

Territorial Digital Twins: A key for increasing the community resilience of fragile mountain inner territories?

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Abstract

Areas suffering territorial imbalances are at risk, as climate change and inherent social-spatial vulnerabilities bring uncertainty over their capacity to achieve sustainable development. To enable policy-makers' vision for them, the paper proposes adopting digitally-enhanced disaster risk reduction practices which promote civic engagement and evidence-based decision-making. The study introduces the concept of Territorial Digital Twins (TDTs) demonstrating the potential benefits of networking distributed information resources and enabling their integration in two paradigmatic Italian inner mountain areas, which are linked to different priorities of the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR). This contribution argues the importance of complementing the technical approach with the social perspective in the development of TDTs oriented at increasing the community resilience of territorially imbalanced areas. It then illustrates the usefulness of exploiting TDTs (from photogrammetry, GIS mapping, Space Syntax analysis) to overcome the barriers to the SFDRR, and enable its effective implementation in localities.

KEYWORDS

adaptive landscape, community resilience, digital transition, disaster risk reduction, ecological transition, inner area planning, territorial digital twin

1 | INTRODUCTION

Europe is a polycentric territory populated by unequally distributed assets, resulting from a millennia-long history of development cutting across different economic systems, in which settlements have experienced cycles of growth and degrowth. The strategic objective of the previous 2014–2020 European Cohesion Policy was to foster smart, sustainable and inclusive growth across the EU by promoting opportunities for endogenous development in areas suffering territorial imbalances (European Union, [n.d.-a](#)). This policy recognised the critical importance of reducing current structural weaknesses, innovation gaps, shrinking and marginalisation processes in peripheral areas in Europe, penalised by their geographic remoteness, negative economic and demographic trend, exclusion from economic, institutional, and

cultural networks, and marginal decision-making power. Nonetheless, the current 2021–2027 European Cohesion Policy implies that a lot is yet to be done to tackle this challenge in practice, possibly unlocking opportunities connected to both the green and digital transitions (see the Next Generation EU plan, European Union, [n.d.-b](#)).

The ongoing environmental and economic crisis has demonstrated that the anthropogenic footprint on Earth comes at the expense of natural capital, for example, via land-use change and species exploitation, with disastrous consequences (Dasgupta, 2021). This offers a new lens to look at territorially imbalanced areas as critical reservoirs of resilience (due to their richness in environmental resources, vernacular knowledge, cultural artefacts, and potential uses), which ought to be understood, planned, and managed in an integrated way with other – more central – areas, to protect the

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prosperity of whole territories (Favargiotti, 2016). The scientific production on this topic is mainly concentrated in Asia (China) and in Europe (Italy, United Kingdom, and Spain) – amid nuances in understanding reflected in the use of a variety of adjectives such as ‘peripheral’, ‘marginal’, ‘inner’ and ‘inland’ areas – with Italy resulting the second most active country globally, and first in Europe, in researching practices related to territorially imbalanced areas (Oppido et al., 2020). However, academic research is still in its early stages, as demonstrated by the prevalence of exploratory studies in the literature. More research is needed towards developing a decision-driven analytical approach to their spatial planning (regional and urban) and design, which embeds sustainable development aspirations in the implementation of Disaster Risk Reduction (DRR) actions (Chmutina et al., 2021), being both environmentally sensitive and socially oriented.

To this end, novel opportunities are emerging due to the ongoing digital transformation and the rise of smart technologies, which promise to enable higher value creation and better living through the implementation of ‘intelligent’ solutions for territorial planning and management. For instance, the digital and information revolution of the last thirty years has offered “new analytical instruments and perspectives of recording, representation and projection” (Gausa, 2019, p. 144) applicable to urban and territorial governance and design, which have unlocked opportunities for the adoption of effective multi-level and multi-scale, dynamic and n-dimensional modelling and mapping approaches (Juan Gutiérrez & Marcos Alba, 2019).

This contribution therefore aims to explore how, and under which conditions, novel digital methods and tools may be used to deliver a networked technological service system (Rotondo et al., 2020), offering value to residents and businesses in territorially imbalanced areas. This system should enable a multi-scale and multidimensional understanding of urban management, planning and design problems and inform their holistic resolution plus promote stakeholder engagement and community empowerment (Dembski et al., 2020; Fricker & Munkel, 2015; Hermansdorfer et al., 2020).

The paper suggests that the ever-increasing availability of (almost) real-time data about the natural and built environment could be exploited in Territorial Digital Twins (TDT)¹ to envisage novel options for the integrated urban design, planning and environmental management of fragile mountain inner areas, towards increasing their community resilience as embedded in the broader social-ecological resilience perspective applied to urban systems (Chelleri, 2012; Mannocci, 2022) and which implies consideration of spatial aspects, environmental features of both built and natural environments, as well as issues of equity, inclusion, and justice (Davoudi et al., 2012; Imperiale & Vanclay, 2016; Imperiale & Vanclay, 2021; Magis, 2010; Skerratt, 2013). The idea underlying the TDT proposition is that connecting and operationalising existing distributed information resources by enabling (almost) real-time information integration can enhance the capacity of these areas to respond more sustainably to complex challenges, including reducing risks connected to multiple types of hazards.

¹The general concept of (Urban) Digital Twin is introduced in Section 2.2, while the conceptualization of a Territorial Digital Twin is the focus of this contribution. This unfolds through the text, including in the presentation of the case studies, until the discussion (Section 5), where a more formalised definition is finally advanced.

Given that operative applications of resilience concepts remain naturally bound to the specifics of each territory (Cutter et al., 2008; Elmqvist et al., 2013), two paradigmatic Italian case studies located in different inner mountain regions were selected to demonstrate the potential benefits of applying the proposed concept of TDT: (i) the Val di Sole, an Alpine valley interested by risks connected to man-made and natural hazards, located in Trentino-Alto Adige region; and (ii) the epicentre area of the 2016–2017 seismic crater in the Central Apennines. The selected case studies differ in that the latter is an area recently hit by a major earthquake disaster and currently recovering from that, while the former has not recently suffered from a similar rapid onset crisis but is threatened by an intensive seasonal tourism and a high-level hydrogeological risk. These areas were therefore digitally modelled and analysed using different methods and tools (i.e., photogrammetry, GIS mapping and Space Syntax analysis), as suitable to each case. However, the outputs of both analysis processes can be discussed with a complementary view to how their integration within a Territorial Digital Twin can help achieve the Sendai Framework for Disaster Risk Reduction (SFDRR) (United Nations Office for Disaster Risk Reduction, 2015) priorities for action by tackling territorial disparities which drive vulnerability to disasters and are linked to ill-managed development dynamics. The command-and-control approach to knowledge and resources for disaster risk reduction has been found to be one of the main barriers to implementing actions in each of the four priority areas of the SFDRR by Imperiale and Vanclay (2019, 2020, 2021), who have also identified gaps in knowledge, capacity, as well as financing and governance, particularly at the local level. Against this background, this contribution specifically addresses flaws related to the absence of methodologies to engage and empower resilience in society (Imperiale & Vanclay, 2021) to foster the shift from government to governance approaches, by giving special attention to the case of spatially marginal localities.

The paper is structured into six sections. Section 2 illustrates the current policy framework for imbalanced territories in Europe and in Italy and presents the concept of Digital Twin, by critically discussing its transferability to the territorial scale. Section 3 describes the methodological framework and is followed by Section 4, which presents selected examples of modelling the present to simulate and plan better futures for mountain inner areas at risk. Finally, Section 5 discusses the results of this research and its outlook, setting the basis for the creation of a Territorial Digital Twin oriented at reducing disparities and disaster risk. The conclusions of this paper are then summarised in Section 6.

2 | BACKGROUND

This section is divided in two parts which present the governance framework (Section 2.1) and the theoretical foundations (Section 2.2) of this research.

