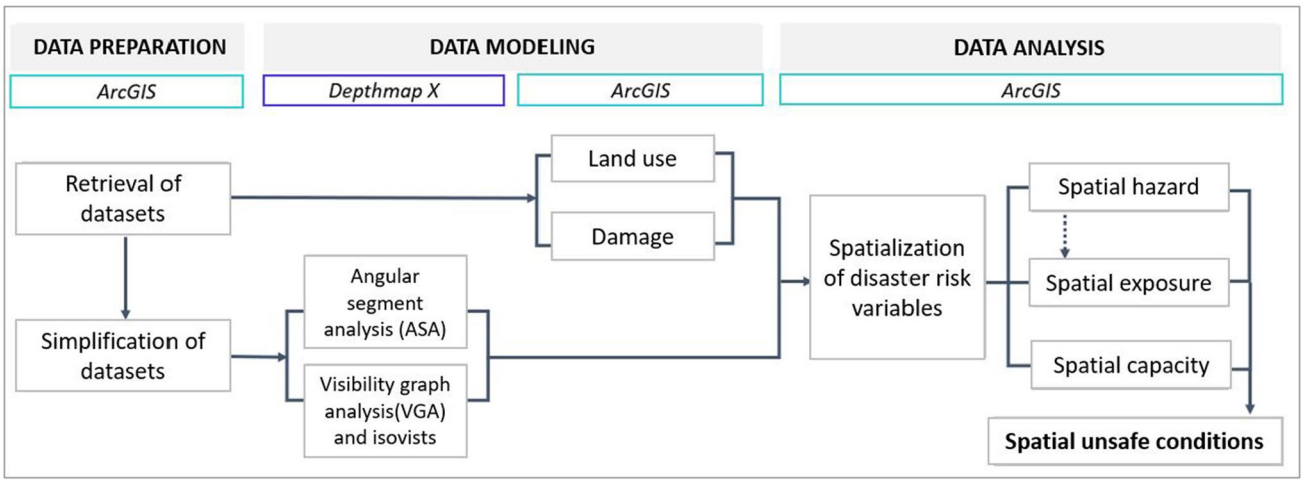

Fig. 4 Diagram illustrating the integrated spatial analysis workflow developed to spatially translate disaster risk variables through configurational measures

shaped the understanding of emerging processes and the interplay of policymaking, planning, and spatial practices behind urban disaster risk creation in the studied locations.

Spatial analysis involved using tools and methods grounded in space syntax theory, to enable an understanding of space as a network. The analysis adopted a novel workflow developed for the study, integrating DepthmapX for configurational analysis and ArcGIS for data preparation, modeling, and visualization (Fig. 4). Specifically, ArcGIS was used to map information embedded in the building stock (land use, damage, debris obstructions) and to associate them to selected configurational measures to perform the spatialization of disaster risk variables. DepthmapX was used to perform angular segment analysis (ASA) (Turner 2001) and visibility graph analysis (VGA) (Turner et al. 2001) on the spatial network. In ASA, the limitation linked to manually drawn axial maps, potentially influencing replicability, was overcome by adopting simplified Road Centre Lines (RCLs) maps extracted by OpenStreetMap (Turner 2007; Krenz 2017). Spatial analysis stages were as follows:

- The ASA on Road Centre Lines (RCLs) (Turner 2007), to study pedestrian movement in the network. Selected measures for movement potential of street segments, in combination with land use and damage information along the street fronts, enabled defining Spatial Hazard and then develop indicators for Spatial Exposure in space (Del Pinto et al. 2021). These were high movement potential indicating overcrowding (CIC), highly damaged front length/street segment length ratio (HD/SL), and presence of obstructions along a street segment (OBS).
- The VGA on the uninterrupted spatial network, to study visual accessibility and visual permeability. The VGA measures for intervisibility relations between points in the network enabled defining indicators for Capacity of Self-Protection in space—namely, routes' proximity to catchment areas, and stability of visual fields and visual dominance along routes (Del Pinto et al. 2021).

Fluctuations of indicators were associated with variations in spatial unsafe conditions—that is, safety of pedestrians in the spatial network.

5.6 Overview of Results

To visualize the spatial vulnerability progression over time, a spatial Pressure and Release model was compiled, with results informing about Root Causes, Dynamic Pressures, and Unsafe Conditions. Results of spatial analysis informed the Spatial Unsafe Conditions generated by and insisting on the spatial network, and endangering pedestrians' safety. Spatial Exposure (SE) and Capacity of Self-Protection (CSP) in space were assessed and visualized along the informal evacuation routes used in the aftermath of the mainshocks (Fig. 5), as reported in interviews. In assessing SE, indicators were expressed in three formats: tables with the numerical values of indicators per street segment, radar charts with the normalized values for global route assessment, and maps with color-coded visualization of street segments along the routes. In assessing CSP, indicators were expressed in two formats: maps with color-coded visualization of simplified VGA results along the routes, and a summary table to evaluate the combination of routes' proximity to catchment areas, visual stability, and visual dominance.

