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Bridging the Gap

The Measure of Urban Resilience

Edited by

Grazia Brunetta, Alessandra Faggian and Ombretta Caldarice

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Editorial

Bridging the Gap: The Measure of Urban Resilience

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1. Understanding Resilience

The concept of resilience has arisen as a "new way of thinking". It was applied in planning at the end of the last century as a concept that encourages policies to face stress factors and react by renewing and innovating cities. Resilience becomes instrumental in addressing both causes and effects of significant global challenges. As it motivates the transformative potentials of cities, resilience is commonly named "co-evolutionary resilience" [1] or, most recently, "transformative resilience" [2]. Following this more profound meaning, resilience is not only the opposite of vulnerability [3] but also a "broad concept", whose final purpose is to prevent and manage unforeseen events together with the improvement of the environmental and social quality of a territorial system [4]. In a nutshell, this approach characterises resilience as a territorial systems' capacity to respond systemically and dynamically to the present and future shocks related to significant global challenges through non-linear transformation processes. Such processes involve the natural and anthropic characteristics of a territorial system, their performance, quality, and functions [5]. Although the theoretical debate on resilience is deeply investigated, several methodological challenges remain mainly related to the concept's practical sphere. As a matter of fact, resilience is commonly criticised for being too ambiguous and empty meaning. At the same time, turning resilience into practice is not easy to do [6]. We need to measure resilience because its assessment allows consideration of what resilience is practical and what it is possible, and at which point resilience is realistically likely to fail. This will be arguably one of the most impactful global issues for future research on resilience [7].

The Special Issue "Bridging the Gap: The Measure of Urban Resilience" falls under this heading. To the best of our knowledge, it seeks to synthesise the state-of-the-art knowledge of theories and practices on measuring resilience. We were particularly interested in papers that address one or more of the following questions: "What are the theoretical perspectives of measuring urban resilience? How can urban resilience a property to be measured? What are the existing models and methods for measuring urban resilience? What are the main features that a technique for measuring urban resilience needs to guide proper adaptation and territorial governance? What is the role of measuring urban resilience in operationalising cities' ability to adapt, recover and benefit from shocks?"

2. Measuring Resilience

For over 40 years, resilience has emerged as a unifying concept in many disciplines linked to sustainability. Efforts to apply resilience within different fields have stimulated interest in measuring resilience, giving rise to various approaches, i.e., qualitative and quantitative methods, participatory assessments, statistical analyses, modelling and metrics [8]. As stated during the 2014 International Food Policy Research Institute (IFPRI) international conference, questions of what to measure, whom to measure, how often to measure, and what methods to use to capture resilience are still being debated. Simultaneously, if no clear guidelines on how to measure resilience reliably exist, decision-makers will not make informed choices about how to use it. Resilience will miss the opportunity to be an organising principle, malleable but able to attract different interests and stakeholders together.

Basically, we can identify two main barriers in measuring resilience. The first one is a conceptual barrier, as it is difficult to measure something unless we know precisely what has to be measured. At the same time, the definition of resilience does not facilitate this. Coming to a common and shared understanding of what resilience means is a necessary starting point. As resilience is a continually changing process leading to the idea of dynamic non-equilibrium, the measure of resilience cannot be a single number or a result [9]. The second one is a methodological barrier, as it may not be easy to obtain reliable and meaningful data. As outlined by [10], there is a reliance on using the available data rather than data from a systematic approach. Although several frameworks have been proposed for "capturing resilience" in academic and public discourse, the existing techniques are limited to measuring specific disturbances. Less attention has been directed to consider resilience as a continually changing process. Moreover, the developed resilient metrics are set indicators of what is easy to measure rather than what is important [11].

Based on this introduction, this Special Issue of *Sustainability* aimed to cover urban resilience measurement by introducing pioneering approaches, discussing experimenting methodologies, and showing possible opportunities for the concept's development. In a very short time, the Special Issue attracted attention from the scientific research community, including 11 published papers, one of which is a review paper focused on comprehensive knowledge regarding multiple methods for measuring resilience. Long Nguyen and Akerar [12] conduct a systematic review of 77 different literature records published from 2000 to 2020, providing an investigation and a more comprehensive picture into the state-of-the-art on modelling, measuring, and visualising community resilience, summarising qualitative, quantitative, and hybrid approaches, and identifying critical points in building community resilience.

Six research papers of this Special Issue assume a methodological perspective that discusses new approaches and required changes to existing methods of measuring resilience. Feldmeyer and colleagues [13] present the result of a project funded by the German Federal Ministry of Education and Research named monitoring of adaptation measures and climate resilience in cities (MONARES). They identify 24 indicators to measure and monitor urban climate resilience for municipalities, assessing the requirements of indicators and implementing a mixed method for adapting global approaches to the local context. The article by Pilone, Demichela and Baldissone [14] presents a semi-quantitative methodology for assessing multiple risks to increase the awareness of municipal technicians. The methodology is based on the assignation of rates to the risks, revealing good feasibility in the results obtained for the interactions, and highlighting some problems neglected in the sectorial risk plans. Brunetta and Salata [15] want to move a step forward from theoretical works on measuring resilience, and particularly they work toward the application of a pioneering empirical methodology to measure and spatially represent the degree of vulnerability (as it is counterpoised to resilience, even if they act simultaneously). The paper by Rota, Bagliani and Feleting [16] proposes a taxonomy of regional resilience using a shift–share analysis based on the region's capacity of improving its employment rate during the pre-crisis period. The paper by Assumma and colleagues [17] investigates the role covered by the system dynamics model (SDM) and Lotka–Volterra models (LV) in supporting the decision-making process in the evaluation of resilience policies. Both the SDM and LV models may be considered reliable supporting tools for policy planning, thanks to their ability to predict possible future behaviours of selected key variables, thus helping stakeholders to identify and prioritise shared strategies for increasing resilience. Lastly, the paper by Mutani, Todeschi and Beltramino [18] aims to cover a research gap of the exiting simulation energy tools and models; namely, to translate the measurement of energy performance from the block of buildings or neighbourhood scale to the city level. The proposed methodology is based on buildings' energy balance, and it is able to carry out simulations at the territorial scale toward energy resilience.

The remaining four research papers of this Special Issue assume a case-study approach that reads and examines resilience measurement application, thoroughly identifying possible solutions to apply resilience in practice. Urso, Modica and Faggian [19] present Italian inner areas' response to the 2007–2009 Great Recession. The purpose of their paper is to analyse the potential structural change of Italian inner vs. non-inner areas, assessing their adaptive capacity. The authors found that urban poles and inner areas had different capabilities to re-adapt their local industrial compositions in response to the economic crisis with noticeable effects on their future resilience. In the paper by Mohabat Doost and colleagues [20], an empirical application to provide an overall assessment of the solar production capacity in the City of Moncalieri (Turin, Italy) is presented. Results demonstrate that the current minimum energy levels required by law are generally much lower than the effective potential solar energy production that each land use parcel-zone could effectively produce. Abastante and colleagues [21] support that a walkable city means creating a resilient and healthy city. Their paper presents case study research, the Main Campus of the Politecnico di Torino, as a fertile ground for studying a walkability assessment. Lastly, Voghera and Giudice [22] sustain that green infrastructure (GI) is a nature-based solution capable of enhancing the social–ecological quality of a specific territory, both in a sustainable and resilient way. Their paper attempts to fill the gap between evaluation methodology and planning tools compared to GI's indicators in Italy and France.

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Review

Modelling, Measuring, and Visualising Community Resilience: A Systematic Review

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Abstract: The concept of community resilience receives much attention in studies and applications due to its ability to provide preparedness against hazards, to protect our life against risks, and to recover to stable living conditions. Nevertheless, community resilience is complex, contextual, multifaceted, and therefore hard to define, recognise, and operationalise. An essential advantage of having a complete process for community resilience is the capacity to be aware of and respond appropriately in times of adversity. A three-step process constituting of modelling, measurement, and visualisation is crucial to determine components, to assess value, and to represent information of community resilience, respectively. The goal of this review is to offer a general overview of multiple perspectives for modelling, measuring, and visualising community resilience derived from related and emerging studies, projects, and tools. By engaging throughout the entire process, which involves three sequential steps as we mentioned above, communities can discover important components of resilience, optimise available local and natural resources, and mitigate the impact of impairments effectively and efficiently. To this end, we conduct a systematic review of 77 different literature records published from 2000 to 2020, concentrating on five research questions. We believe that researchers, practitioners, and policymakers can utilise this paper as a potential reference and a starting point to surpass current hindrances as well as to sharpen their future research directions.

