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Urban morphology in support of disaster risk reduction: toward theory and methods for a spatial approach to tackling urban vulnerability to earthquakes.

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Abstract

Among the most recent directions of urban morphology research is its integration with disaster studies, in support of disaster risk reduction (DRR) efforts at the urban scale. Yet, the built and unbuilt components of urban form are still disproportionately investigated for DRR purposes, with predominant approaches centred on buildings leaving the DRR potential of the urban spatial network relatively under-investigated.

This paper, at the intersection of urban morphology and disaster studies, is the first of a series looking at the spatial component of urban form through the lens of risk, with a focus on urban vulnerability to earthquakes. After discussing how the interplay of configuration, governance, and use of space impact urban disaster risk in earthquake-prone settlements, the paper introduces a method for the exposure assessment of urban spatial layout.

The method, applied on the configurational analysis of four settlements hit by the 2016 Central Italy Earthquakes, associates disaster risk variables to the urban spatial network's core elements. It develops (i) a theoretical re-definition of the significant disaster risk variables in relation to configurational measures; and (ii) an integrated spatial analysis workflow for visualisation and classification of street segments and routes based on their degree of exposure, to inform both ordinary and emergency planning. In (i), the spatial-configurational dimensions of disaster concepts (hazard, exposure) are identified to unfold the spatial potential in DRR. In (ii), the spatial analysis workflow builds upon the recently developed applications of space syntax angular segment analysis on OSM RCL network, by combining Volunteered Geographic Information (VGI) with land use and disaster-related datasets, to generate hybrid exposure segment maps within the ArcGIS environment.

The paper provides a twofold contribution : recontextualization and incorporation of space syntax theoretical knowledge into DRR, and innovative employ of existing applications for multidisciplinary and comprehensive approach to urban vulnerability assessment.

Keyword: *urban form, disaster risk, spatial vulnerability, spatial exposure*

Introduction

This is the first of a series of papers presenting the findings of a doctoral thesis on urban and disaster studies, redefining the relationship between urban public open spaces (UPOS) and urban vulnerability to earthquakes. Through the analysis of a set of case studies, chosen among the settlements hit by the 2016/17 Central Italy earthquakes, the main study provides a spatial interpretation of the core disaster risk variables, filling the gaps of the typically a-aspatial approach observed in both disaster theory and Disaster Risk Reduction (DRR) practice. After demonstrating that the approach to urban disaster risk overlooks the spatial components of cities, the thesis unfolded production and progression of spatial vulnerability in earthquake prone urban areas, provided a theoretical redefinition of the concept and the related variables of exposure and capacities, and developed a method for their spatial assessment and visualization (Del Pinto, 2021). In this work, *Spatial Vulnerability* has been redefined 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 manifests as reduced capacities and increased exposure of portions of the spatial network, and of its occupants''* (Del Pinto, 2021, p.191).

Recent discussions in the field of urban design and planning highlight the role of urban form in resilience (Romice *et al*, 2018). However, the relation of urban form to risk production and reproduction remains understudied - a missed opportunity for urban morphology in relation to emergency planning and Disaster Risk Management (DRM). This paper, as an extract of the main study, presents the assessment and visualization of spatial exposure, a precondition for spatial vulnerability (Cardona *et al.*, 2012), in the settlement of Amatrice, Italy. The following sections provide an overview of the significant gaps in theory and practice, introduce the integrated spatial analysis workflow to assess spatial exposure, and present the exposure assessment. Additional background information on the case study is provided in the appendix.

Background: the disconnect between spatial and disaster risk dimension

In the current DRR discourse, neither theory, nor practice, refer to the urban spatial network as functional element in relation to disaster risk: in theory, space is used either in its geographical connotation as a background or a canvas to project other information, to map indicators and analyse their spatial distribution, or as ancillary to buildings (Aubrecht *et al.*, 2012; Roy and Blaschke, 2015). In practice, only a fraction of the spatial network is generally used to serve the emergency evacuation in the civil protection plans (Del Pinto, 2021; Bramerini *et al.*, 2013; Regione Umbria, 2010). The treatment of space as a secondary element reflects the trend to spatiality characterising also the mainstream planning approaches and theories, where space is not considered in itself, but rather as background to human activities, and accordingly defined and connotated (Hillier, 2005, 2008; Peponis, 1989).

Promising analytical contributions toward a spatial approach to DRR come from the most recent developments in space syntax research on disaster risk, with works investigating the connection between spatial configuration and urban resilience (Karimi, 2012; Marin Maureira and Karimi, 2017) or spatial configuration and wayfinding in the disaster-prone systems (Allan *et al.*, 2013; Fakhrurrazi and Van Nes, 2012; Marin Maureira and Karimi, 2017). The role of urban configuration during disasters in Italian contexts is discussed in the research on post-earthquake emergency management that also introduces some spatial indicators for disaster risk (Cutini *et al.*, 2019; Giuliani *et al.*, 2020; Pezzica *et al.*, 2019). Attention to the urban street network in disaster studies is demonstrated by recent research focusing on the risk assessment of urban evacuation routes (Giuliani *et al.*, 2020; Quagliarini *et al.*, 2018) yet, these efforts are still a fraction in the majority of building-centred works.