2.1 | Governance framework: EU Policies and spatial strategies

The European operative framework for the definition of ‘Inner Peripheries’ was developed by the programs GEOSPECS (Geographic

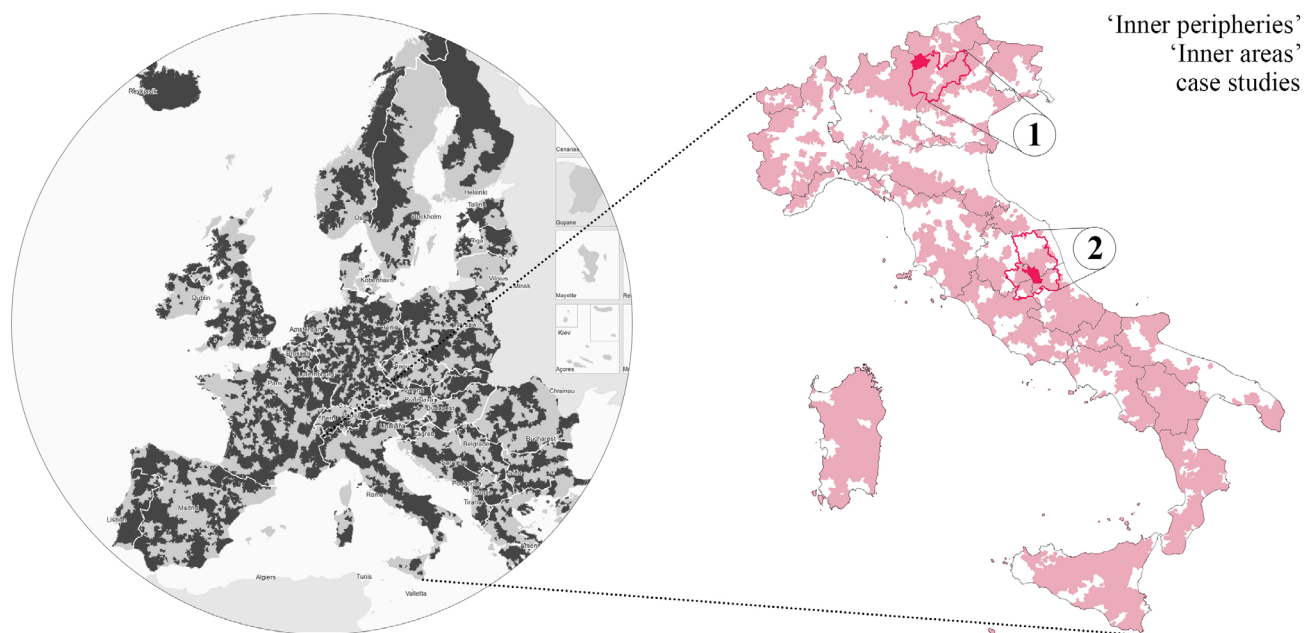


FIGURE 1 (a) Left, 'Inner Peripheries' in Europe identified using the four delineation approach. (b) Right, map of Italian 'Inner areas' according to the classification into poles and places with different degrees of peripherality, plus location of the selected Case Studies: (1) Val di Sole, (2) 2016–2017 seismic crater.

Specificities and Development Potentials in Europe, 2010–2012; ESPON & University of Geneva, 2012), and PROFECY (Processes, Features and Cycles of Inner Peripheries in Europe, 2016–2017; ESPON, 2017), both led by the European Spatial Planning Observation Network (ESPON). As a result, four types of 'Inner Peripheries' were defined according to three different drivers of territorial imbalance (social, economic, and spatial): (1) areas with higher travel time to regional centres; (2) interstitial areas having lower economic potential; (3) areas with poor access to services of general interests; and (4) depleting areas (Figure 1a).

In Italy, an overarching national-level strategic planning instrument was developed for counteracting the marginalisation and demographic decline of the so-called 'inner areas': the 2014–2020 National Strategy for Inner Areas, also known as SNAI (Barca, 2009; Dipartimento per lo Sviluppo e la Coesione Economica, 2013). This identified that areas located away from the more developed zones,² which include most of the territory in the Apennines and in the Alps, are anything but residual in Italy as they account for about 60% of the entire national territory (Dipartimento per lo Sviluppo e la Coesione Economica, 2013, p. 26), (Figure 1b).

The strategy has recently made inroads also into the 2021 National Recovery and Resilience Plan (PNRR), which establishes the special interventions and funding allocated by the Italian government in response to the Covid-19 pandemic (Piano Nazionale di Ripresa e Resilienza, n.d.). In fact, the PNRR expressly refers to the SNAI in measures for improving levels and quality of education, health, and social

services in Italian inner areas (Piano Nazionale di Ripresa e Resilienza, n.d., p. 217), which have asymmetrically suffered the effects of the crisis (Fenu, 2020; Pittalunga et al., 2020). Notably, the SNAI links the terms 'resilience', 'adaptation' and 'mitigation' to global climate change and associated risks: for example, in the "Active protection of the territory and local communities" section of the 2014–2020 Partnership Agreement (Dipartimento per lo Sviluppo e la Coesione Economica, 2013, p. 45) and in the sections "Climate and risks" and "Framework for effective disaster risk management" of the 2021–2027 Partnership Agreement draft (Dipartimento per le Politiche di Coesione, 2021, pp. 15, 51–52).

Although the programmatic attention currently given to Italian inner areas is bringing some benefits, the national cohesion policies have addressed the problem only partially since:

- At the methodological level, they have focused on issues of economic, services and infrastructure marginality, basing the classification of the inner areas on narrow-focused quantitative indicators. They have therefore excluded contexts of varying marginality (e.g., small, and medium-sized towns, parts of the urban–rural continuum, foothills/piedmont areas), (Esposito De Vita et al., 2020).
- At the process level, the Framework Programme Agreement between the project area, the competent Region, the Technical Committee, the central administrations, and the Cohesion Agency, has often been the result of long and complex negotiation processes. Consequently, the focus has been shifted away from the real issues as the agreement represents only the initial step in the implementation of the *area strategies* and not a final goal in itself (Pappalardo et al., 2020).

²To define the boundaries of the so-called 'inner areas' an indicator of the level of physical accessibility of certain essential services is used, which considers that is, the full range of upper secondary education services, a first level emergency care hospital structure and a regional category railway station.

- At the operative level, the SNAI did not identify resources or mechanisms to strengthen the capacity of local administrations to act, neither by using their own staff nor by liaising with external competence centres in innovative ways (Carrosio, 2020).

As a result, most of these areas are still at risk, with climate and inherent social-spatial vulnerabilities bringing further uncertainty over their capacity to achieve Sustainable Development Goals (SDGs) (particularly Goal 9, Industry, innovation and infrastructure; Goal 10, Reduced inequalities; and Goal 11, Sustainable cities and communities).

When it comes to the indicators used in 'quality of life' evaluations, the value of natural resources, the contemporary interpretation of ancient land management processes, and the innovative practices developed to take care of landscape and building heritage in vulnerable contexts, should all be considered.

2.2 | Theoretical framework: Exploring smart development and digital twinning at different spatial scales

To achieve the goals of the 2014–2020 European Cohesion Policy, and to be consistent with the new 'Smart Specialisation' principles of the 2021–2027 EU cohesion programme, it is necessary to develop Information and Communication Technologies (ICT) that support participatory governance and digital tools capable to inform long-term integrated development strategies at both the urban and regional levels (Barzotto et al., 2020; United Nations, 2020).