Keywords: community resilience; systematic overview; resilience modelling; knowledge representation; resilience assessment; information visualisation

1. Introduction

The word resilience originally stems from the Latin term “resiliere” that means to jump back or bounce back. The first careful consideration of the term resilience arose in the field of mechanics in 1858, followed by psychology in the 1950s, human ecology in the 1990s, and ending up with disaster risk reduction and climate change adaptation in the 2000s [1]. Resilience concentrates on improving the capacity of a system in the face of multiple hazards, rather than precluding or diminishing the loss of assets because of specified events. Resilience accepts the condition that a wide range of disruptive events—both stresses and shocks—may take place but are not inevitably foreseeable. This research topic has received significant interest from not only researchers but also practitioners and service-users. Recognising the importance of resilience, many definitions at multiple domains have been offered, as shown in Figure 1, including physical [2,3], social [4,5], ecological [6–8], economic [9], individual [10,11], and community [12,13]. According to mentioned literature, there is no commonly accepted way to define the concept of resilience formally; besides, several definitions are even overlapping with existing concepts [14], some of which are robustness, fault-tolerance, flexibility, survivability, and agility.

As the formal definition given by the United Nations Office for Disaster Risk Reduction (UNDRR), resilience is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner [15]", in not only pre- but also post-disaster. During pre-disaster, we aim at anticipating vulnerabilities and risks proactively to mitigate harmful effects. On the other hand, the capability of valid and sufficient recovery is an essential objective in the post-disaster period [16]. Studies about resilience can help our societies in reducing disaster risk, adapting to climate changes, and coming up with strategies to develop more sustainably and efficiently.

Figure 1. Multiple domains of resilience.

In this paper, we focus on giving an overview of multiple perspectives regarding community resilience. Community resilience aims at representing the abilities of a local community as a complex system, including actions and interactions of local agencies, natural and built environments, critical infrastructures, and citizens, to reduce, withstand, and even turn back from impacts of hazards, as well as the competence to adapt and thrive themselves to be less vulnerable to future disasters and emergencies. There are more and more studies concentrating on building community resilience across various application domains (e.g., tourism [17], biodiversity management [18], energy [19], and mental health [20]) in either global [21] or regional levels, some of which are Brazil [22], Greece [23], and the United Kingdom [24]. Nonetheless, this research field still needs many efforts from researchers and practitioners to come up with comprehensive methodologies to model, measure, and understand community resilience. These three mandatory phases can support communities in proposing additional activities and new approaches to the comprehension of how to ensure that our communities can be better prepared, more flexible, and have the ability to bounce back promptly from an event, whatever form it may take.

Our motivation is to provide crucial knowledge regarding multiple methods for modelling, measuring, and visualising community resilience in this paper. For coming up with optimal decision-making criteria and strategies to make our communities resilient, we should focus on the entire process—all of these three phases. In particular, we address various components and properties to model community resilience; different qualitative, quantitative, and hybrid approaches for measuring resilience value; and several visualisation methods at the end to show resilience-related information. We believe that this paper can support not only academic researchers but also practitioners in recognising what frameworks are already out there and how we can build on them.

In this section, we introduced the problem and emphasised our motivation for conducting this review. The rest of this paper includes the following structure. In the next section, the necessary background will be given. Section 3 will provide vital information about the materials and methods to conduct this review. Further, Section 4 summarises different methodologies for modelling community resilience. Then, we will describe qualitative, quantitative, and hybrid approaches to measure community resilience in Section 5. Section 6 will provide various visualisation techniques for representing resilience information. Finally, we will give some discussion, draw essential conclusions, and express future directions in the last section.

2. Background

Community resilience is a complicated concept that cannot be captured and turned into explicit knowledge effortlessly. What is generally accepted among researchers is the fact that community resilience tremendously depends on multiple components that affect and influence the overall resilience of a community [25]. Such elements can be related to particular risks, temporal and spatial contexts, and community features that resilience refers to (e.g., perception, hazards, and capacities). Even more complex, the term community resilience also has diverse meanings between communities by referring to different components of the community, including, but not limited to, the resilience of community infrastructure [26] and the resilience of social relationships [27]. Hence, it is necessary to identify, define, and describe the particular components and properties of community resilience in the process of modelling.

Based on components and properties defined in the modelling step, we can apply qualitative, quantitative, or hybrid methodologies to translate resilience dimensions, indicators, and proxies into tractable and understandable frameworks, expressions, formulations, or values. The target of qualitative methods is to provide detailed descriptions depending on specific contexts. To enable the ability to understand and transfer results, experts account for their viewpoints and perspectives [28] through case studies, grounded theories, interviews, ethnography, phenomenology, and hermeneutics [29]. It is ordinary to represent qualitative results as charts, diagrams, and other graphics by using visualisation methods. On the other hand, we measure quantitative value by paying attention to community resilience at a particular time point or by comparing resilience value before and after an event [30]. Generally, the community resilience value is appropriate for internal use. To compare a community with others, we may use their rank or percentile equivalent of the community resilience value; however, we have to ensure that the measurements should be taken in similar contexts. Our data should be comparable, comprehensible, measurable, and relevant [21] so that it is suitable for quantitative methodologies. Further, hybrid approaches are the integration of quantitative and qualitative methods; therefore, they can estimate both tangible and intangible value of community resilience.

Visualisation is the final puzzle piece to complete a big-picture of community resilience. In emergencies, especially in situations requiring immediate actions, we may face a massive amount of community resilience information. Visualisation is an effective and efficient solution that has the capacity to represent resilience-related information of communities in systematic forms without missing essential details [31]. We can also utilise information visualisation to discover latent patterns, which are arduous to recognise manually [32]. Additionally, emerging digital visualisation tools can involve end-users in many interactions (e.g., zooming in or out, employing dynamic charts, and changing visual appearances such as colours and shapes). With the support of disruptive technologies (e.g., machine learning and artificial intelligence) [33], we can leverage information visualisation to build recommender systems and dashboards for potential use in emergencies, disasters, and catastrophes as well.

3. Methodological Approach

This section describes in detail how we identify relevant and credible literature addressing resilience at different community levels. In the following sections, common themes are determined and summarised to generate insights into community resilience. The interest of this review is to find and evaluate studies, projects, and tools that draw upon new solutions for communities to model, measure, and visualise resilience.

3.1. Research Question

There is a need for a more transparent analytical overview and a selection of the studies, projects, and tools most relevant to what we can focus on in more detail. The results of this review will summarise and discuss the following research questions. Generally, different communities could benefit from this paper's much more comprehensive overview of:

1. What resilience studies, projects, and tools at community-based levels already exist?
2. What types of threats, hazards, shocks, disasters, etc. do they face?
3. What and how many resilience components and properties do they define?
4. How do they measure community resilience—i.e., using more qualitative evidence, quantitative indicators, or a combination of the two?
5. What are the appropriate visualisation techniques to express community resilience information?

We conduct this review study to fulfil the information required by communities in both static and dynamic phases. In the static phase, our target is to define what we have and what we suffer from. On the other hand, we aim at understanding whether those variables represent objects or contexts that we can work towards in the dynamic phase.

3.2. Search Strategy

Concerning geographic-based communities and resilience, the concept of community resilience may contain two proxies which are urban and rural resilience [34]. Urban resilience puts more focus on the ability of cities or urban systems to rebound from destruction [35], whereas rural resilience aims to conserve a satisfactory standard of living in rural areas [36]. For the sake of generalisation, we take into account studies, projects, and tools related to not only community resilience but also urban and rural resilience. We started this work by searching the published articles on Google Scholar, Scopus, Web of Science, and ScienceDirect, which are not limited to particular disciplines, using text strings "community resilience", "urban resilience", "rural resilience", "resilience assessment", and "resilience visualisation" and their combinations. Meanwhile, the systematic search of relevant projects and tools is conducted on Google search engine. We also check the reference lists of the selected articles to discover additional related work. Supplementary data sources involve our pre-existing knowledge of the literature.

3.3. Eligibility Criteria and Selection Process

To be included in this review, the inclusion criteria established that the literature must adhere to the following rules. No restrictions are imposed with regards to the time or country of publication.