These contributions are typically emerging from a spatial perspective and thus do not aim to address comprehensively the disaster risk production mechanisms as considered in disaster risk theory. Although offering valid inputs for methodological developments in configurational and spatial analysis, they impede integration of urban morphological insight in DRM and limits its potential role in DRR.

Introduction to spatial exposure

The concept of *exposure* in disaster risk is used to assess human and physical geography of risk, identifying the susceptible assets and people within hazard-prone areas (UNISDR, 2009). Assets' proximity to hazardous sources is direct consequence of their location, in turn linked to planning decisions, built environment transformations, and the construction process itself (Cardona *et al.*, 2012; Chmutina and Bosher, 2015). People, on the other hand, would tend to settle in, or gravitate towards, different areas - from the working to living places, up to the areas devoted to social aggregation – thus recording fluctuations in exposure to specific hazards changing with the location (Hewitt, 1997; UNISDR, 2009; Wisner, 2012). Exposure is known as a precondition for vulnerability, since a specific positioning or occupancy, in the absence of active mitigation countermeasures, can make unsafe - hence vulnerable - even otherwise safe assets or people (Hewitt, 1997; Lindell, 2011). The present analysis unfolds *spatial exposure* – intended as exposure *of* space, and *from* space, to secondary hazards – which contributes to exacerbate unsafe conditions for pedestrians during the earthquake evacuation in historical urban areas (Del Pinto, 2021).

Methodology

Underpinned by a critical realist perspective and employing mixed-method approach, the envisaged methodology unfolds spatial exposure as a combined product of built form, spatial configuration, and land use, in relation to the relevant patterns of spatial hazard. The proposed hybrid spatial analysis method employs space syntax tools and ArcGIS and is performed on VGI datasets extracted from OpenStreetMap – namely, Road Centre Lines maps (RCL) and land use maps. A preliminary operation, before the analytical steps, is the theoretical *spatialization* of disaster risk variables, to define the spatial counterpart of hazard and exposure through configurational measures, land use, and damage information (ref. table 1). The chosen configurational measures were *T1024 integration*, *T1024 choice* and the *Combined Integration and Choice (CIC)* in that they indicate the potential for natural movement of street segments - herein translated in likelihood of use, but also potential for overcrowding, for the routes (table 1).

Table 1. Table showing the disaster risk variables spatialization (author)

Spatial variables (primary variables)		Disaster risk variables (secondary variables)	
Variables	**Core Information**	**Hazard**	**Exposure**
Land use	*Residential and non-residential, with subcategories*		**x**
Damage to buildings	*Impact of earthquake on building stock*	**x**	
Road Obstructions	*Debris from collapsed or damaged buildings*	**x**	
T1024 Integration	*To-movement*		**x**
T21024 Choice	*Through-movement*		**x**
Combined Integration and Choice CIC	*Highest sensitivity to natural movement (overcrowding)*	**x**	**x**

Proposed spatial analysis workflow

The key elements for the workflow to assess spatial exposure, part of the broader methodology ideated in the analysis of spatial unsafe conditions (Del Pinto, 2021), consists of:

- **Data Extraction**, retrieving data from VGI datasets, including OpenStreetMap Road Centre Line (OSM RCL) maps and land use maps.
- **Data preparation**, where the OpenStreetMap Road Centre Line (OSM RCL) map is simplified based on the process proposed by Krenz (2017)
- **Data modelling**, within Depthmap and ArcGIS environment, with Angular Segment Analysis performed in the Depthmap environment, and land use and damage mapped in the ArcGIS environment
- **Data analysis**, where the independent spatial variables are translated into the dependent disaster-related variables of spatial hazard and exposure

The extraction of OSM RCL segment maps followed the process introduced by Boeing (2017), whereas the land use maps were retrieved from the Humanitarian OpenStreetMap Team online repository. The raw dataset was then pre-processed in the ArcGIS environment through i) simplification of Road Centre Line in preparation for space syntax Angular Segment Analysis (Krenz, 2017) and ii) cross-check of land use maps and incorporation of further land use and damage information.