An important step in this direction is currently being made by researchers from the Department of ICT Engineering and Technologies for Energy and Transport (DIITET, Italian National Research Council), who are attempting to operationalise the paradigm of *Urban Intelligence* moving from prior researches developed at the MIT (Senseable city) and at New York University's Urban Intelligent Lab. The experimentation, conducted together with the Italian National Institute of Urban Planning (Framework Agreement, 2019), involves expanding the consolidated concept of Smart City – mainly based on a continuous collection and dissemination of sensed data – to develop a so-called Digital Twin (DT) applied to an entire urban community, capable of learning, virtually replicating, and dynamically predicting the behaviour of an urban system. This aligns with broader international trends, as demonstrated by the many ongoing theoretical and applied experimentations in the field of urban planning (i.e., Helsinki's 3D city models, Rotterdam 3D, Virtual Singapore). Here, Industry 4.0 technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) have been exploited to transfer the concept of DT – born in the field of production engineering as digital representation of systems enriched with real-time information (Grieves, 2014) – to whole towns (Dembski et al., 2020), cities (Batty, 2018; Ketzler et al., 2020), and even nations (i.e., the Netherlands' 3D Baseregister Addresses and Buildings, the Switzerland and Liechtenstein's swissTLM3D), according to different levels of technical "maturity" (Kim et al., 2020,

pp. 109–122). The ultimate goal of these explorations is to develop a tool which offers multi-source real-time data aggregation and predictive analysis capabilities for decision-making. This should inform choices about short- and long-term changes to different urban systems and subsystems, which consider safety and quality of life requirements and user needs, inform urban revitalisation and redevelopment planning actions, and enable monitoring the behaviour of the whole system.

Due to its potential benefits in supporting the assessment of future conditions based on an evaluation of current situations and possible impacts of choices, the conceptual modelling of DTs in Disaster Risk Reduction applications is rapidly increasing (Fan et al., 2021; Ford & Wolf, 2020; Ham & Kim, 2020; Zhang et al., 2019). Yet, the uptake of these ideas and solutions at a territorial scale is rather slow. In fact, numerous researchers (Ervin, 2001; Nessel, 2013; Yang et al., 2019; Zhang, 2021) have identified an enduring gap between mainstream tools used for landscape design and industry-standard mapping and modelling technologies (such as Building/Landscape Information Modelling and Geographic Information Systems), capable of producing meaningful information about the natural and the built environment, at different scales and levels of detail.

Hence, the smart development and digital twinning of natural and built environments are currently divided into two sets of frameworks: the urban (already well established) and the intermediate, rural or mountain (gaining momentum, but lagging technical innovations). Pioneering conceptualizations of the latter include that of a distributed DT for agricultural landscapes, but the idea of a 'smart', 'responsive' or even 'sensory' landscape is still in its infancy (Ervin, 2018). Starting from an analogue concept in the urban context, Moshrefzadeh et al. (2017, 2020) developed the framework model of a "smart rural area data infrastructure" and tested it in an agricultural landscape research environment. Their initial results indicate that implementing the idea at a territorial scale requires overcoming two main challenges, namely (i) networking the distributed data and information resources; and (ii) integrating them in real-time in raw environmental conditions (poor Internet connectivity, lack of sensors, etc.). The technological and digital components of the transition towards "smartness" are still a challenging and critical issue in the realisation of Smart Villages (Zavratnik et al., 2018), Smart Valleys, and distributed DTs of agricultural landscape (Moshrefzadeh et al., 2020). However, they are not the only nor the most important aspects of smart landscapes' conceptualisations. Indeed, the 'smart landscape' – which in the literature is mainly connected with climate-related objectives, land use, and agriculture – can be understood as a complex context which promotes social, cultural, and environmental sustainability and resilience, by fostering positive synergies among its different territorial systems (the natural, the urban and the rural). So, 'intelligent' landscape management models must primarily foster the adoption of technologies which respond to local needs and enable the enactment of context-based micro action plans promoting social, technological and infrastructure innovation, plus local knowledge (Cerreta & Fusco, 2016), what requires the integration of a social perspective in their development.

To sum up, adopting a whole system approach to the resilient and sustainable planning of inner areas, requires reformulating high-level objectives and developing adequate decision-support tools to guide priority actions which will ensure that local resources are protected, and risks connected to the exposure of communities, infrastructures and enterprises to hazards are reduced. To this end, Territorial Digital Twins (TDTs) can play a role in preserving the functions that derive from natural capital and promote climate change adaptation, risk prevention, disaster mitigation, disaster recovery capacity, besides the adoption of all the essential safety measures according to local risk levels, as set out in the Italian Civil Protection Code (Legislative Decree No. 4 of 6, 2020). Furthermore, to strengthen disaster governance for resilience (Imperiale & Vanclay, 2020), TDTs should support the understanding of all dimensions of risk, and help in its management during crises while strengthening the capacity of local communities to learn from the present and implement transformative actions towards enhancing their wellbeing.

3 | METHODOLOGICAL FRAMEWORK

The paper contributes to the debate around the responsive and integrated application of digital tools, technologies and techniques in the planning and management of vulnerable Italian mountain inner areas (and by extension of European inner peripheries). This is done by presenting selected results from two non-trivial, but yet sufficiently self-contained, real-world applied research explorations which have addressed different, albeit inherently related, problems in disaster risk management.

The first example includes some reflections from the “B4R Branding4Resilience” project (PRIN 2017 – Young Line, 2020–2023), linked to an on-going doctoral research conducted at the University of Trento. The B4R project investigates the use of tourist infrastructure as a tool to promote sustainable development in small inner villages (Figure 1b, study area 1) by drawing resilient communities and new open habitats and asks if this can foster new polycentric settlement models in fragile rural-urban contexts (Ferretti et al., 2022). Within this framework, the PhD research adopts an innovative cross-sectoral approach to develop and test a virtual-physical system supporting landscape planning and design by focusing on the context of the Val di Sole: an Alpine valley in the Trentino-Alto Adige region, which coincides with the homonymous inner area in the SNAI (Favargiotti et al., 2022).

The second example is extracted from another research project which aims to support better informed disaster recovery planning and whose focus is the construction of Temporary Housing (TH) sites (Chioni, 2019; Pezzica, 2021). This advocates a more holistic and human-centric approach to temporary housing planning, design, and management, which requires consideration of people's needs and views as well as of architectural and urban heritage. The connected empirical research has interested the territory falling within the administrative limits of four historic municipalities in the Apennines, which were severely hit by the 2016–2017 Central Italy earthquakes, namely Norcia, Amatrice, Accumoli, and Arquata del Tronto, included

in the ‘Valnerina’, ‘Monti Reatini’ and ‘Ascoli Piceno’ SNAI inner areas (Figure 1b, study area 2).

The two researches hereby presented, share approaches and principles that suggest the opportunity to conduct a study with a parallel focus on them. They are both fundamentally interdisciplinary and connect a wide range of research methods to tackle planning-oriented information management activities and their different steps, among which data acquisition and transformation, data elaboration through analysis and results' visualisation, validation, and deployment for value generation.

Although the workflows and methods adopted to collect and process the data in order to perform a multidimensional (cross-scale and multitemporal) analysis differ in each case (as described in Sections 4.1 and 4.2), another common element in these two studies is the use of open and collaborative data to enrich digital maps and spatial models towards informing more engaging and democratic planning and design processes as part of strategic, resilience-oriented, actions (Fakhruddin et al., 2022). Volunteered, crowd-sourced and social media data and geographic information can provide insights about the opinions, needs, perceptions and movement patterns of local communities both in urban and rural environments, useful to define design requirements and strategies (Nikšič et al., 2017; Witanto et al., 2018). Therefore, both studies consider urban design and planning, landscape architecture and civic innovation – and hacking – as key parts of the larger social and infrastructural webbing of a territory, and raise questions about data and information interoperability in all their multidimensional aspects (Chioni, Barbini, et al., 2021). This aligns with the “real-time” and “senseable” city conceptualisations (Calabrese & Ratti, 2006; Kloeckl et al., 2012; Ratti & Claudel, 2016) – mentioned in the previous section – which assume physical and social networks to be in constant interplay. In light of these considerations, the two experiences are illustrated considering how the technical approach was complemented by the social perspective in developing operative proposals which aim to enhance community resilience by improving the accessibility and fruition of relevant knowledge and resources for risk reduction.