- Focusing on modelling, measuring, or visualising community, urban, or rural resilience.
- Having full-text publications or descriptions.
- Publishing in the English language.

On the contrary, we define the exclusion criteria used to filter literature that is not relevant for this study as follows.

- The literature is a letter, thesis, dissertation, or conference abstract.
- The literature is not related to defined research questions.

After screening the data, full-text documents are collected to extract necessary study-specific parameters (e.g., type of resilience at community-based levels, number of resilience components, methodologies to assess resilience, and techniques for representing resilience information) for further analysis. Upon our search using the search strategy and inclusion criteria devised, we identify 77 studies, projects, and tools in the last 20 years, from 2000 to 2020, for inclusion in this review, as shown in Table 1.

Table 1. Resilience studies, projects, and tools at community-based levels.

Level	Study/Project/Tool	Focus
Rural	Community Resilience Manual [37]	Community resources
	Insurance for Rural Resilience and Economic Development (INSURED) [38]	Climate risks
	MIME Project [39]	Pre-hospital emergencies
	McManus et al. [40]	Local economy, job, and environment
	Ross and Clay [41]	Capital assets
	Rural Coastal Community Resilience (RCCR) Framework [42]	Sea level rise and saltwater intrusion
	Rural Diversity Index (RDI) [43]	Rural diversity
	Rural Resilience Framework [44]	Climate change
	Rural Social Protection [45]	Risks and threats
	Steiner and Atterton [46]	Private sector enterprises
	Withdrawal Mechanism for Rural Homesteads (WMRH) [47]	Land use policies
	Woolvin [48]	Family estates
Urban	City Resilience Framework [49]	Stresses accumulate and sudden shocks
	City Resilience Roadmap [50]	Acute shocks and long-term stresses
	Coastal Megacity Resilience Simulator (CMRS) [51]	Climate change
	Disaster Resilience Index (DRI) [52]	Urban flood
	Disaster Resilience Indicators [53]	Disasters
	Disaster Resilience Scorecard for Cities [54]	Acute shocks (natural and man-made)
	emBRACE Framework [55]	Disasters
	European Resilience Management Guideline (ERMG) [56]	Climate change and social dynamics
	FEW-Nexus City Index [57]	Food, energy, and water
	Flood Resilience Index (FRI) [58]	Flood
	Foundational Infrastructure Framework (FIF) [59]	Infrastructure sectors
	Grosvenor Research [60]	Shocks and adverse events
	ICLEI ACCCRN Process (IAP) [61]	Climate risks
	Maturity Model (MM) [62]	City stakeholders
	Porębska et al. [63]	Evacuation route planning and design
	RESCCUE Project [64]	Multihazard threats and climate change
	Resilience City Planning Framework (RCPF) [65]	Climate change and environmental risk
	Resilience Diagnostic Tool [66]	Urban planning
	Resiliency Cube [67]	Transportation network in earthquake
	Risk Management Index (RMI) [68]	Urban disasters
	TURaS Project [69]	Urban planning and policy
	Urban Resilience Concept Note [70]	Shocks and stresses
	Urban Resilience Index [71]	Urban social-ecological systems
	Urban Resilience Framework [72]	Heterogeneous risk factors
Community	Analysis of Resilience of Communities to Disasters (ARC-D) Toolkit [73]	Disasters
	Australian Natural Disaster Resilience Index [74]	Hot-spots of high or low disasters
	Baseline Resilience Indicators for Communities (BRIC) [75]	Disasters
	Bay Localize Community Resilience Toolkit [76]	Community assets
	Chandra et al. [77]	National health security
	Climate-related Disaster Community Resilience Framework (CDCRF) [78]	Climate-related disasters
	Community Advancing Resilience Toolkit (CART) [79]	All-hazards environment
	Community And Regional Resilience Initiative (CARRI) Research Report [80]	Natural and human-made disasters
	Community Based Resilience Analysis (CoBRA) [81]	Crises and disasters
	Community Disaster Resilience Index (CDRI) [82,83]	Disasters

Table 1. *Cont.*

Level	Study/Project/Tool	Focus
Community	Community Disaster Resilience Toolkit [84]	Disasters
	Community Resilience Framework (CRDSA) [85,86]	Disasters
	Community Resilience Index [87]	Natural hazards
	Community Resilience System (CRS) [88,89]	Man-made and natural disasters
	Community Self-Assessment [90]	Disasters
	Conjoint Community Resilience Assessment Measurement (CCRAM) [91]	Emergencies
	Costs, Opportunities, Benefits, and Risks Analysis (COBRA) Framework [92]	E-government services
	Disaster Resilience of Place (DROP) Model [93]	Natural disasters
	Flood Resilience Measurement for Communities (FRMC) [94]	Flood
	Framework for Community Resilience (FCR) [95]	Disasters, crises, shocks and stresses
	IMPROVER Project [96]	Critical infrastructure
	Jordan and Javernick-Will [97]	Disasters
	Localized Disaster-Resilience Index [98]	Disasters
	Moreno et al. [99]	Tsunami
	Natural Hazard Resilience Screening Index (NaHRSI) [100]	Natural hazard events
	Pilquimán-Vera et al. [101]	Community based tourism
	PEOPLES Resilience Framework [102]	Extreme events or disasters
	POP-ALERT Project [103]	Crises and cross-border disasters
	Rabinovich et al. [104]	Soil erosion
	Rahman and Kausel [105]	Tsunami
	RELi Resilience Action List & Credit Catalog [106]	Next generation community
	Resilience Matrix (RM) [107]	Disruptive events in coastal areas
	Resilience Modelling Tool [108]	Natural hazards
	School-Community Collaborative Network (SCCN) Conceptual Model [109]	Disaster education
	Sherrieb et al. [110]	Economic development and social capital
	Shesh Kanta Kafle [111]	Disasters
	Tool for Health and Resilience in Vulnerable Environments (THRIVE) [112]	Health, safety, and health equity
	Uddin et al. [113]	Cyclone and storm surge disasters

4. Modelling Community Resilience

Determining and defining community resilience's components and properties is an essential step for further developing clear strategies and undertaking practical activities to attain resilience in our community. This section presents different studies that have been conducted to achieve a better understanding and clarification of the community resilience through modelling step.

4.1. *Defining Key Components*

Although the importance of modelling resilience is widely recognised and researched, proposing an appropriate number of resilience components is still a significant challenge. Researchers find out that short-term human memory works best when we have fewer elements to remember. People are usually good at remembering no more than seven different components [114]. The community resilience, therefore, almost encompasses from three to seven components. Noting that in most studies, the order of components does not reflect their importance.

Table 2 presents different studies, projects, and tools arranged by the number of components, their focuses, and years of publication. We use the year of publication instead of the year of study as it is relatively more accessible.

Table 2. Summary of community resilience components along with focuses and years of publication.

Number of Components	Focus	Year	Reference
Three components	Acute shocks (natural and man-made)	2017	[54]
	Climate-related disasters	2012	[78]
	Community based tourism	2020	[101]
	Disasters	2017	[55]
	Economic development and social capital	2010	[110]
	Food, energy, and water	2018	[57]
	Health, safety, and health equity	2004	[112]
	Local economy, job, and environment	2012	[40]
	Private sector enterprises	2015	[46]
	Risks and threats	2020	[45]
	Urban planning and policy	2016	[69]
Four components	Acute shocks and long-term stresses	2019	[50]
	All-hazards environment	2013	[79]
	Community resources	2000	[37]
	Disasters	2010	[82]
		2013	[97]
		2014	[84]
	Family estates	2013	[48]
	Land use policies	2018	[47]
	Man-made and natural disasters	2014	[88]
	Natural hazards	2015	[108]
	Next generation community	2014	[106]
	Rural diversity	2014	[43]
	Stresses accumulate and sudden shocks	2015	[49]
Five components	Climate change	2013	[51]
	Disasters	2010	[53]
	Flood	2016	[58]
		2019	[94]
	Sea level rise and saltwater intrusion	2017	[42]
	Soil erosion	2019	[104]
Six components	Community assets	2009	[76]
	Critical infrastructure	2018	[96]
	Disasters	2014	[75]
		2015	[85,86]
		2016	[83]
	Disasters, crises, shocks and stresses	2014	[95]
	Emergencies	2013	[91]
	Natural disasters	2008	[93]
	Urban flood	2019	[52]
Seven components	Disasters	2010	[90]
		2013	[98]
	Extreme events or disasters	2016	[102]

Table 2. *Cont.*

Number of Components	Focus	Year	Reference
More than seven components	Cyclone and storm surge disasters	2020	[113]
	Disasters	2020	[73]
	Hot-spots of high or low disasters	2016	[74]
	Infrastructure sectors	2017	[59]
	Man-made and natural disasters	2013	[89]
	National health security	2011	[77]
	Shocks and adverse events	2014	[60]
	Tsunami	2013	[105]

Figure 2 shows a diagram including nodes and edges, which represent resilience components and their relations based on the literature in Table 2, respectively. A connection exists among two components in case they co-occur in a model. For example, economy and institution are two of five indices defined in [53]; hence, there exists a relationship among these two nodes. Besides, the size of a node depicts the frequency of this component in the literature (i.e., a bigger node points out that this component appears more times than smaller ones). We may recognise from Figure 2 that society, economy, community, physical, resource, and infrastructure are mostly defined in different models.