The combined results, overlaying SE and CSP, portray the spatial unsafe conditions on each route, representing the manifestation of their potential for spatial vulnerability. Specifically, the predisposition to overcrowding (resulting from

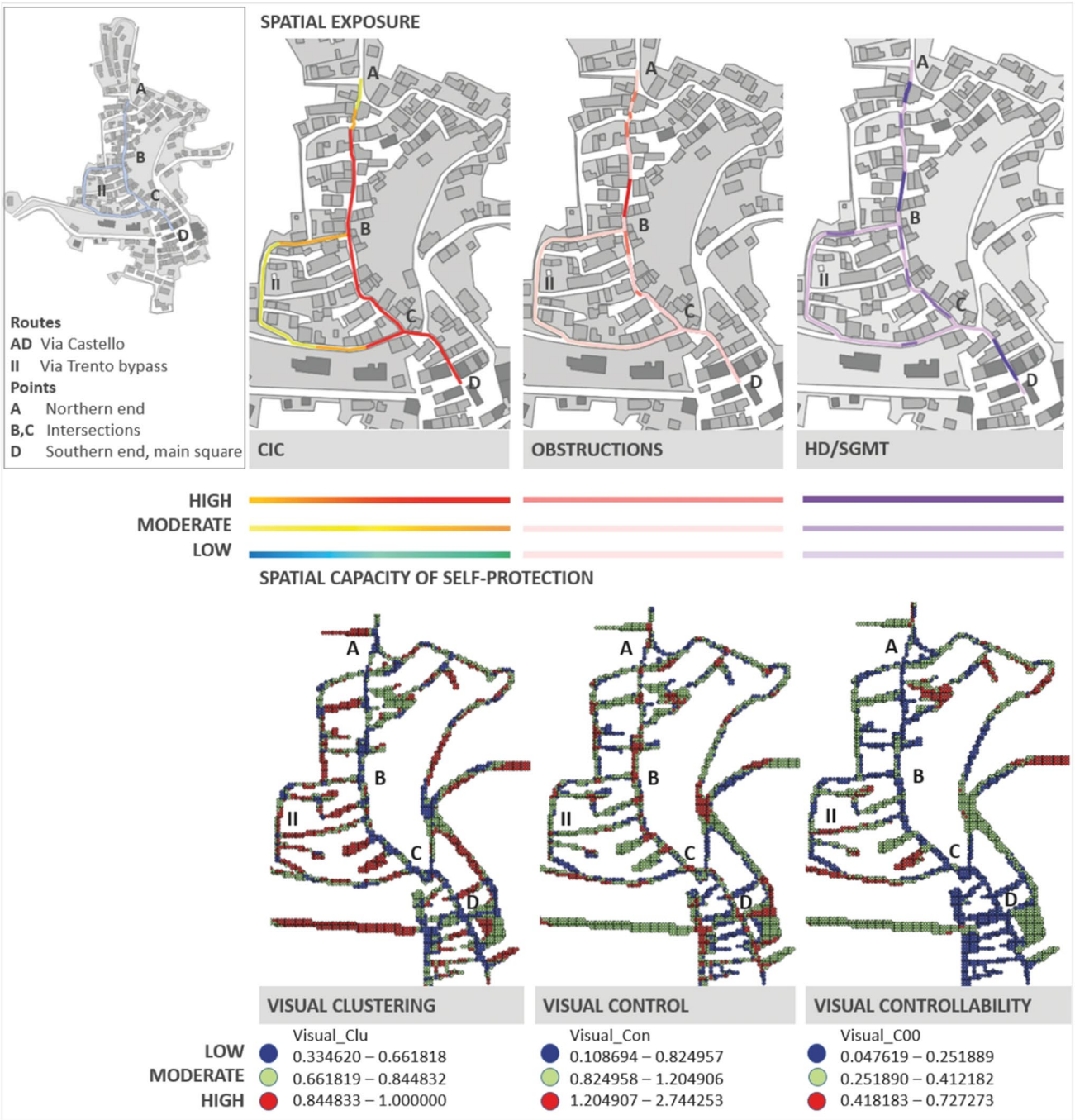

Fig. 5 Example of spatial analysis performed on the informal evacuation routes in the settlement of Campotosto (Abruzzo Region), with visualization of indicators of spatial exposure (top) and capacity of self-protection in space (bottom) using simplified space syntax results. *CIC* combined integration and choice parameter, *HD* highly damaged front, *SGMT* street segment

network configuration combined with clusters of attractors) and the presence of strips of fragile building fronts, indicated a route's spatial exposure to secondary hazards. The presence of consecutive decision points along a route and presence of gathering areas within walking distance, were enablers for capacity of self-protection in space. Values of SE and CSP can fluctuate along the same route, with segments scoring higher exposure than others, and intersections supporting better decision making than others, demonstrating that exposure and capacity are not mutually exclusive but, instead, co-exist. These variations can only be detected by adopting a granular approach to urban disaster risk and performing context-specific reading of the combined effect of spatial network properties and land-use information.