Finally, both of these research examples develop decision support methods and tools which help assess current territorial conditions and strategies, and their future impacts, to better tackle issues connected to DRR challenges in fragile mountain areas and achieve desired future results. The former mainly addresses priorities 2 (manage risk by strengthening disaster risk governance) and 3 (invest in DRR for resilience), while the latter targets priority 4 (enhance disaster preparedness for effective response and to “Build Back Better” (BBB) in recovery, rehabilitation, and reconstruction) of the SFDRR, (United Nations Office for Disaster Risk Reduction, 2015). Priority 1 (understanding disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment) is an important underlying component in both cases.

Thus, in the following, the two case studies are not compared. Rather they are presented as complementary approaches to address long-lasting barriers and gaps in each of the four priority areas of the

TABLE 1 Methodological framework and associated methods and tools explored in the paper.

	Priority 1	Priority 2	Priority 3	Priority 4
Sendai Framework for DRR	Understand disaster risk	Strengthen disaster risk governance	Invest in DRR for resilience	Enhance disaster preparedness
Selected actions (suitable to be pursued in fragile mountain inner areas)	Strengthen disaster risk modelling, assessment, mapping, monitoring and (people-centred, multi-hazard, multisectoral and forecasting) early warning systems (*)		Mainstreaming of disaster risk assessment, mapping and management in land-use policy development and implementation	(*)
	Creation of common information systems to exchange lessons learned, good practices and programmes (*)		Sustainable usage and management of ecosystems and environmental resources	(*)
	Improvement of cooperation among scientific and technological communities, relevant stakeholders, and policymakers for effective decision-making (*)		Integration of disaster risk management approaches throughout the tourism industry	(*)
	Collection, analysis, management, and dissemination of (real-time) disaster risk data and information			
Methods and tools (used in the hereby presented case studies)	Use of open and collaborative data (e.g., in scenario visualisation and simulation)			
	Elaboration of dynamic and responsive (3D) models supporting interaction with local stakeholders about landscape management, territory planning and design			
	Diachronic and “functionally graded” analysis workflow (and associated information packages), which enables assessing different spatial configurations at subsequent points in time and whose complexity varies according to the level of detail required at different scales (*)			(*)

Note: The symbol (*) and the grey background recall the same action in Priority 4.

SFDRR. Namely, denial of the multiple dimensions of understanding risk (priority 1), exclusion of local stakeholders from decision-making and inequalities' creation (priority 2), unregulated and arbitrary investments fostering disaster capitalism (priority 3), and top-down, technocentric and short-sighted, post-disaster planning (priority 4), (Imperiale & Vanclay, 2021).

The examples will be examined in Section 4 by mapping – against the 4 SFDRR priorities – digital methods, techniques and approaches underlying the construction and deployment of TDTs which aim to promote community resilience in fragile mountain areas (Table 1). Previous and ongoing research approaches and results in the two selected cases are separately examined, in qualitative terms, by reflecting on the main strengths and potential benefits of the tools and technologies used in each case. To this end, they will be connected to selected actions in the

SFDRR, relevant to fragile mountain inner areas. This research design ultimately aims to bring together under one umbrella, complementary research efforts which were originally unrelated but contribute to the proposed conceptualisation and construction of TDTs from a community resilience perspective. For an indication of the paradigms and theoretical perspectives that underlie the presented case studies analysis, we refer the reader to Section 2 of this paper.

4 | SIMULATING FUTURES TO ENHANCE RESILIENCE

This section presents some examples of modelling the present to simulate and plan better futures for fragile inner mountain areas.

4.1 | Enabling priorities 1, 2 and 3: Support for participative planning and design processes

Since the representation and visualisation of landscapes (a robust interdisciplinary theme cutting across STEM and Humanities disciplines) requires the processing of geo-data as well as the depiction of sensory information relating to both tangible and intangible territorial components (Salerno, 2019), the first exploration combines qualitative and quantitative approaches to create a comprehensive territorial portrait of mountain inner areas. The Val di Sole is assumed as the testbed for the use of emerging models in landscape digital representation to support information management activities relevant to planning and urban design. This is achieved through the integration of heterogeneous research methods and analysis techniques from landscape architecture and digital modelling, following the multi-disciplinary and multi-level methodological approach of the B4R project (Ferretti et al., 2022). The core research activities, shared by each of the four B4R research units focusing on different Italian inner mountain areas, have been organised in the following three main phases, reflecting as many methodological aspects and outputs:

- Exploration. Based on a collaborative and incremental collection of data within many thematic areas clustered in four macro 'dimensions': (1) infrastructure, landscape and ecosystems; (2) built/cultural heritage and settlements dynamics; (3) economies and values; and (4) networks and services, community and governance models.
- Co-design. Operative and done in collaboration with local actors during a four-days intensive workshop.
- Co-visioning. Oriented to the formulation of strategic guidelines for policymakers and local communities.

These activities jointly aim to tackle territorial imbalances by developing a collaborative online platform which incrementally builds on bottom-up data and local views to support ideas' exchange around tourism management and infrastructure between private stakeholders, public decision-makers, and the people (Ferretti et al., 2022).

Currently, the B4R research units are reorganising results from the first two phases of the project within an atlas containing thematic maps, diagrams, and plots of cross-cutting indicators. This is being developed in a Geographic Information Systems (GIS) environment to help comprehend, store, and transmit the values and assets of the analysed marginal territories. The Trento research unit in particular has explored the identity features of the Val di Sole (e.g., its fragile thermal water landscapes; Pasquali et al., 2022), by integrating concepts and methods from landscape ecology, territorial metabolism, digital mapping, and spatial data analytics (Favargiotti et al., 2022). It collected open-source and collaborative data from different databases at various geographic scales and levels of detail (European, national, provincial, valley community, and municipal). This data was then categorised, grouped, and spatialized to create a digital multi-domain information profile for the valley.

The results of this digital mapping work revealed that the valley is rich in living organisms, air, water, soil, hydrological resources, etc. and

this natural capital is legally protected for almost half of its extension (e.g., Stelvio National Park, Adamello Brenta Provincial Park, Alto Noce reserve network), but is also exposed to hydrogeological risk from floods, landslides, and avalanches for about the same amount of territory, as shown in Figure 2.

Maintaining a balance between the protection of valuable natural resources and their fruition during mass seasonal flows of tourists linked to the presence of natural curative waters (Dai Prà, 2014), mountain discovery and skiing, that depend on them, requires managing connected risks. Including by understanding disaster risk (i.e., through the atlas, as a shared knowledge repository), strengthening disaster risk governance (i.e., by involving local policy makers in the co-design workshop), and investing in disaster risk reduction for resilience (i.e., by involving local stakeholders in the co-visioning phase), in line with priorities 1, 2 and 3 of the SFDRR, respectively.

Reflections about the relationship between ongoing touristic phenomena in the valley and their physical imprint on the territory, which followed a collective inspection of the materials contained in the atlas, therefore guided the activities of the four-day co-design workshop by the B4R research team in February 2022. This focused on the two upper side valleys of Peio and Rabbi's thermal landscapes and tackled three thematic areas (previously defined in collaboration with selected stakeholders), namely 'proximity territories', 'co-creative communities', and 'new forms of living'. Local actors accompanied and critically supported the collaborative creation of a *cross-valley*³ strategic vision, in the form of operative branding actions based on the territorial exploration and the development of connected design proposals (Favargiotti et al., 2022). Here, the 2D digital interactive maps contained in the atlas were used to inform the development of project proposals and provided a useful representative base for visualising and communicating ideas in quick slideshows during the closing day, in front of political decision-makers and the attending audience. Opportunities were nonetheless identified for increasing their quality and usability as design support tools in view of the forthcoming activities linked to the concluding co-visioning phase.

In particular, in parallel to the spatial database creation and stakeholders' engagement activities, efforts have been made to conceptualise the construction of 3D landscape models which embed all the information previously collected. To this end, the PhD research has tested the use of some geometric digital modelling workflows from accessible online data; including via image-based modelling from ®Google Earth, and via the use of UAV imagery acquired in situ (by the photographer Nicola Cagol during his photo campaign in 2021) as part of an image-based 3D modelling pipeline. Although these techniques have been originally developed for photogrammetric applications, this investigation has focused mainly on their capacity to support the 3D digital documentation of the Val di Sole territory and in particular of portions of the two upper side valleys of Peio and Rabbi.