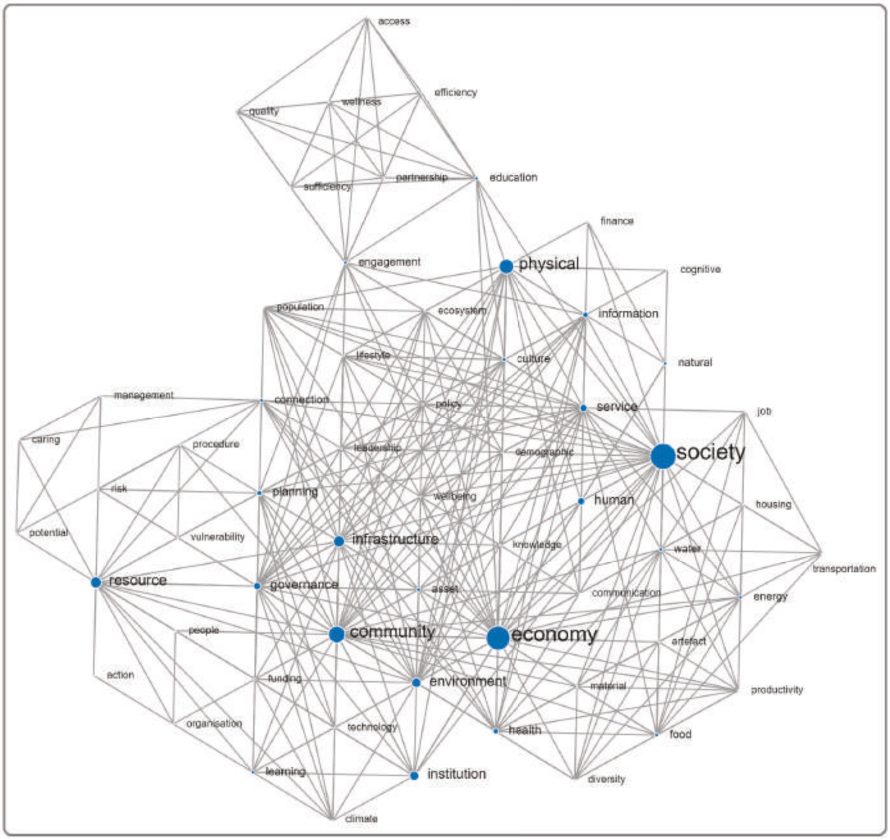

Figure 2. Community resilience components and their relations.

4.1.1. Less than Five Components

In [55], the emBRACE framework proposes the three community resilience domains, including resource and capacity, action, and learning followed by 17 different resilience indicators. Due to the nonstraightforward allocation property, a defined indicator can fit in not only one but also many dimensions. In addition, focusing on three components for modelling resilience [110], the authors build and verify the correlations of indicators through using the Mississippi county data. The combination of the refined indicators belongs to three community resilience components, which are economic development, social capital, and an additive index of community resilience. Meanwhile, in [112], the THRIVE tool of the Prevention Institute represents community resilience with three interconnected clusters, which are (i) social-cultural environment (people), (ii) physical/built environment (place), and (iii) economic/educational environment (equitable opportunity). This tool guarantees community resilience by increasing the quality of life and handling the biased distribution of health-related resources. Furthermore, social, economic, and environmental components are highly targeted and focused in [40,45,46].

Instead of using three components, the Community Disaster Resilience Framework (CDRF) addresses four different capital assets of a community comprising social, economic, physical, and human capital [82]. Similarly, Jordan and Javernick-Will [97] proposed four recovery indicators that are categorised as social, economic, environmental, and infrastructural. In addition, focusing on social and economic components, together with natural and institutional ones, the RDI [43] provides a better understanding of the connection between diversity in socio-ecological systems and its resilience. In [106], the C3 Living Design Project proposes a comprehensive action list, which can guide actions for a resilience present and future of communities, buildings, homes, and infrastructure, consisting of CV (community cohesion, social, and economic vitality), PH (productivity, health, and diversity), EW (energy, water, and food), and MA (material and artefact). In addition, Huang et al. [47] develop the assessment index system including four components, which are engineering, ecological, economic and social, to assess the changes in rural resilience.

Apart from that, the authors in [79] refer to community capacity and competence-based studies in social psychology and public health to develop the Communities Advancing Resilience Toolkit (CART). The CART describes four overlapping and interrelated domains of community resilience including (i) connection and caring, (ii) resource, (iii) transformative potential, and (iv) disaster management. A community with higher capability in these four defined domains can be more successful in reducing the harmful effects of disasters and other related difficulties. In a different approach [37], the Canadian Centre for Community Renewal (CCCR) focuses on people, organisation, resource, and community process. Among four dimensions, the people and organisation represent attitudes and behaviours of a community; the resource depicts awareness and use; and the community process portrays strategic thinking, participation, and action. These dimensions are further separated into 23 characteristics of resilience. In addition to the studies mentioned above, the authors in [84,115] model the community resilience with community connectedness, risk and vulnerability, available resources, and planning and procedures, which are logically overlapping and able to interact with each other. This demonstrates the equivalence among domains in constructing community resilience towards multiple disasters.

4.1.2. From Five to Seven Components

By applying a five-components approach, the Zurich Flood Resilience Alliance (ZFRA) models community resilience with five capitals comprising human, social, physical, financial, and natural [94]. These five capitals can assist people in their development as well as enhance the ability to cope with and make a response to various flood-related shocks. Following [51], Simonovic and Peck propose the quantitative resilience framework, which combines economic, social, organisational, health and physical impacts, for dealing with climate change on coastal megacities. In [53], the authors propose five indices, which are social, economic, institutional, infrastructure, and community capacities, to examine community-level resilience. With baseline conditions defined in this study, the authors can not only keep track of changes of resilience at a specific time in a particular place but also compare resilience among locations. The studies in [52,75] are similar; however, the authors extend their model by supplementing one more index that is the environmental capacity.

The similar idea can be found in [95] in which the International Federation of Red Cross and Red Crescent Societies (IFRC) describes six resilience indicators to fortifying community resilience including knowledge and health, society, infrastructure and service, economy, natural asset, and connectivity. These indicators are designed to effectively and efficiently support three critical constituents of the Framework for Community Resilience (FCR) that are (i) assisting communities towards risks promptly and proposing solutions to portray underlying vulnerabilities comprehensively, (ii) placing people and their demands in the centre, and (iii) being retrievable by people at anytime and anywhere. According to [96], The IMPROVER project provides physical, social, human, natural, economic, and institutional capitals as six crucial components along with the IMPROVER Societal Resilience Analysis (ISRA) (for qualitative measuring indicators) to self-assess and guarantee community resilience. In [76], the Bay Localize constructs the community resilience toolkit concentrating on six key components being composed of food, water, energy, transportation and housing, jobs and economy, and civic services. This toolkit is beneficial in helping communities facing risks and hazards in the area of climate change and peak oil. Following Alshehri et al. [85,86], the authors discuss social, economic, physical and environmental, governance, health and well-being, and information and communication dimensions. The featured contribution of these two studies is that the authors discovered the correlation between the six identified dimensions and 62 criteria (i.e., from seven to fourteen criteria connect to every dimension). In [83], Yoon et al. build a set of indicators to measure community disaster resilience index utilising human, social, economic, institutional, physical, and environmental factors that are related to vulnerability and capacity aspects of South Korea.