Data modelling

Performing the Angular Segment Analysis

Angular Segment Analysis (ASA) was performed on the simplified segment map of the historical urban areas. The values of interest, T0124 Choice and T0124 Integration, were extracted from the output map, whereas their combination, Combined Integration and Choice (CIC) was calculated based on formula (1) (Al Sayed *et al.*, 2014) on a radius R=200 mt:

CIC = [value("T1024 Integration R200 metric")]{log[value("T1024 Choice R200 metric")+2]}* (1)

The top 25% CIC values, corresponding to the CIC core and highlighting the portion of segments retaining the highest movement potential (figure 4) were used as a proxy for overcrowding in the spatial hazard assessment of routes.

ArcGIS modelling: mapping land use and damage

The building polygons dataset was modelled in ArcGIS to review or assign land use and damage values to buildings, as follows:

- *Land use*: the information on land use and attractors' distribution embedded in the VGI shapefile was cross-checked against, and integrated with, the information from town plan and from on-site spatial survey.
- *Damage*: the distribution of damage on buildings was mapped combining the information in the HOT dataset, the aerial views produced by the National Fire Brigades, and AEDES reports from Civil Protection elaborated in Borri et al (2017). The damage values were then classified in high, moderate, and low, and the high damage class - corresponding to potential façade failure and consequent expulsion of debris - was considered as proxy for secondary hazard. The building polygons were then split into their component segments, to enable the calculation of metres of highly damaged façade pertinent to street segments.
- *Debris obstructions:* the distribution of debris was mapped from aerial views of the aftermath provided by the National Fire Brigades (Corpo Nazionale dei Vigili del Fuoco), then represented as debris points along the routes.

Hazard spatialization

Hazard spatialization enables visualising the distribution of spatial hazards, i.e. damage from buildings and potential for overcrowding of street segments, by linking the information on damage and obstructions to the segment maps generated in the ASA. The ArcGIS *spatial join* functionality allowed joining the attributes of facades to the closest segments, and the debris points to segments. The output is a segment map retaining configurational information, damage, and debris information, to be used for the spatial exposure assessment.

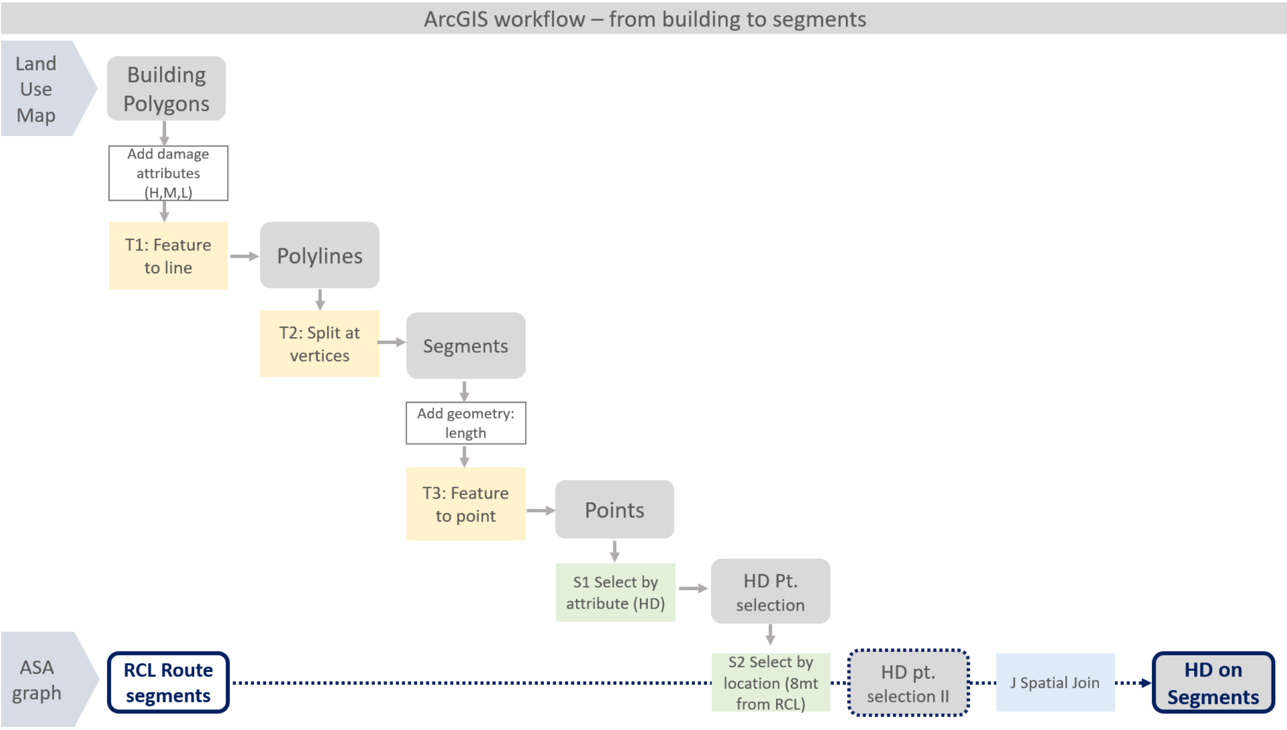


Figure 1. *Table showing the workflow for spatialization of High Damage (HD) variables (author)*