Figure 3 shows some outputs from these experiments at different scales and levels of detail. They proceed from the two-dimensional thematic maps produced in the framework of the B4R project and the

³Shared between the two upper side valleys of Peio and Rabbi municipalities.

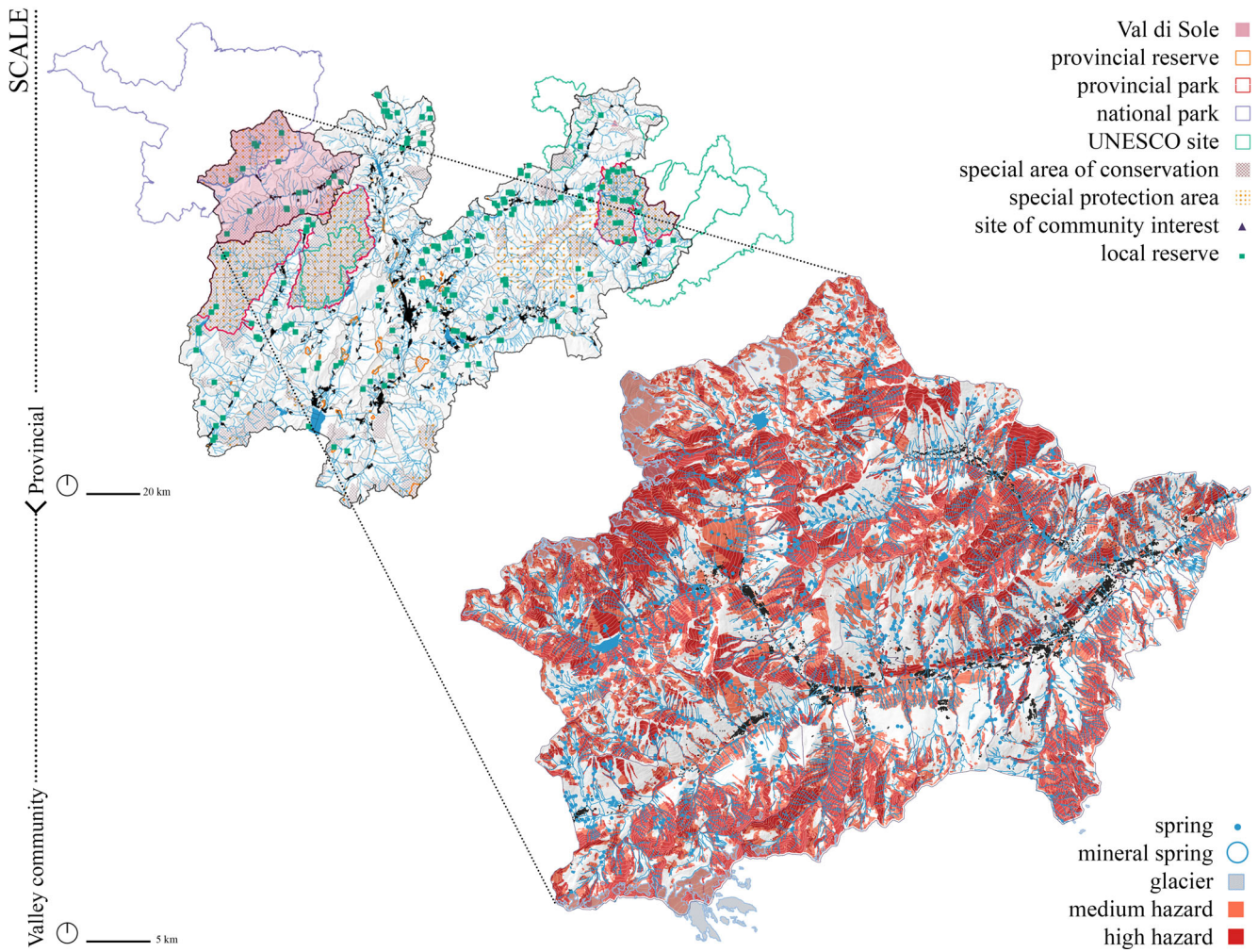
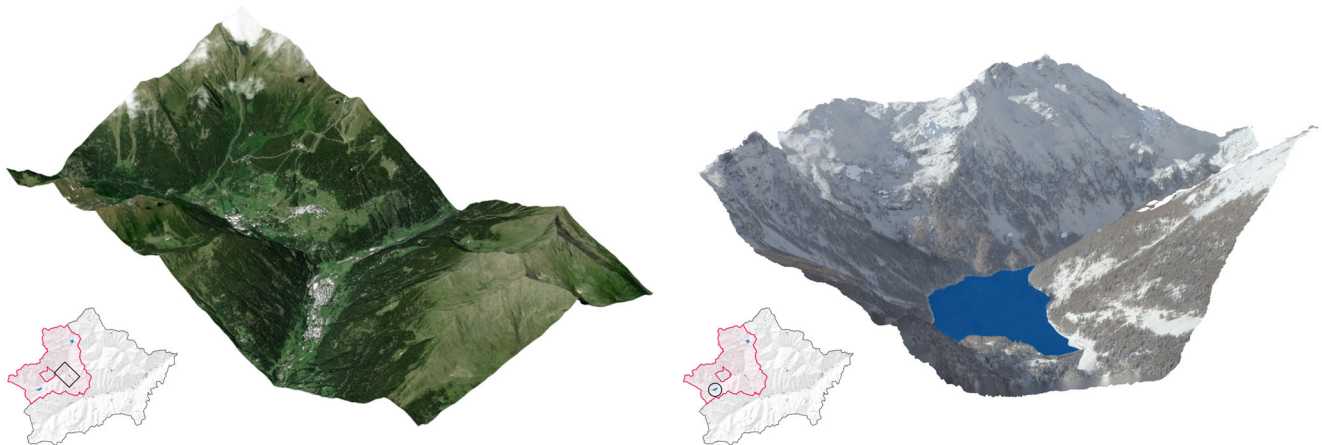


FIGURE 2 Val di Sole maps. Left: location of the valley within the Trentino autonomous province, and the protected natural sites. Right: medium-high multi-hazard risk (hydrogeological, avalanche, seismic and forest fire) and hydrological resources.



Automatic geometric modelling from the browser
Software: Rhinoceros, Lands Design
Output: textured mesh surface with 3D buildings

Image-based geometric modelling from video UAV
Software: Metashape
Output: textured mesh surface

FIGURE 3 Peio 3D models. Left, 3D textured mesh surface of a portion of Peio municipality from rapid satellite image processing. Right, 3D textured mesh surface of Pian Palù lake from UAV image data processed using [®]Metashape.

traditional Landscape Charter concept⁴ towards the creation of a responsive, and semantically rich, 3D valley model. This is expected to improve the (real-time) visualisation of useful information from the sensors available in-situ (e.g., soil quality sensors, weather stations, GPS trackers) and remotely (e.g., satellite) so as to better facilitate decision-making in participative planning and design processes. It also represents a further important step towards the development of a Territorial Digital Twin (TDTs) serving both as three-dimensional queryable repository of knowledge (i.e., an information system), and as simulator (and actuator) of more resilient futures for the valley. Indeed, by improving accessibility of scattered multidimensional data and making the fruition of technical information more intuitive and interactive, this can assist understanding of risk-related components in the territory by all stakeholders, prompt concerted spatial planning action, and help assess if investments are risk-informed (Wisner, 2020, p. 243), with implications for community resilience building.