Concerning seven dimensions depicting community functionality, the PEOPLES framework is constructed in [102] to represent population and demographic, environmental and ecosystem, organised governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital. This framework can promote the empowerment of local planners, decision-makers, and stakeholders to evaluate and improve their community resilience in different temporal-spatial contexts.

4.1.3. More than Seven Components

There are not many studies which are conducted in terms of using more than seven components. In [74], the authors leverage the top-down approach to put forward eight different indices for consideration, which are clustered into (i) coping capacity (i.e., social character, economic capital, infrastructure and planning, emergency services, community capital, and information and engagement) and (ii) adaptive capacity (i.e., governance, policy and leadership and community and social engagement). Along with each index is a set of measurable indicators. Hence, we can use either one number or sets of numbers to represent a resilience index in this study. Further, Barkham et al. [60] propose ten key components classified into two distinct themes that are vulnerability and adaptive capacity. The vulnerability includes climate, environment, resource, infrastructure, and community; whereas the adaptive capacity is made up of governance, institution, technical and learning, planning systems, and funding structures. Concerning this approach, a community is resilient in case it possesses low vulnerability and high adaptive capacity. In [89], the Community and Regional Resilience Institute (CARRI) defines Community Service Areas (CSAs) to support communities in realising strengths and shortages of resilience. The CSAs include 18 different aspects, some of which are communications, education, energy, and water, for improving community life and function together.

4.2. Determining Community Resilience Properties

Due to the diversity of definitions of community resilience and their components as we stated in the previous section, the properties of community resilience are therefore divergent as well. In this section, we describe different studies that sought to determine the properties of community resilience in various disciplines. In [94], the authors define four features of a resilient system taking into consideration assets, interactions and interconnections at the community level, including the robustness, redundancy, resourcefulness, and rapidity. These four properties are also determined for both physical and social systems in [30]. In another approach, the Bay Localize mentions the equity, quality, sustainability, and ownership as essential criteria for communities to adapt with resilience requirements related to climate change and peak oil [76].

Besides that, the simplicity, adaptation, dependency (i.e., not stand alone), and (future) orientation are defined as properties to guide the community in modelling resilience regarding a diverse range of philosophies [108]. Similarly, the authors in [88] propose four properties of community resilience involving the attribute, continuity, adaptation, and trajectory. Eventually, community resilience can be considered as a dynamic concept; wherefore, assigning a fixed value for a community over a long-term duration is inappropriate because it may change promptly [9,116]. Table 3 provides properties of community resilience and their descriptions in detail. A community resilience model should satisfy not all but at least some of these properties.

Table 3. Properties of community resilience and their descriptions.

Property	**Description**
Adaptation	The ability of a community in overcoming regular evaluation and alteration to adjust, update, and acclimate to resilience standards over time
Attribute	The concept of community resilience should be comprehended in not only as an internal resident but also as a general entity
Continuity	The requirement of having inherent, dynamic, and persistent characteristic to guarantee community resilience
Dependency	The interaction and integration with a wide range of related models and frameworks to build community resilience
Dynamic	The effective utilisation and enhancement of resources to repair, reconstruct, and recover from surprising events quickly
Equity	The quality of being fair and impartial for all community members towards basic human needs, no matter who they are, regardless of origin, race, gender, or whatever
Orientation	The utilisations of predicate assumptions to guarantee that the model will follow defined directions strictly
Ownership	The acts, states, and rights of communities in owning resources collectively and securely
Rapidity	The capability of a community to prepare, respond, adapt, and recover from disruptive events promptly
Redundancy	The diversity in giving solutions or strategies in a particular situation
Resourcefulness	The latent qualities or potentiality to mobilise in menacing circumstances
Robustness	The capacity of a community in withstanding the actions or effects of adverse shocks
Simplicity	The ability to transform important and complicated factors into a simple model that allow measuring community resilience easily
Sustainability	The potentiality to maintain resources good enough for producing in the future
Trajectory	The accomplishment of positive outcomes that is relative to "after" state of entities
Quality	The crucial goods and services used to evaluate whether a community achieves good standards, some of which are purified air, healthy food, and safe transportation

5. Measuring Community Resilience

After modelling community resilience, it is indispensable to select appropriate methodologies for aggregating and assessing identified components to come up with general systems [39], comprehensive frameworks [44,65,103], management guidelines [56], innovative models [64,72], a resilience “value”, a feasibility assessment [38], or underlying correlations among components [48]. To measure community resilience, we can apply either qualitative, quantitative, or combine these two methodologies as a hybrid one. Qualitative approaches, which are suitable for processes required professional experience of experts, are used to evaluate community resilience without providing a particular numerical descriptor. Apart from that, quantitative methods leverage numerical data along with statistical models to measure community resilience. From a practical perspective, both qualitative and quantitative approaches have proved beneficial and useful in measuring complex community resilience. Several appropriate methods for use include, for example, in-depth interview [46], semi-structured interview [62], observation [73], and survey [92]. Table 4 shows the summary of qualitative, quantitative, and hybrid approaches to measure community resilience.

5.1. Qualitative Approaches

Qualitative approaches can be applied either at (i) the framework level or at (ii) the component level. At the framework level, qualitative techniques aim at giving understanding into actions, themes, patterns, and overall structures of community resilience, for designing and developing processes, phases, or procedures pragmatically. They are usually designed in a step-by-step format to involve communities in sequences and activities, not only assessment but also engagement, implementation, planning, and others. On the other hand, we concentrate on more detailed and qualitative analyses of community resilience factors and their internal relationships at the component level [117]. Generally, a partial implementation of a framework-based approach can be considered as a component-based one. Qualitative methods are sometimes difficult to conduct due to the diversity of standards, interfaces, and coding.

5.1.1. Framework Level

At the framework level, a completed process including continuous cycle or a sequential series of steps is defined and designed with the ultimate goal aiming at comprehending community resilience for effective development and implementation. Table 5 describes steps, stages, or phases of qualitative approaches at the framework level.

The IAP [61] comes up with six consecutive phases to evaluate climate risk, which are engagement, climate research and impacts assessment, vulnerabilities assessment, city resilience strategy, implementation, and monitoring and review. Along with each phase is the set of tools including objectives, guidance, questionnaires, and exercises. They help cities, local governments, and relevant stakeholders, either with a lot or little experience in climate change planning, to build urban resilience. In a similar manner, the Community Resilience System (CRS) also offers six stages (i.e., engagement, assessment, visioning, planning, implementing, and monitoring and maintaining) to support communities in understanding resilience, defining goals, creating strategies, deciding on tools and processes, and evaluating resilience [89]. To derive robust consequences, the authors describe appropriate steps for each stage in which each stage involves specific actions (together with related and supporting resources) required to accomplish.

In another approach, the CART [79] proposes a process, which encompasses assessment, feedback, planning, and action, to engage stakeholders in addressing community problems through field-tested surveys, key informant interviews, community conversations, and supplemental instruments. This toolkit contributes to empowering communities in leveraging their assets and strengths for overcoming multiple disasters. According to [77], the RAND Corporation aims at providing a roadmap to represent an essential step forward for determining the critical elements of community resilience. Based on eight levers, five core components and their interactions, the literature review, focus groups, and SME meetings are conducted for comprehending and strengthening community resilience. This proposed framework is suitable for various communities in reinforcing resilience concerning health security.

Table 4. Summary of qualitative, quantitative, and hybrid approaches to measure community resilience.