Figure 2. *Maps showing damage and obstructions visualization ante- and post- spatialization process. The land use map on the left shows the distribution of high damage on buildings in dark purple, and obstructions points, in red; the maps in the middle and right side respectively display the high damage on the segment map, and the obstructions on the segment maps (source: author).*

Analysis of spatial exposure - indicators and assessment

To assess spatial exposure, three indicators were created combining configurational information to risk-related aspects, then used to identify high- and low-sensitivity segments. The indicators were divided into endogenous (ENDO) (from configurational properties) and exogenous (EXO) (from the built component) corresponding to CIC, obstructions frequency, and metres of highly damaged façade along segments.

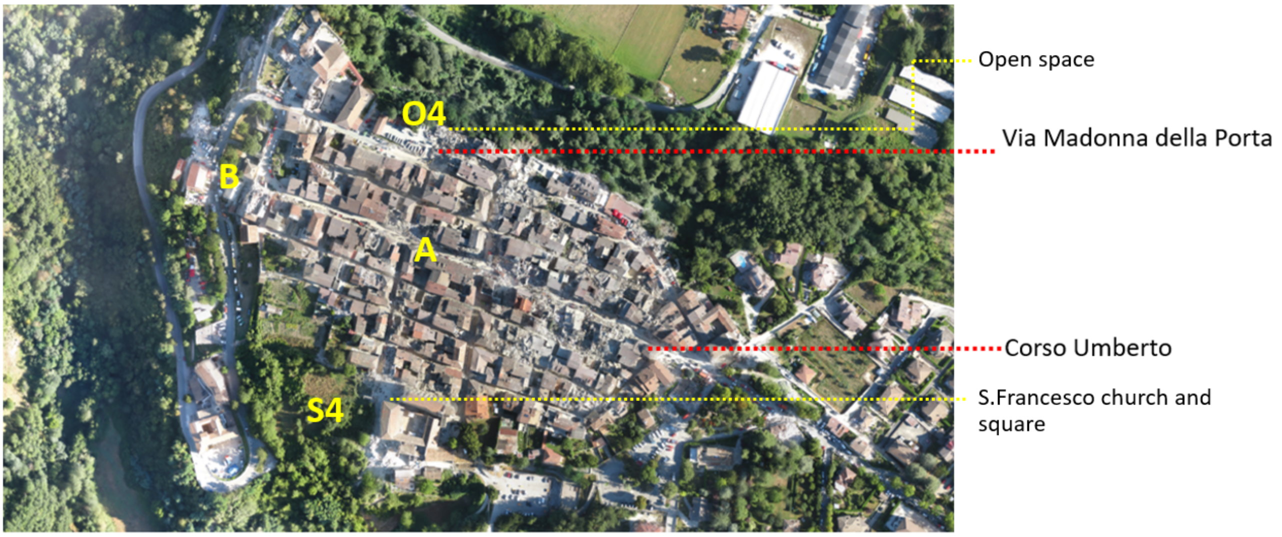
- ENDO: Combined Integration & Choice (CIC) - potential for movement and linked to overcrowding
- EXO: Obstructions' frequency (OBS) - presence and amount of obstruction along the segments
- EXO: High Damage per segment (HD/SL) - the length of facades scoring high damage along a segment

The indicators' values for each route were calculated in ArcGIS, normalised, ranked in three intervals (L,M,H) and visualised on the segment maps; radar charts were used to display the unique combination of indicators for individual segments in every route, and to quickly assess the route exposure as the combination of highest indicators; summary tables provide the analytical values of exposure per segments and routes.

- **Route map -** Portion of street segment map, colour coded and weighted based on the indicators. It shows the strength of the three studied indicators on each segment and offers an initial, quick visual summary of the information that is further presented in the radar chart and the table.
- **Radar Chart** – for a global exposure assessment of the route based on the highest indicators' values. In the chart, each series is a segment composing the route, for which we can visualise normalised values of overcrowding (CIC), damage (HD/SL), and obstructions (OBS) - and assess endogenous (CIC) and exogenous (HS/SL, OBS) exposure potential based on the graph shape.
- **Table** - enables in-depth assessment of segments. It provides numerical detail on the content of a radar chart, while displaying and ranking (by colour-coding) the single values, and calculate the exposure value for segments (E_s) as average of the three indicators E_s = (CIC+OBS+HD/SL)/3.