Other key considerations concern the use of expeditious techniques for the multiscale 3D reconstruction of the valley model, which would enable monitoring the places of greatest tourist concentration, with particular regard to local resources severely exposed to hazards. At an operative level, the input data updating is more sustainable (economically and temporally) than carrying out extensive and resource-consuming survey campaigns, for example, using airborne LiDAR technologies.⁵ Indeed, quality and metric precision requirements for the output model are more relaxed in planning and design applications and simulation reasoning at the territorial scale. Moreover, images found on the internet and/or collected and shared by tourists and citizen-scientists (Agarwal et al., 2011; Bshouty et al., 2020; Grün et al., 2004; Wahbeh et al., 2016), can be used to improve and refine results obtained using remotely sensed images by punctually integrating point-cloud models⁶ with collaborative photogrammetry outputs (as discussed also in Pezzica et al., 2019 with reference to the Central Italy case presented in Section 4.2).

The global availability of smartphones and the increasing popularity of cameras and drones among non-professionals have transformed citizens into *prosumers* (i.e., both consumers and producers) of data and information for landscape and urban design. Nonetheless, the actualisation of information technologies' affordances in marginal rural and mountain villages may rely on citizen participation, considered as both an environmental/organisational factor and a determinant of citizens' capabilities to exploit them. Within this context, civic hacking initiatives ensure information is accessible and/or extra data (raw, unstructured, or semi-structured) is in place for large-scale digital

processing (Kelly et al., 2017). While combining crowdsourced street-level and/or aerial imagery with other data sources requires further research on integrating citizen science inputs into data collection and elaboration processes, cloud-based photogrammetric processing mobile apps promise to significantly reduce the future costs of 3D digital documentation campaigns (Nocerino et al., 2017).

4.2 | Enabling priorities 1 and 4: Multidimensional scenario generation and assessment

Integrating priorities 1 and 4, the second study mainly aims to provide temporal information and knowledge to support the delivery of a better temporary housing assistance post-disaster by producing digital information packages and workflows linked to multiple collaborative digital platforms. To this end, it combines research methods and analysis techniques – from Network Science (Barabási, 2002), Space Syntax theory (Hillier, 2007) and Public Life Studies (Ghel & Svarre, 2013) among others – for generating models useful to visualise alternative future scenarios and support “what if” explorations and assessments at different scales, including via statistical learning. These involve an audit of the short- and long-term impacts of urban form transformations in earthquake-affected inner areas linked to the construction of temporary housing sites (e.g., on road-infrastructure networks and the social performance of public open spaces); what can inform corrective and preventive planning and design risk reduction actions.

The method considers the importance of urban configuration for the social and economic functioning of (disaster-affected) inner settlements and the role of the analysis in assessing changes at different spatial scales and time steps (Figure 4). This involves discretizing a continuous timeline to conduct a multitemporal study, by comparing the following past, present and projected future scenarios: T_1 before the earthquakes; T_2 right after the disaster and during the immediate emergency phase, when access to the (many) areas which pose a threat to the safety of the public is denied; T_3 months after the disaster, when temporary housing sites are built amid the continued inaccessibility of dangerous urban areas (the so-called ‘red zones’) to be reconstructed; T_{4+i} several years after the earthquake and after the end of the reconstruction, including an hypothetical regenerative intervention scenario. The modelling of different scenarios at multiple significant moments for emergency management (T_1 – T_i) supports the identification of nuances, relational similarities, and subtle configurational differences among them (Pezzica et al., 2021).

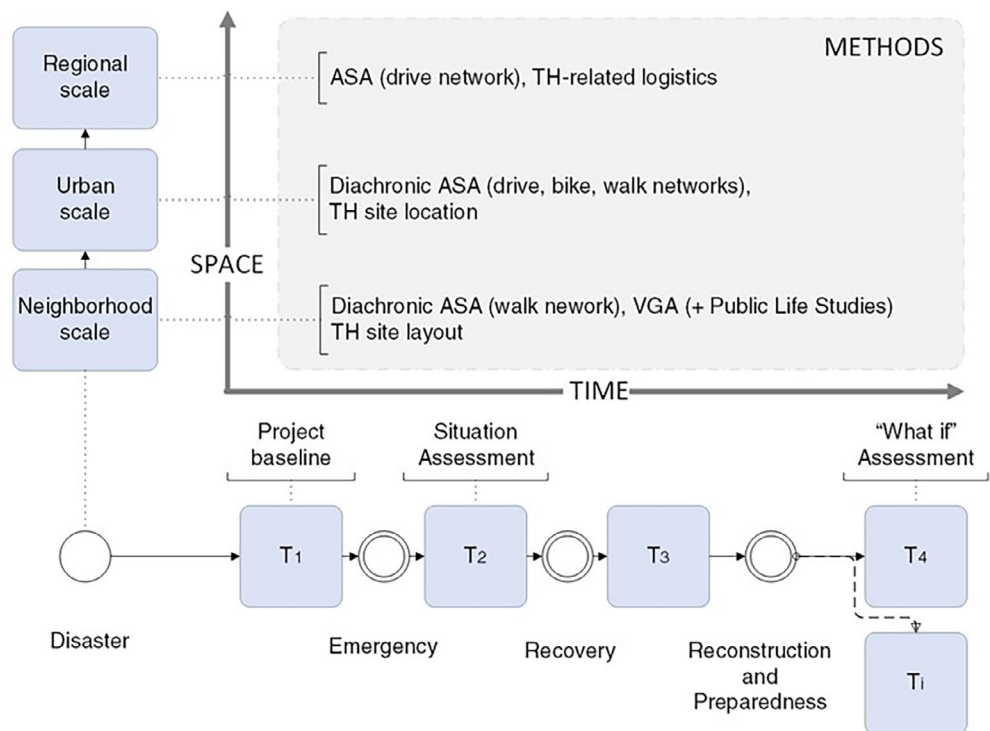
At each subsequent stage and in relation to the situation at T_1 , it flags interventions which affect the redundancy of path connections and movement dynamics – and with it the attractiveness of locations, place character and patterns of social encounter – of a settlement or territory. Enabling the visualisation of configurational changes can, hence, inform disaster-activated community resilience mechanisms in emergency (T_2), plus enhance experts' accountability in recovery (T_3) and reconstruction (T_4), to promote the implementation of people-centric spatial planning strategies which protect the livelihood of the displaced and their well-being (e.g., by

⁴The prescriptions of the Landscape Plans, in countries that have adopted the European Landscape Convention, are represented in static documents called Landscape Charters (Sala et al., 2014). Although digital, these are still costly-to-update 2D maps, compliant with cartographic symbolization and generalisation conventions. These rarely embed the qualitative features of the landscape assets – such as sensorial perception, cultural values, or evolution in time – that are critical for the comprehension, conservation, environmental management, and design of the landscape.

⁵In the Trentino autonomous province, the last LiDAR survey was carried out in 2014 with integrations in 2018.

⁶The importance of point clouds is reflected in the concept of ‘cloudism’ which is considered a novel form of art, where the creative process of landscape design ideation and development is initially driven by the use of point cloud modelling (Giro, 2020, p. 96).

FIGURE 4 Scenario generation framework: spatial scales, key timesteps and analysis techniques.



strengthening their social bonds and enhancing their capacity to cope with future perturbations).

The digital replicas ultimately represent a useful tool to align planning activities before and after disasters with a shared vision of urban resilience, establishing best pathways to achieve sustainable development objectives (Ti). In fact, the diachronic approach enables assessing not only the impact of spatial modifications on urban social-spatial performance at subsequent points in time, but also across a virtually unlimited number of alternative spatial arrangements, possibly reflecting different planning priorities and stakeholders' views. Thus, it can easily be transferred to more ordinary planning and design activities, for example, for evaluating different urban regeneration plans, including supporting participatory planning and co-design workshops for the revitalisation of small historic centres (Chioni, Pezzica, et al., 2021).

The latter point seems particularly important since, beyond disaster-related emergencies, inner areas such as those hit by the 2016–2017 Central Italy earthquakes endure a long-lasting crisis connected to ongoing processes of depopulation, economic shrinking, abandonment, and decay. Within this broader context, the research can be understood as a pilot test towards the development of a more sophisticated and responsive information management system relying on real-time updating. The use of one overarching approach improves the interoperability of analysis results having different levels of granularity (including via the exploitation of homothetic behaviours and recursive properties of certain network centrality metrics; Pezzica, Altafini, & Cutini, 2022). This enables a formal exploration of cross-scale dependencies so that they can be considered in decision-making (Pezzica et al., 2020). What opens doors to the creative resolution of difficult trade-offs by design and enables resources-saving opportunities.