The results also show that some of the chosen spatial metrics retain twofold potential. For example, the configurational proxy for spatial exposure detecting streets' sensitivity to movement (that is, the space syntax Combined Integration and Choice parameter, CIC), also highlights what portions of the spatial network are used more intensely in the everyday practices; this is fundamental for pedestrians to acquire and consolidate spatial knowledge that can be mobilized in the emergency (spatial capacity building).

Thematic analysis unpacked root causes and dynamic pressures, informing on urban transformations (land use changes, urban conservation measures) and everyday spatial practices culminating into the spatial unsafe conditions manifested during the emergency. Interviews validated the spatial analysis results, reporting that the use of the spatial network during informal pedestrian evacuation replicated the patterns of everyday use, in turn affected by presence and distribution of specific activities and attractors along the network and hindered by the combined effects of configuration, land use, geometry, and building stock maintenance. Specifically, triangulation of interview records, spatial analysis results, and physical survey, showed that in the four locations, evacuees used the most popular yet not necessarily safest routes (that is, the main streets, scoring highest movement potential in ASA, and in all cases bordered by damaged buildings' fronts) to reach the main squares, prevalently overlooking other open areas closest to their original location. Interviews also suggested that the emergency use of space of permanent users (residents) and transitory users (prevalently tourists) was influenced by their different experience of and permanence in specific areas of the spatial network.[1] Overall, the citizens' first response was left to self-organization because the enforced Municipal Civil Protection Plans (MCPP), mainly serving as technical documents for experts/rescuers, did not explicitly account for pedestrian evacuation routes. Interviewees associated the place-specific features of historical urban form to both sociocultural/identity values, and navigation constraints. Specifically, streets and squares were reported as on the one hand the cities' social hubs and popular tourist destinations and, on the other hand, an infrastructure insufficient to support contemporary land use, traffic needs, and emergency operations.

Policy documents brought to light the influence of national planning and disaster risk governance upon local dynamics of spatial vulnerabilization. City planning and municipal civil protection planning reflected the national trends toward technocratization and centralization of the Italian planning process, rooted in the post-WWII urban planning law, and determining the subordination of qualitative spatial design to quantitative principles. The separation of the spheres of ordinary and emergency planning and the consequent segregation of expertise were reflected in local urban planning devoid of risk awareness and mitigation elements. The reactive character of national DRR governance was also replicated at the local scale, and the decades-long centralization of civil protection action prevented the organic development of local DRR systems while exacerbating the over-reliance on the national disaster response system.

6 Discussion: Spatial Vulnerability Reconceptualized

Findings have confirmed the dissociation between physical space, social space, and planned space in ordinary and emergency planning, and shown how this generates specific vulnerable conditions. This study redefined spatial vulnerability at the urban scale as "The condition linked to reduced performances of UPOS in the emergency, potentially making the whole urban system more sensitive to the impact of an earthquake, and manifesting as reduced capacities and increased exposure of portions of the spatial network and its occupants."

In this connotation, the variable retains a twofold nature associated to endogenous and exogenous features of the spatial network. The exogenous features determine vulnerability of space, with the network made vulnerable by external agents such as land use, or adjacent vulnerable buildings representing a threat. Endogenous features determine vulnerability from space, with the network intrinsically vulnerable by configuration. Endogenous and exogenous spatial vulnerability features may not be apparent or unsafe in the everyday—yet, during the emergency, they can delay or impede wayfinding.

The reconceptualized spatial vulnerability is rooted in the exclusion of the role of the spatial network and its users from the planning and DRR discourse—an aspect manifesting the progressive erasure of the "space of experience" in favor of the "non-space of the mind" (Psarra 2014), relegating users to the passive role of consumers in the everyday or aided in the emergency. In such a perspective, the connection of spatial planning, profit, and power dynamics emerges

[1] The distinction between residents and tourists in the use of space recurred in interviews recalling the aftermath of the 24 August mainshock, occurred at the peak of seasonal tourism in the studied locations. "There was a massive evacuation of tourists […] Visso counts 1000 residents but over the summer numbers skyrocket and we performed a large evacuation during the night of 24 August, specific for tourists […] we found all people gathered in the main square […] partially because of the fear, partially because it was the largest space they knew." (first aider, Visso) "[…] People evacuated the buildings […] only a couple [of hotels] are in the historical center. Those people, in the historical center, headed straight to Piazza San Benedetto." (first aider, Norcia). Translation by lead author.

clearly: in the everyday, users are expected/guided to use space according to the attractors' distribution; in the emergency, users are expected to navigate space being guided by rescuers—their individual agency and capacity of self-protection disregarded.