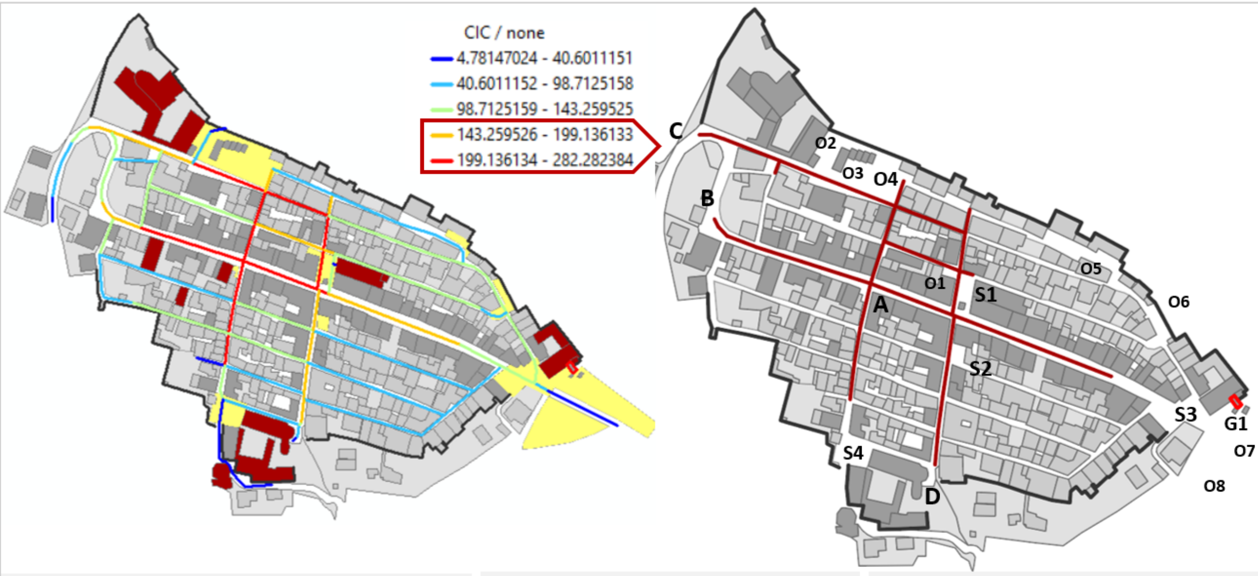
Performing the analysis: selection of informal evacuation routes

Due to the absence of formal evacuation routes in the emergency planning documents, the analysis focused on the informal evacuation routes extrapolated from the interviews; variations in spatial exposure were assessed along the streets recording the highest presence of occupants during the first emergency response**.** In Amatrice, due to the destructive impact of the earthquake on August 24th, 2016, large part of the urban street network was in fact not practicable: the analysis tested the three routes in the western quarter that were still accessible, from the main intersection (Corso Umberto/Via Madonna della Porta) to the first safe open space (A-B; A-O4; A-S4) as shown in figure 3. Figure 4 shows that the routes' segments fall in the CIC core, an indication – confirmed by interviews - suggesting the likelihood of the route to be used as a path not only in the everyday but also in the emergency.



Amatrice, aerial view showing the collapsed buildings on August 24th 2016

Figure 3. *Aerial view of Amatrice in the aftermath of the first main shock (August 24th, 2016) showing the damage to the building stock and the impact on the UPOS network (source: author elaboration on aerial view from National Fire Brigades)*



Egress routes in CIC core			Gates location in CIC core			UPOS location in the CIC core		
Core	Peripheral	External	Core	Peripheral	External	Core	Peripheral	External
C-O4; B-A-S1/S2, S4 - A- O4	S1-S3;	O5-S3; D-S3;	-	-	G1	S1, S2, O1	S3, S4 O2, O3, O4	O5, O6, O7,O8

Figure 4. *The CIC graph for Amatrice (on the left) and the extraction of the CIC core (right) with the indication of routes, open spaces, and gates. These elements are then compared against the CIC core and classified based on core, peripheral, or external to the CIC core*

Results and Discussions

The results are displayed via segment map, radar chart, and summary table - each offering a different analytical insight to the assessment of spatial exposure.

The segment maps (table 2a) facilitate the visualization of high/low values distribution on the routes: they display high CIC - potential for overcrowding - for all the segments departing from point A, and the presence of obstructions and damage along all the routes. Particularly, on route AB, the longest segment is exposed to high damage and obstructions, whereas on route A-O4 obstructions block the last segment right before to the open space, and damage all along the route.