In the Central Italy case, this approach allowed generating quantitative information about the 2016–2017 disaster recovery trajectory, useful to effectively inform the development of corrective urban design interventions and assist the evaluation of alternative TH planning options to achieve BBB goals (Chioni, Pezzica, et al., 2021; Pezzica et al., 2021; Pezzica & Cutini, 2021). Selected examples are presented in what follows according to a progressive zoom in, moving from the regional scale (encompassing the 2016–2017 crater area), to the urban (the four epicentral municipalities), and finally to the neighbourhood level (*Borgo1* TH site in Arquata del Tronto).

Figure 5 shows the results of the Angular Segment Analysis (ASA) conducted on the regional (drive) road network at T₁ (more details in Pezzica, 2021, pp. 216–222). The map highlights an unbalanced distribution of accessibility levels in the seismic crater, which appears populated by a system of weakly connected small urban centralities, generally lacking territorial endowments. These results align with the demographic and economic picture of the territory which emerges from a study by the Italian National Institute of Statistics (Istat, 2016) and closely mirror the territorial classification proposed by the SNAL. Through the identification and mapping of these territorial disparities, the analysis makes available to decision-makers information which are important for strategic and spatial-economic development planning. Additionally, it helps identify infrastructural links (i.e., topological bridges – or weak ties – as in Cutini & Pezzica, 2020 and Pezzica, Altafini, & Cutini, 2022) which are critical to guarantee the resilient functioning of the whole regional road network system in the face of localised interruptions, and thus should be prioritised in disaster recovery and reconstruction operations.

The diachronic (T₁–T₄) urban scale analysis (Figure 5), when comparatively conducted on the four towns of Arquata del Tronto, Norcia,

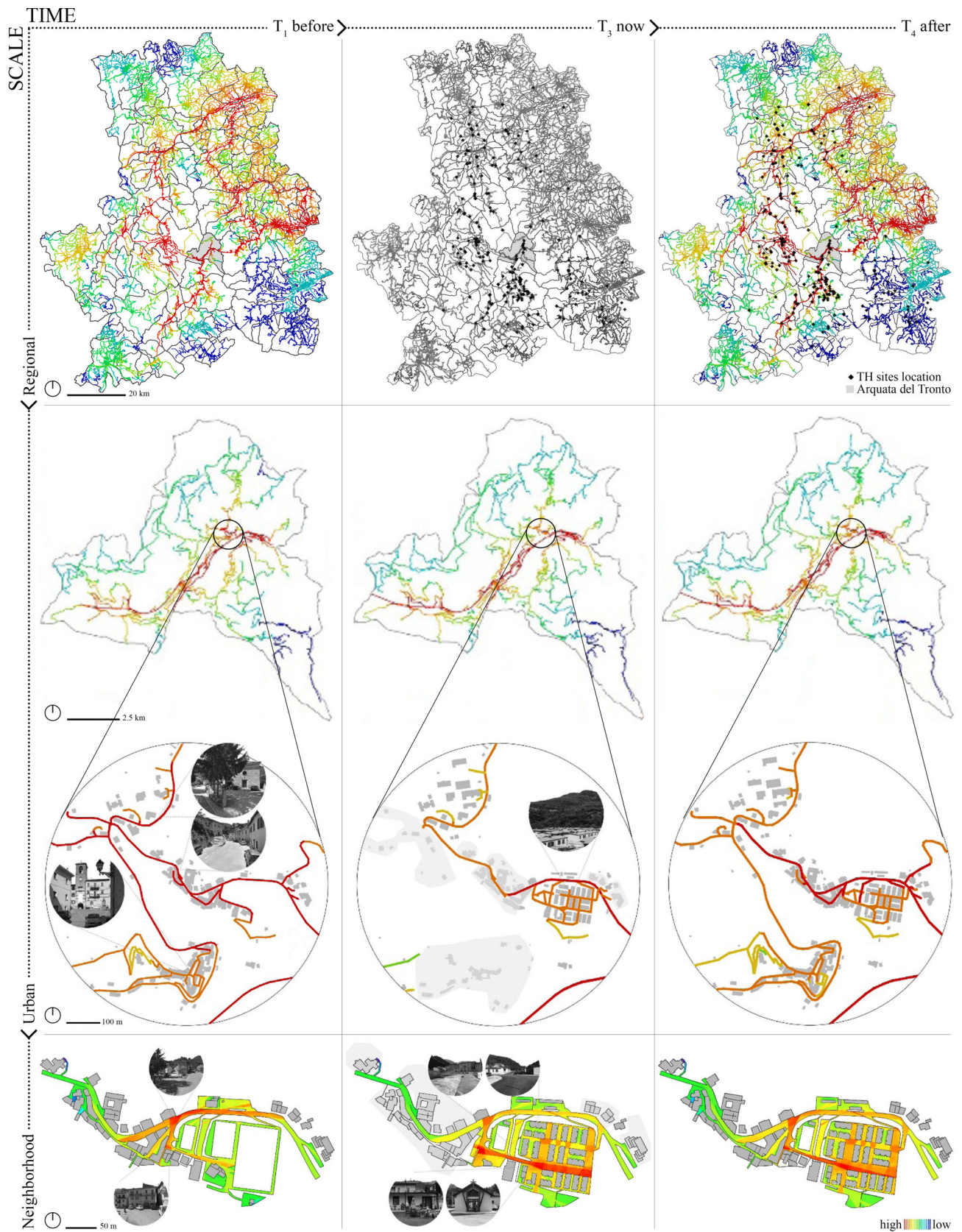


FIGURE 5 Multitemporal (from left to right: T_1 , T_3 and T_4) and multiscale (from top to bottom: regional, urban and neighbourhood scales) ASA (NAIN) and VGA (Integration Index).

Amatrice and Accumoli (more details in: Pezzica et al., 2020, pp. 332–334; Pezzica, 2021, pp. 222–232), revealed the different influence of allegedly similar TH plans on their urban spatial functioning. Based on current policy directions, in this instance, the T_4 analysis considered the hypothesis of reconstruction “as it was, where it was”. At T_4 there are no more “unsafe” inaccessible areas, but the infrastructure services built to support the functioning of the temporary housing sites are still present as currently there is no end-of-life plan for them. This helped assess in which cases the spatial changes introduced by the construction of a distributed system of small TH settlement around the main routes are more likely to cause a structural decrease in the centrality levels of the streets located in the original urban core (a phenomenon previously observed by Alexander, 1989 in a similar context).

The simultaneous assessment of several layered metrics via a Hierarchical Cluster (HC) analysis (Pezzica et al., 2021) ultimately revealed that in Norcia, Amatrice and Accumoli it may be possible to integrate the temporary settlements in the recovered urban system (as new neighbourhoods or commercial/leisure hubs, once the reconstruction is completed), whereas in Arquata the new TH sites will compete with the historic town as duplicate centres, unless they are completely dismantled or redesigned.

The latter case called for a neighbourhood scale study to guide the generation of a corrective urban design proposal (Chioni, Pezzica, et al., 2021), linking the old town to the area of *Borgo1* (T_5). A Visual Graph Analysis (VGA) was used to shift the focus from one-dimensional road segments to two-dimensional open spaces whose results showed the potential of a particular urban void to work as an effective public space. Notably, the correspondence observed between the model at T_3 (recovery phase) and the real social attractiveness of the space suggests relying on the models' predictive capacity for further analysis and design purposes. This opens doors to different uses of the models to advance performance-based and resilience-oriented collaborative design practices; for example, they can support the creation of novel tools, which resort to the wealth of existing built examples to prompt ideas' generation and broader debates during participatory planning initiatives pre-disaster, as part of wider strategic planning efforts (Pezzica, Cutini, et al., 2022).