Approach	Focus	Outcome	Reference
Qualitative	All-hazards environment	4-stage process for identifying issues, solving problems, and planning activities	[79]
	Climate risks	6-phase process (4 phases for preparation and 2 phases for implementation and monitoring)	[61]
	Community based tourism	Relationship between tourism experiences with community resilience processes	[101]
	Evacuation route planning and design	Limits of punctual treatments and impacts on dimensions of urban walkability	[63]
	Man-made and natural disasters	6-stage process with detailed guidance, tools, and resources identified for each module	[89]
	National health security	Roadmap used as a starting point to develop local community resilience strategy	[77]
	Soil erosion	Impacts on soil erosion based on social, psychological, and cultural parameters	[104]
	Stresses accumulate and sudden shocks	4 categories, 12 goals, 52 indicators, and 156 variables for city resilience	[49]
	Tsunami	Strength and weakness of tsunami preparedness based on eight resilience elements	[105]
		Analysis of resilience capacities and resources activated to cope with disaster	[99]
Quantitative	Acute shocks (natural and man-made)	Resilience scores for preliminary (from 0 to 30) and detailed assessment (from 0 to 180)	[54]
	Climate change	Space time dynamic resilience measure (ST-DRM)	[51]
	Disasters	Disaster resilience score ranging between 22 and 110	[84]
		Community disaster resilience index for 4 capital indices across 4 management phases	[82]
		A single, scalar measure combined from six multidimensional components	[83]
		Resilience index based on the percentage of check marks and the number of Yes answers	[90]
		Disaster-resilience index score based on process- and outcome-indicator scores	[98]
	Economic development and social capital	Composite scores of economic development, social capital and community resilience	[110]
	Health, safety, and health equity	Top three priorities to increase health and safety and reduce health inequities	[112]
	Natural hazards	Composite resilience index ranging between 0 and 100	[108]
	Rural diversity	Rural diversity index ranging between 0 and 1	[43]
	Shocks and adverse events	Overall rank along with vulnerability, adaptive capacity, and resilience scores	[60]
Hybrid	Community resources	Community portrait involving community perceptions, attitudes, feelings, and others	[37]
	Community assets	Toolkit for specific resources and action ideas in six key sectors	[76]
	Disasters	19 indicators of recovery along with rating of the importance of each indicator	[97]
		Resilience framework involving 7 to 14 criteria in each of six defined dimensions	[85]
	Disaster education	Conceptual model for collaborative network and knowledge management	[109]
	Disruptive events in coastal areas	Resilience Matrix (RM) framework with performance score for each cell ranging from 0 to 1	[107]
	Land use policies	Rural resilience assessment index ranging between 0 and 1	[47]
	Natural and human-made disasters	Resilience baseline and its schematic representation based on GIS methodology	[80]
	Urban disasters	Risk management index ranging between 0 and 100	[68]

Table 5. Summary of steps, stages, or phases of qualitative approaches at the framework level.

Reference	Step/Stage/Phase	Description
[61]	1. Engagement	Determine key stakeholders, set up coordination and reporting structures, and conduct a preliminary measurement of the city's progress to tackle climate change
	2. Climate research and impacts assessment	Analyse climate change data, build a projection of likely climate changes, and evaluate the impact on critical urban systems and resultant risks
	3. Vulnerabilities assessment	Produce maps of high priority climate risks, measure the impact on the most vulnerable groups of people, and inspect the adaptive capability
	4. Resilience strategy	Construct a list of feasible adaptation activities, prioritise interventions, link to existing city plans, and aggregate all the essential information
	5. Implementation	Determine funding options, distribute responsibilities and resources, and put the initiatives into effect
	6. Monitoring and review	Set up performance indicators and reporting systems, monitor and report against defined indicators, and initiate review phase
[77]	1. Wellness and access	Promote pre- and post-incident population health and guarantee access to social services, high-quality and behavioural health
	2. Education	Make certain that information is available to public concerning risks, preparedness, and resources before, during, and after a disaster
	3. Engagement and self-sufficiency	Encourage participatory decision-making in planning, response and recovery activities and support individuals/communities in assuming responsibility for their preparedness
	4. Partnership	Grow evolving, reliable, and strong partnerships within and between government and nongovernmental organisations
	5. Quality and efficiency	Collect, analyse, and make use of data to build community resilience and leverage resources for multiple use and maximal helpfulness
[79]	1. Generation	Create an initial community profile through local demographics, CART survey data, and key informant interviews
	2. Refinement	Determine and analyse assets and needs through CART community conversations, infrastructure mapping, ecological mapping of local relationships, stakeholder analysis, and other group processes
	3. Development	Build a strategic plan to construct targets and objectives by interacting in groups with the involvement of formal and informal community leaders
	4. Implementation	Adopt and implement the strategic plan by spreading the plan among community members, organisations, and leaders
[89]	1. Engagement	Seek for resilience champions, organise them into a logical and consistent leadership team, and build well-established and trusted community networks
	2. Assessment	Derive self awareness by comprehending its interdependencies and vulnerabilities, categorise its accessible resources, and discover which resources are at risk
	3. Visioning	Give a summary of the importance of possessing a resilience-focused vision and explain how community can include resilience into an existing vision or generate a new vision
	4. Planning	Link present state of community and determine a series of activities that are particular, assessable, and supportive of improved daily community function
	5. Implementing	Ensure an organisational home for community resilience program either through establishing a new organisational entity or by integrating into existing public or private organisations
	6. Monitoring and maintenance	Monitor and assess the progress of individual projects and entire community resilience program, making adjustments and alterations as required

5.1.2. Component Level

At the component level, only resilience components are focused on and taken into account. According to [104], the authors first derive experiences from agro-pastoralist stakeholders through semi-structured interviews. In the following step, the theoretical thematic analysis, which is based on community resilience and social dilemmas frameworks, is applied for strengthening community resilience with respect to the soil erosion reduction concerning five different domains (i.e., economic domain, social domain , cultural domain, governance, and environmental domain). By leveraging in-depth interviews, adding field observation and reading documents, Rahman and Kausel [105] determine planning capacity and social capacity of a community towards a tsunami based on eight essential resilience elements that are governance, society and economy, resource management, land use and structural design, risk knowledge, warning and evacuation, emergency response, and disaster recovery.

Further, the City Resilience Framework supplies a lens through which the cities' complication and the numerous factors that contribute to a city resilience can be acknowledged. To this end, they define 12 indispensable goals, which fit into four categories and seven qualities, as the backbone for the planning of a resilient city [49]. Cities can receive this framework as a compass to guide learning activities from literature, case studies, and other related areas. Equivalently, other authors also apply case study methodology to analyse, understand, and gain insights into community resilience with respect to community-based tourism [101] and evacuation route planning [63].

Referring to [99], this study spends six months to discover relevant and available capacities and resources of a community during a disaster through various resources that are semi-structured interviews, observation, informal conversations, and documentary and social media review. This qualitative research demonstrates the paramount importance of resilience capacities (i.e., local knowledge, sense of community, cooperation, organisation, social capital, and trust) in terms of responding to emergencies.

5.2. Quantitative Approaches

Quantitative approaches aim at measuring community resilience in recognisable ways to reduce the whims and opinions of analysts, experts, or other populations of the study. They can evaluate community resilience through the use of ordinal, interval, and ratio data obtained from surveys, observations, or secondary data. Towards qualitative approaches, the values of resilience components and their relationships need to be validated by discernible outcomes [111]. Based on components determined in the modelling step, a direct approach is to apply the composite index formula [108] as follows.

$$CR = \sum_{j=1}^{|C|} \sum_{k=1}^{|I_{c_j}|} i_k \times w_k, \forall j, k \in \mathbb{N}, j > 0, k > 0 \tag{1}$$

where CR represents community resilience, C is the set of resilience components, I_{c_j} is the set of indicators of component c_j, and i_k, w_k denote for kth indicator and its weight, respectively. According to [54], the UNDRR identifies an ordinal scale in the range of $[0, 3]$ (i.e., preliminary assessment) and the range of $[0, 5]$ (i.e., detailed assessment) to evaluate ten different essentials, which are used to build resilient cities, including (i) three essentials regarding governance and financial capacity, (ii) five essentials related to planning and disaster preparation, and (iii) two essentials considering disaster response and post-event recovery. Local governments then define their weighting for each essential to reflect its importance and to assist the measurement.

As stated in [84], the authors identify a score range from 1 (low degree of resilience, it means the red zone) to 5 (high degree of resilience, it means the green zone) for every question in the scorecards. We obtain the final score by summing all the individual scores. If the overall score is above 99, our community is very resilient to disasters; if it is below 33, we are under the risk of preventing and recovering from disasters. We should especially put the greatest attention to a particular element in case its scores are significantly smaller than the others.

Instead of using an adding function, we can use an unweighted average of based scores [60] or standardised z-scores (due to the diversity of indicators' values) [82,110] on entire indicators. To compare the resilience among cities, the authors in [60] attempt to calculate the average one more time based on cities' scores. The precision of the resilience comparison highly depends on the context similarity among cities at the time they are examined. As alternatives to explicit numbers, we can also use a priority rating (low/medium/high) [90,112], an effectiveness score range (A–F) [112], a vulnerability/capacity category (V/C), or an effect value (positive/negative) [83] for quantitative approaches.