Radar charts (table 2b) are used for global route assessment through the indicator values. The routes score ***AB***=3-2-1, ***A-O4***= 3-3-1, ***A-S4*** = 3-3-1 for CIC, HD/SL, OBS, respectively. Through the example of route A-O4, scoring 3-3-1, we can observe:

- High *Endogenous exposure,* with CIC values = 3, corresponding to the highest values of integration + choice meaning that the segment retains high potential for overcrowding.
- High *Exogenous exposure* , with HD/SL = 3, meaning that vulnerable facades insist on both sides of a street segment, for the whole length (see segment 6 on route A-O4); and OBS= 1 signifying the presence of at least one recorded debris point, that can narrow the street width and potentially threaten pedestrians' life.

The exposure table (table 2c) shows that, on route A-O4, segment 6 scores 3 for CIC, 3 for damage, and 1 for obstructions, with a 2.33 overall spatial exposure value - the highest within the route, and among the three routes. The output table is then imported back as attribute table for the segment map in ArcGIS, so that the weighted values of spatial exposure can be visualised on each segment.

The high values of CIC for all the selected routes (table 2) indicate that the informal choice of evacuation routes relates to the configurational properties and suggests that the CIC core can be considered a route predictor, at least in the absence of evacuation plans mobilising other routes. A relevant indicator of exogenous exposure is the value HD/SL (damage from facades/segment length), used to classify segments based on the percentage of their length exposed to highly damaged facades . For every examined route there is at least one segment falling in class 2 of HD/SL ratio, meaning that the total length of highly damaged facades facing the segment equals the segment length. This is, in other words, equivalent to a segment exposed along its full length to highly damage facades along one street side. For class 3, the segment is faced by highly damaged fronts on both street sides. The HD/SL ratio can be seen as a reinterpretation, on a disaster risk perspective, of the concept of double loaded street introduced by Caniggia and Maffei (Kropf, 2014) and provides complementary information to the meaning of pertinence strip (ibidem).

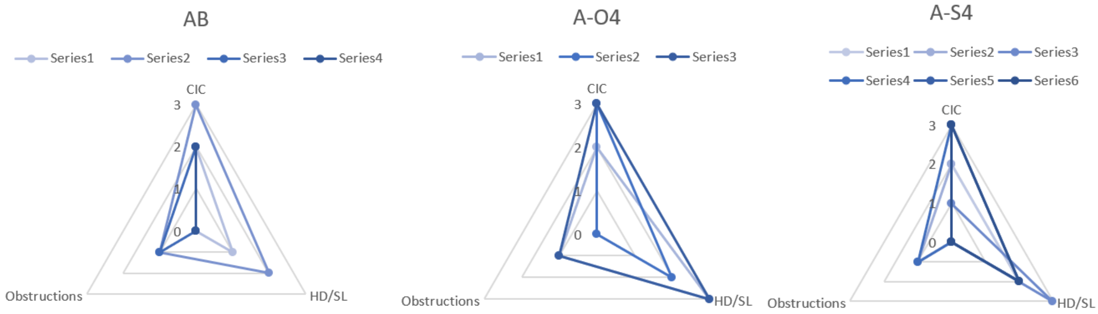
The route exposure from radar chart captures the highest exposure values of all the series (=segments). As shown in table 2.c, a route scoring high exposure (for example, A-S4, scoring values 3-3-1 for CIC, HD/SL, OBS respectively) can be the sum of segments that, individually, show moderate exposure values, but whose combination generates a path with diffused unsafe conditions threatening the occupants. This means, for example, that even a single hazardous façade along a route punctuated with multiple attractors, hence occupants, has a high potential for unsafety.

Table 2. Table summarising the route exposure assessment in Amatrice. The exposure to overcrowding, obstructions, and high damage is visualised in the segment maps (a); the three radar charts one for each route, show the segments' (series) score (b); the table shows the single segments values and their visualization in the segment exposure map (c)

Amatrice

a- segment maps

b – radar chart



c – summary table and map

AMATRICE	FID	CIC	HD/SL	Obstructions	Exposure
A-B	16	2	1	0	1
	39	**3**	**2**	**1**	**2**
	59	2	0	1	1
	60	2	0	0	0.67
A-O4	**52**	**2**	**3**	**1**	**2**
	3	**3**	**2**	**0**	**1.67**
	6	**3**	**3**	**1**	**2.33**
A-S4	54	2	2	0	1.33
	55	2	0	1	1
	104	1	3	0	1.33
	8	3	0	1	1.33
	9	**3**	**2**	**0**	**1.67**
	15	**3**	**2**	**0**	**1.67**

a. In the maps, each segment is visualised with a different colour corresponding to OBS-CIC-HD/SL values.

b. In the radar chart, each segment becomes a series, and is characterised by a unique OBS-CIC-HD/SL combination; the highest values among the segments characterise the route.

c. In the table, the OBS-CIC-HD/SL values for each segment (FID) are displayed, and the segment exposure is calculated as average value. Values are visualised in the segment map.