Finally, Table 1 summarises the results of the case studies analysis by bringing together the 4 priorities of the SFDRR with selected associated actions carried out in the two cases presented above. This sets the basis to further explore, evaluate and identify possible common solutions from different research experiences, transferable to other mountain inner areas at risk, in Italy and more broadly.

5 | DISCUSSION AND OUTLOOK: TOWARDS A TERRITORIAL DIGITAL TWIN (TDT) FOR FRAGILE MOUNTAIN INNER TERRITORIES

The paper presented and critically discussed selected examples from two research experiences which started to move some important

steps in the conceptualisation and deployment of TDTs from a DRR perspective, exploring how such models can contribute to resilience building in practice. Even though they are still at low levels of the DT maturity spectrum, they share the ambition to evolve towards a responsive DRR model and provide some important insights on different ways in which TDTs can enhance the community resilience of fragile mountain regions and their capacity to respond more sustainably to different types of hazards. This includes ways to assist understanding of the root causes of vulnerability, improve people's well-being, and develop their capacity to cope with hazards through the promotion of context-aware and inclusive spatial planning and landscape design practices before and after disasters. For example, the TDT of the water system of the Val di Sole prompted the inclusion of this element in the communication about the territory by local territorial promotion agencies. This has therefore contributed to raising the awareness of individuals and organisations about environmental resources which is a fundamental component of community resilience and promoting social learning for enhancing risk governance (addressing gaps in priorities 1 and 2 of the SFDRR). Additionally, the TDT of the street network system in the Central Italy seismic crater enabled assessing the mid- and long-term impact of post-disaster housing assistance plans on the spatial and social functioning of disaster-affected settlements (addressing gaps in priorities 1 and 4 of the SFDRR), highlighting best practices and prompting proposals for adjusting trajectories whenever a problem was identified in advance. It also provided a tool which can be used to identify critical links (i.e., weak ties) in the street network topology so as to ensure the continued infrastructural connection of the territory in the face of future physical shocks.

In the example of the Val di Sole, innovative mapping and modelling processes have been oriented at increasing awareness about the responsible use of environmental resources in mountain ecosystems, and also, within the framework of the B4R project, at reconciling priorities from disaster risk management and the tourism economy, by translating information collected via the engagement of communities with the TDT into transformative risk reduction actions and targeted investments at the local level which promote equality outcomes (addressing gaps in priority 3 of the SFDRR). The feedback of local stakeholders, involved at various levels in the governance of the territory and in the management of the thermal water resources, will be collated and separately analysed in future research to further conceptualise and develop the proposed TDT tool.

The Central Italy example demonstrated the potential benefits of multidimensional scenario generation and testing for temporary housing planning and urban emergency management in general. For example, via the creation of configurational analysis models and the harvesting of volunteered (geographic) data, whose activation in disaster-affected contexts has often proven valuable to emergency and recovery operations. Additionally, it showed that simulating futures can make the consequence of decisions (e.g., related to site location, site layout, construction management) more explicit to stakeholders, help anticipate connected social, cultural and economic implications and advance BBB practices.

It follows that TDTs – as interactive and people-centred digital replicas supporting the collective exploration of the temporal dynamics of interconnected systems underlying the functioning of complex territories – can contribute to increasing the community resilience of territorially imbalanced mountain areas. This is achieved via digitally-enhanced Disaster Risk Reduction practices, which reduce territorial vulnerabilities by promoting civic engagement, transparency and accountability (Chmutina et al., 2021), as well as local capacity in assessing and reducing risk. Furthermore, the idea of a TDT fits well with the European strategic goal of accelerating both the digital and green transitions towards a more sustainable, resilient, and human-centric Industry 5.0 which complements and extends Industry 4.0. It also fits the concept of ‘innovability’ (from the two terms ‘innovation’ and ‘sustainability’, De la Vega Hernández & Barcellos de Paula, 2021), which links these two concepts together and seems particularly relevant for the sustainable development of fragile areas in mountain regions.

6 | CONCLUSIONS

The paper proposes a vision in which (almost) real-time data about the natural and built environment is exploited to build digital territorial models capable of supporting the integrated and democratic urban design, planning and environmental management of inner territories. To enable this vision, it advocates the development of Territorial Digital Twins (TDTs, defined in Section 5), as decentralised community empowerment systems, that could help: (i) democratise DRR mitigation and monitoring activities by enabling knowledge, technologies and resources' sharing; (ii) facilitate the inclusion and participation of local actors in disaster risk assessment and reduction activities; (iii) move beyond a technocratic and paternalistic perspective where risk reduction actions and investments are delegated to a close circle of expert decision-makers.

The article identifies different opportunities for the use of TDT in all four DRR priority areas (listed in Section 5), which justify further theoretical and technical research efforts. Among other things, TDTs can support day-to-day participative planning and be used by different stakeholders (e.g., experts, local actors, and citizens) during workshops, seminars, and meetings to assess situations as they unfold, plus propose, and test alternative ideas. Additionally, the elaboration of such dynamic and responsive models, enriched with site specific parameters, can inform more holistic and agile decision-making in the design and management of large-scale disaster scenarios and sudden territorial transformations.

The experience of the B4R project suggests that digitally enhanced participatory workshops can support resilience building and help complement the technical approach with the social perspective towards promoting sustainable development in areas suffering from territorial imbalances. However, as observed in the Central Italy case, this requires adequate guidance and genuine and continuous support from the experts rather than a narrow focus on developing technology-centric solutions for the public.

On the one hand, both research experiences highlight the relevance of informed plans in supporting the resilient and sustainable management and design of inner territories and the development of whole systems solutions. This will ultimately ensure that local resources are protected, reducing risks connected to the exposure of communities, infrastructures, and enterprises to hazards towards equitably reducing disparities in unbalanced mountain territories. On the other hand, all the identified issues concerning guidance and support provision – plus ongoing challenges in relation to data retrieval in inner territories, the implementation of SFDRR actions in mountain regions, the adaption of the Digital Twin paradigm for DRR – represent important research gaps and were only partially addressed in this paper. It is the authors' opinion that further research in these areas is therefore needed.

In particular, the proposed spatial models remain quasi static and would benefit from a more responsive interface and real-time updating to move in the direction of digital replicas of a more advanced level of maturity. However, there are still some clear challenges in closing the connection loop in complex and ‘infrastructurally’ raw systems such as inner areas, to enable the real-time data exchange between physical components and virtual models (where the former send raw data, while the latter return processed data).

One approach to be explored in future research could be assigning people not only the role of ‘sensors’, but also that of ‘actuators’, possibly following collaborative decision-making sessions facilitated by experts. This would also help overcome some of the issues connected to the digital divide and lack of digital literacy. Indeed, the feedback from the virtual realm to the physical world, because of the lack of adequate technological tools, networks, and structures, might as well come from automatic or semi-automatic decisional models supporting disaster risk management and subsequent operative actions, which contribute to closing gaps in strategic planning and process management. Moreover, future studies could further explore how TDTs can contribute to the development of knowledge tools, collaboration networks, and structures early in advance, as part of disaster preparedness activities, to ensure that all the necessary technical and governance/policy conditions underpinning the use of TDTs for Disaster Risk Reduction are in place when they need to be activated.

AUTHOR CONTRIBUTIONS

Conceptualization: Chiara Chioni, Camilla Pezzica and Sara Favargiotti; **Methodology:** Chiara Chioni, Camilla Pezzica and Sara Favargiotti; **Investigation:** Chiara Chioni and Camilla Pezzica; **Data curation:** Chiara Chioni and Camilla Pezzica; **Writing—original draft preparation:** Chiara Chioni and Camilla Pezzica; **Writing—review and editing:** Chiara Chioni, Camilla Pezzica and Sara Favargiotti; **Visualisation:** Chiara Chioni and Camilla Pezzica; **Supervision:** Camilla Pezzica and Sara Favargiotti. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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