On the other hand, the Analytic Hierarchy Process (AHP) is put to use in [98] to determine disaster-resilient indicators at the local level. The outcome-indicator score is further calculated based on criterion score and their weights. Besides, a six-point scale, which is extended from [118], is used to rank indicators for measuring process-indicator score. Level 0 represents the "absence of a clear and coherent activity/activities in an overall disaster risk reduction program", while level 5 refers to "a culture of safety exists among all stakeholders". Subsequently, the authors propose the weighted linear average (WLC) to measure composite indices based on these two evaluated scores.

Last but not least, several approaches attempt to capture dynamic resilience directly at the community level. Community resilience value that changes throughout an event due to risk perceptions of citizens or relationships between resilience components. To reflect the dynamic of community resilience, we can measure value at different time points [119] concerning the entirety components. In [51], Simonovic and Peck recognise that community resilience value can be dynamic in both time and space as well.

5.3. Hybrid Approaches

The measurement of community resilience in a variety of situations requires both qualitative and quantitative approaches [40,41] to capture perceptions, vulnerabilities, exposed values, and other resilience-related factors. A hybrid approach is one where both tangible and intangible elements are applicable [120] for enhancing analytical accuracy and deepening the understanding of community resilience. In [37], the authors harvest various information, which is related to characteristics of resilience, involving specific numbers, percentages, yes/no answers, opinions, and perceptions from interviews, organisation inventory, meetings, focus groups, and surveys. Similarly, both qualitative (i.e., literature review, group interview, and discussions) and quantitative (i.e., scales and surveys) data are usable in [42,109]. Nevertheless, we should keep in mind that hybrid approaches may require much effort and may be time-consuming in the data collection process.

The flexible combination of quantitative and qualitative approaches has been demonstrated in different studies. By mixing both methods, we can generally aggregate opinions of experts along multiple dimensions, indicators, and proxies. In [80], Cutter et al. combine the qualitative GIS (Geographic Information System) map and quantitative indicators to generate social vulnerability, built environment/infrastructure, hazard exposure, and hazards mitigation layers. The overlaying of these four layers provides a schematic representation of resilience baseline for communities. In a similar approach, the Bay Localize Community Resilience Toolkit [76] applies a scale from 0–4 to measure community-based resilience indicators. In consonance with rated values, the authors utilise the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, which is an extremely helpful planning and problem-solving technique, to determine and define community's capabilities for overcoming challenges. Strengths and weaknesses are typically internal factors aiming at representing the conditions within our community. On the other hand, opportunities and threats are able to put our community in a clear picture of external influences [121].

In contrast, we can apply a quantitative measurement based on both quantitative and qualitative targets to come up with specific resilience indices [68]. Following this methodology, the following matrix

$$\begin{array}{c|cccc|} & Prepare & Absorb & Recover & Adapt \\ Physical & P-P & Ab-P & R-P & Ad-P \\ Information & P-I & Ab-I & R-I & Ad-I \\ Cognitive & P-C & Ab-C & R-C & Ad-C \\ Social & P-S & Ab-S & R-S & Ad-S \end{array} \tag{2}$$

utilises both qualitative and quantitative data in which qualitative values (obtained through personal communications with stakeholders) are placed at Prepare-Information ($P - I$), Prepare-Social ($P - S$), Recover-Information ($R - I$), and Adapt-Physical ($Ad - P$) positions [107].

According to [97], the authors make use of a three-round Delphi method to determine necessary resilience indicators. The first round begins with a comprehensive literature review to understand and derive a good set of indicators. Experts further evaluate each dimension in the second round in consideration of a five-point Likert type scale that is anchored with 1 (not applicable) and 5 (very important). Besides, the experts are also encouraged to provide their insights into other elements that are crucial for a community to be resilient to change and cope with disasters. All following rounds will continue until we acquire a general agreement of all panel members [85]. Besides, the Delphi method is also used to determine index weights for quantitative calculations [47]. It is noted that a Delphi technique can meet difficulties in case local communities or qualified respondents do not have adequate previous experience.

6. Visualising Community Resilience

This section explores different visualisation techniques to deal with various scales and units of analysis to enhance community resilience. In emergency circumstances, a mass amount of resilience-related information can be generated from diverse data sources. Hence, utilising multiple visualisation techniques to understand and illustrate this information is essential for a more detailed and complete resilience comprehension, community-based resilience planning, and decision-making processes. Besides, employing utilisation technologies can bring us valuable and actionable insights at the application level. Table 6 summarises different visualisation techniques to represent community resilience.

Table 6. Summary of community resilience visualisation techniques.

Type of Visualisation	Technique	Focus	Reference
Geospatial information	Density map	Disasters	[53,75,83]
		Economic development and social capital	[110]
		Flood	[58]
		Hot-spots of high or low disasters	[74]
		Natural hazards	[87,108]
		Urban social-ecological systems	[71]
Multidimensional information	Stacked bar chart	Crises and disasters	[81]
		Shocks and adverse events	[60]
	Spider chart	Crises and disasters	[81]
		Disasters	[73]
		Soil erosion	[104]
		Tsunami	[105]
		Urban planning	[66]
	Radial stacked bar chart	Natural hazard events	[100]
		Stresses accumulate and sudden shocks	[49]
		Urban planning and policy	[69]
	Hypercube	Cyclone and storm surge disasters	[113]
		Transportation network in earthquake	[67]
Others	Bar chart	Food, energy, and water	[57]
		Urban flood	[52]

6.1. Geospatial Information Visualisation

In case geospatial information of community resilience is available, we can use a density map to highlight and demarcate critical locations [74] through different colour codes in which dark and cold colours usually indicate high resilience. In contrast, light and warm colours stand for low resilience. To show colours in a map, we are able to use either qualitative, sequential, or diverging scheme. The density map is advantageous in case many data points (or data lines) exist in a small geographic area. According to [71], the authors combine both numbers and colours to represent urban resilience indices and rankings for 50 Spanish province capitals following the standard deviation classification methodology of ArcGIS. However, the selection of red colour for high resilience areas may mislead readers because this colour is often associated with emergencies. With reference to [53], the authors depict the spatial distribution of disaster resilience and its components (i.e., social, economic, institutional, and infrastructure resilience) for 736 counties in the FEMA Region IV. The disaster resilience scores are expressed as standard deviations in order to emphasise high or low resilient counties extraordinarily. The authors further portray high and low resilient areas as dark blue and red, respectively.

In a similar approach, the authors in [75] visualise disaster resilience as well as six components based on a diverging scheme, from low (standard deviation < -1.5) to high resilience (standard deviation > 1.5). Furthermore, leveraging standard deviations [58,87], other studies create the density map to represent community resilience indices of Mississippi counties [110], disaster resilience indices of 11 local government areas (e.g., Greater Brisbane Area, Sunshine Coast, and others) [108], and community disaster resilience indices of 229 local municipalities in South Korea [83]. Despite the ability to present a holistic perspective of the resilience of a community and its neighbours, the density map shows the disadvantage if we want to represent all dimensions because each dimension will require a separate diagram.

Without tangible geospatial information, a bar chart can be the right selection [52,57] to visualise an overall value of resilience for various communities.

6.2. Multidimensional Information Visualisation

Stacked bar charts, spider charts (which is also known as radar charts), and radial stacked bar charts are beneficial for displaying multiple dimensions of community resilience. Among these three types, stacked bar charts are designed to concurrently compare the overall resilience between communities and recognise essential dimensions within a community. In [60], the authors use a stacked bar chart to display five aspects of vulnerability, five key themes of adaptive capacity, and overall resilience of 50 cities that have significant influence in the world. In another work, stacked bar charts are used to indicate top-ranking resilience dimensions by gender/age group, livelihood group, and level of intervention [81]. Despite that, one major disadvantage of a stacked bar chart is that we find it hard to compare a particular dimension of a community with others since they are not aligned with a common baseline.