The results provide a first important information on disaster risk in historical urban areas, indicating that the routes with higher movement potential, where attractors (i.e. heritage locations, points of worship, landmarks, shops, and recreational activities) are clustered, are not only intrinsically predisposed to overcrowding as a result of endogenous/configurational and exogenous/land-use factors, but they are also further exposed to external damage from the pertinent building stock. It is the case of the main streets, that are likely to be bordered with non-residential, often vulnerable buildings (ref. appendix) hosting activities attracting residents and tourists; it is also the case of squares and churchyards, performing as large and popular gathering areas that are exposed to the fragility of the adjacent religious buildings.

Conclusions

This paper presented the workflow to unfold the spatial functioning of UPOS in relation to disaster risk, with the reinterpretation of configurational and land use variables in relation to spatial exposure – a core disaster variable, and precondition for spatial vulnerability. A set of spatial indicators, developed to assess and visualise endogenous and exogenous determinants for spatial exposure, was also presented. The results have demonstrated the relevance of the CIC measure, and of its core, in relation to spatial exposure, and as a possible valid predictor of informal evacuation routes – hence relevant to inform local DRR strategies. It was also suggested the relevance of the HD/SL indicator in relation to the pertinence strip and the double loaded street – an aspect suggesting the potential of core urban morphology concepts for a broader understanding of the disaster risk dimension. Although currently limited to the selected cases, the study can be considered as a starting point for the redefinition of the spatial morphological role in urban DRR, and a further step to unfold the relations between urban form and disaster risk.

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APPENDIX 1

Case study background: the settlement of Amatrice, Lazio region (Italy)

The territory of Amatrice was the epicentre of the first destructive earthquake on 24th August 2016. The historical settlement, established on the spur of rock between Tronto and Castellano rivers, dates back to the Middle Ages and developed from an earliest nucleus which progressively expanded eastwards, saturating the space within the defensive walls bordering the plateau (Giammarini, 2017).The urban layout is a gridiron articulated in elongated blocks, whose directions of growth appear dictated by the main longitudinal axis, Corso Umberto I, and the orthogonal transect Via Madonna della Porta (figure A1). The street network survived urban transformations and historical earthquakes with minor alterations, while churchyards and squares disappeared, shrunk, or were fragmented following buildings' demolitions and reconstructions over the centuries (Giammarini, 2017). The significant open spaces that survived over time were those serving the three main points of worship and the civic palace, apparently organised based on a functional and symbolic hierarchy, with the former positioned at the vertices of an ideal triangle, and the latter located in barycentric position (Giammarini, 2017).