In the studied contexts, the replication of the a-spatial approach in planning keeps spatially unsafe conditions undetected, untreated, and cyclically restored due to the conservative attitudes toward historical urban areas incentivized by their touristification. While preserving the historical value and amplifying the economic value of urban form, however, the practice to freeze it into a specific configuration fails to acknowledge the social value associated to the self-(re)organization of cities and sign of a continuous process of cultural imprinting based on use (Hillier 2008). Consequently, the adaptation process of urban form to its society is interrupted, in favor of an increasingly dehumanized and static spatial organization operated in planning (Hillier 1986). In parallel, Municipal Civil Protection Plans neglect the effect of the spatial network in urban vulnerability assessment and exclude both space and its users when outlining the critical infrastructures for emergency response. Plans are produced by experts, for experts, removing citizens from the pool of direct recipients.

Space as an ancillary entity, subordinated to buildings and profit; space inconsistently codified as critical infrastructure and only for a selected category of users; and space produced through a planning process that removes the collective subject from both creation and use, are all manifestations of the "technological utopia" (Lefebvre 1991, p. 9) endlessly replicating the same mode of production, rooted in the unquestioned, yet partial, knowledge of experts and decision makers (Wisner 1995). The exercise of power through spatial planning and its influence on the agency and experience of pedestrians show how decisions on space are, in fact, decisions on its users. From a disaster risk perspective, this epitomizes the case where the state/local government, expected to provide external protection, fails to do so, and instead reduces individual capacity of self-protection (Wisner et al. 2011). Individual capacity of self-protection is built and consolidated through everyday practices producing knowledge that can then be mobilized in the emergency (Gaillard et al. 2019). By shaping patterns of occupation of the spatial network through land use decisions, planning action indirectly affects the type and quality of spatial knowledge acquired by pedestrians through daily use of space (Lynch 1959; Harvey 2017). The impact of planning on users' ability to safely navigate space can be interpreted as a flaw in the long-term mechanism of external protection provided by the state, which is meant to enhance and never reduce capacity of self-protection (Blaikie et al. 1994; Wisner et al. 2011). An additional shortcoming detected in these mechanisms is represented by the polarization between aiders and aided during the emergency, with the latter treated as passive recipients of assistance delivered by the former. This aspect appears consolidated through national and local emergency planning that removes evacuees' agency in emergency management. Consequently, the enforced first response procedures omit both citizens as active respondents, and the spatial network as an informal and widespread critical infrastructure. These practices go hand in hand with the consolidated approach to urban disaster risk, looking at what happens across space, but not because of it: the spatial distribution of vulnerability and the limited information and action that it enables.

7 Conclusion

A goal of this study was to reclaim the role of space in urban disaster risk analysis in order to overcome the limitations of the current, geodriven approach to spatial vulnerability. The intent was to influence the understanding of disaster risk dynamics at the urban scale. We did so by presenting a study centered on urban form and disaster risk that brought to light the active role of the urban spatial network in the process of increasing the vulnerability of earthquake-prone settlements.

The research not only highlighted the combined role of spatial configuration and land use in fluctuations of pedestrians' exposure to secondary hazards and in their capacity of self-protection in an emergency evacuation, but also exposed some of the mechanisms behind the subordination of qualitative spatial planning to quantitative principles that have led to the current a-spatial planning. The application of space syntax knowledge enabled understanding undetected disaster risk dynamics associated to the urban spatial network, broadening the field of use of morphological techniques to assist urban disaster risk reduction (DRR). The choice of the Pressure and Release (PAR) model was intended to unpack the marginalization of configured space in the planning and DRR discourse. The framework enabled us to illustrate that the pervasive absence of socio-spatial sensitivity in planning is much more than just a diffuse incapacity to incorporate socio-spatial aspects in practice. In fact, it is a structural characteristic of post-WWII planning governance. Specifically, it appears as a manifestation of hegemonic interests enacted through control of space via land use decisions and emergency management, which generate the side effects of spatially unsafe conditions in emergency scenarios.

In this study, planned space emerges as the space of controlled and codified relations of use and power in cities. Its design is driven by the exchange value set by the producers and disregard for the consumer's values and agency. Configuration of the spatial network, formally unacknowledged in planning, emerges clearly as an active codeterminant of urban disaster risk, and has a significant impact on

vulnerability fluctuations of the city and its users. These variations remain widely undetected in the everyday but manifest when disasters strike. While results are context-bound, the theoretical considerations on the network's functional role in disaster risk fluctuation can be generalized. These insights provide prompts for future investigation into user-specific and hazard-specific variations of spatial vulnerability.

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