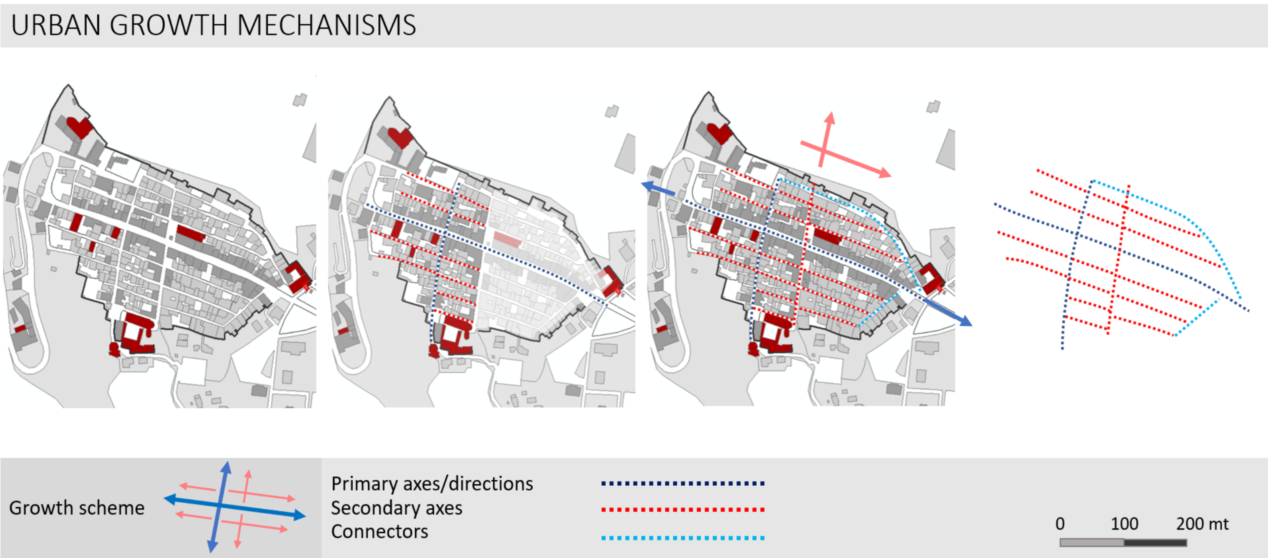
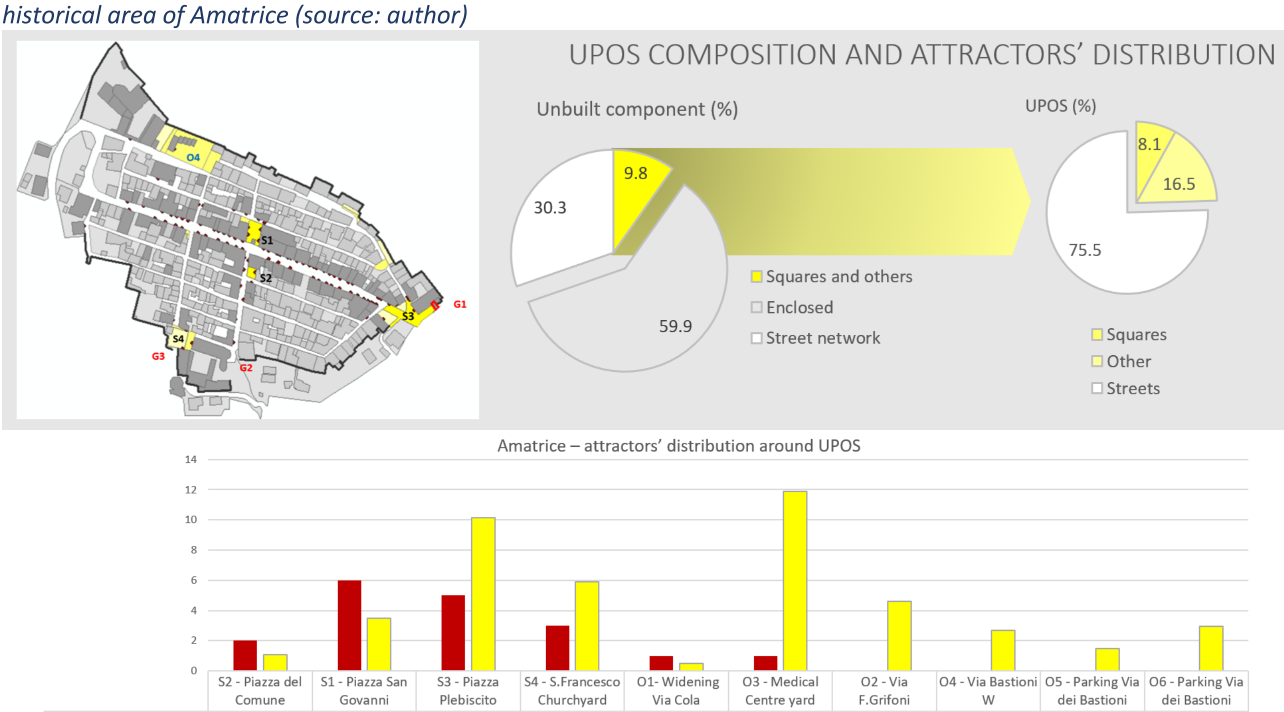


Figure A1. *Schemes of the urban growth mechanisms in the historical centre of Amatrice (source: author)*

Amatrice, Pre-earthquake scenario (2016).

In 2016, the settlement consisted of the historical centre, densely built and enclosed within the remains of the medieval walls (see figure A1) and the adjacent expansion area, developed along Corso Umberto outside the historical core. The land use analysis (figure A2) show that within the walls, 51.1% of the total surface was covered by buildings, 19.9% by the UPOS network, while the remaining open spaces were private enclosed gardens. Corso Umberto recorded the highest number of attractors (figure A3), located in the not-residential buildings along the transect; figure A2 shows that the small squares of San Francesco (S4) Plebiscito square (S3), san Giovanni Square and Piazza del Comune (S1 and S2) were the only squares within the historical areas, with relatively small size in relation to the building density of the area, and all of them immediately surrounded by non-residential buildings. Residential buildings represent more than 60% of the building stock.

***Figure A2**. Analysis of land use, displaying the composition of built and unbuilt components and their ratio in the historical area of Amatrice (source: author)*



	S2 - Piazza del Comune	S1 - Piazza San Govanni	S3 - Piazza Plebiscito	S4 - S.Francesco Churchyard	O1- Widening Via Cola	O3 - Medical Centre yard	O2 - Via F.Grifoni	O4 - Via Bastioni W	O5 - Parking Via dei Bastioni	O6 - Parking Via dei Bastioni
Attractors	2	6	5	3	1	1	0	0	0	0
Units of area (area/100)	1.08	3.49	10.15	5.91	0.51	11.87	4.61	2.69	1.48	2.97

***Figure A3.** Focus on the composition of UPOS and the distribution of attractors around the relevant open spaces in Amatrice (source: author)*