On the other hand, spider charts help us to compare (i) resilience dimensions of a community over time or between communities by placing multiple polygons over or upon each other in a single diagram [105] and (ii) resilience dimensions with a defined standard [73]. Generally, spider charts can enable a better understanding of the strengths and weaknesses of resilience dimensions [104] and therefore very useful for high-level presentation of assessments. In [81], the CoBRA framework describes community attainment of resilience by illustrating five sustainable livelihood framework categories that are financial, human, natural, physical, and social by the current and crisis years. Likewise, Wardekker et al. [66] draw spider charts to elucidate the baseline and adaptation plans for flood-related resilience of Rotterdam based on ten resilience components (e.g., anticipation, robustness, flatness, and others). If measuring scales of axes are different, it would not seem helpful to compare resilience dimension across these axes. Besides, we should avoid concentrating too much on the polygons because the area and the shape of polygons can change depending on how we organise the axes. We may use parallel coordinate charts as an alternative to spider charts. By extending the radial stacked bar chart, the authors in [49,69,100] express multiple indicators associated with defined dimensions required for a resilient community dexterously.

Furthermore, a hypercube has the advantage of providing a direct view of the relationships and correlations among resilient dimensions. Focusing on infrastructure resilience, Jovanović et al. employ a three-dimensional space to visualise three resilience components including matrix-based indicators, complexity (level of detail), and smartness (big data analytics) [122] for healthcare infrastructure exposed to COVID-19 [123]. In another work, a resiliency cube is plotted to manifest the resilience of an urban road network in the time of earthquake [67]. Nevertheless, a hypercube may lose its clarity if there are so many resilient dimensions that need to be represented. A co-occurrence network [113] can be a suitable substitute in this condition.

6.3. Dashboard

A dashboard is a single screen summary of the analysis of different information. The use of dashboard holds great potential in the circumstance that we require multiple visualisations, which influence each other, to offer a comprehensive and engaging view of community resilience. Dashboards are also specialised in their dynamic and interactive capabilities. Infrastructure facility managers [124], local planning for resilience [56], or emergency managers [125] can utilise dashboards to derive critical insights for at-a-glance decision making and comprehensive strategies during a crisis.

To create a successful and helpful dashboard to represent community resilience, whether as an independent element or as a component of a specific framework, we should put our efforts in understanding our data, dealing with outliers, displaying meaningful results, and increasing semantic transparency. On the opposite, it is necessary to minimise response time, futile decorations, and redundant information.

7. Discussion and Conclusions

Acknowledging the importance of community resilience, researchers and practitioners have made significant attempts in not only studies but also practical matters. In particular, the objective of this paper is to provide an investigation and a more comprehensive picture into the state-of-the-art, accessible, and emerging works that are subjected to a three-step sequential process (i.e., modelling, measurement, and visualisation) to build community resilience. The modelling represents what is likely to be components and properties that communities should focus on to guarantee their resilience. Further, the measuring step assists communities in recognising where they are standing. Eventually, the visualisation aims at supporting communities in deriving insights into essential information promptly and precisely with minimum efforts. Based on this skeleton, communities can select most relevant approaches, which we mentioned in this review, to embed into their processes. For a successful resilience plan, communities should consider and follow all these three steps comprehensively. In addition to that, we want to mention critical points that were distilled herein for both research and practical uses.

- The number of components defined in the modelling step is diverse depending on a particular community at a specific time point for certain risks/targets. Nevertheless, we should not define too many components since they can be overlapping and difficult to break down into lower-level elements. Besides, end-users and stakeholders may find it difficult to understand and monitor a large number of components for giving precise actions, especially in the time of adversity.
- Various terminologies are available for modelling community resilience, some of which are, but not limited to, index, dimension, capital, capacity, and domain. The selection of the term highly relies on our practical use. For example, the resilience index, which is usually a combination of indicators, is appropriate for a quantitative assessment. On the other hand, resilience dimension/domain is more descriptive and suitable for qualitative approaches. In

addition, resilience capital/capacity well expresses the potential and abilities of a community to achieve something.

- To measure community resilience, we can leverage not only static (e.g., vulnerabilities, hazards, and exposed values) but also dynamic information (e.g., dynamic risk perception extracted by analysing social media data) at different scales. Information collected at the community level regularly tends to be more informal, undocumented, and implicitly understood than higher scales. It is necessary for us first to determine the goals of our community, target potential end-users, and then stick into them before deciding on any particular approaches to measure resilience.
- This paper presented many studies that aimed at visualising correlation, hierarchy, and geospatial information; however, we should pay more attention to understanding and representing temporal information. Temporal information visualisation can capture common patterns and search for specific sequences, such as the dynamic of community resilience value by time. Area chart and polar area diagram are practical and efficient techniques [126] to portray temporal information of community resilience.

We are living in the fourth industrial revolution with the explosion of disruptive technologies that are essential and valuable for decision-making processes. In the next study, a comprehensive comparative analysis of how to utilise social networking services [127–129] and crowdsourced data for community resilience [130,131] will be taken into account. Besides, we will examine the interrelation and discuss open issues between cutting-edge technologies (e.g., machine learning, Internet of Things, and artificial intelligence) and community resilience. For example, the intelligent and adaptive use of machine learning methodologies to measure community resilience [132] can provide us with excellent opportunities for further development.

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Article

Indicators for Monitoring Urban Climate Change Resilience and Adaptation

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Abstract: In the face of accelerating climate change, urbanization and the need to adapt to these changes, the concept of resilience as an interdisciplinary and positive approach has gained increasing attention over the last decade. However, measuring resilience and monitoring adaptation efforts have received only limited attention from science and practice so far. Thus, this paper aims to provide an indicator set to measure urban climate resilience and monitor adaptation activities. In order to develop this indicator set, a four-step mixed method approach was implemented: (1) based on a literature review, relevant resilience indicators were selected, (2) researchers, consultants and city representatives were then invited to evaluate those indicators in an online survey before the remaining indicator candidates were validated in a workshop (3) and finally reviewed by sector experts (4). This thorough process resulted in 24 indicators distributed over 24 action fields based on secondary data. The participatory approach allowed the research team to take into account the complexity and interdisciplinarity nature of the topic, as well as place- and context-specific parameters. However, it also showed that in order to conduct a holistic assessment of urban climate resilience, a purely quantitative, indicator-based approach is not sufficient, and additional qualitative information is needed.

Keywords: resilience; indicator; monitoring; climate change; climate adaptation

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1. Introduction

Our society is facing multitudinous different challenges—in this paper we are focusing on two main challenges: climate change and urbanization. In 2015, 3.9 billion people were living in cities. By 2050, the population in cities is projected to reach up to 6.7 billion people [1]. Urban agglomerations will continue to grow and are increasingly threatened by the high uncertainty of climate change impacts [2]. In response to these impacts, cities are already implementing climate change adaptation measures in order to prepare for uncertain future changes. Adaptation to climate change and climate variability is not a new phenomenon [3]. However, steadily rising temperatures, increasing magnitude and frequencies of climate-induced extreme events, such as droughts, floods, storms or intense rainfall, as well as the growth of the global human population pose new adaptation challenges to humankind [3]. In our research, we use the term adaptation as defined by the United Nations Climate Change [4]: "Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change". Furthermore, the ability of adaptation is understood as part of resilience, as described by Folke et al. [5]. The concept of resilience can be attributed to Holling [6] and originates from ecology. He described resilience as the "measure of persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between population or state variables" [6]. The original concept of resilience gained increased importance in other disciplines, whereby the definitions of resilience were steadily differentiated, broadened and deepened. There are three main understandings of the character of resilience: "bounce back" which refers to the fast return to an equilibrium state of a system after a shock event, "bounce forward" which focuses on a system which should have capacities to be adapted to uncertainty and "both" which addresses the co-occurrence of the capacities for "bounce back" and "bounce forward" [7]. Meerow et al. [2] analysed 57 academic definitions of urban resilience, with particular regard to these fundamental understandings of urban resilience. The analysis showed that 35 definitions focus on "bouncing back", 15 on "bouncing forward" and only seven see both capacities as elementary for resilience. Figueiredo et al. [8] pointed out that the definitions shifted from an equilibrium-centred understanding of resilience towards an evolutionary/transformational understanding of resilience. Four main approaches to resilience can be identified: disaster risk reduction [9], socio-ecological [10], sustainable livelihoods [11] and the community-oriented approach [12]. Resilience can also be discussed on different scales (county, region, urban area, city, community and household) [8]. Even though it is important to take action on all scales, in this work we are focusing on cities—particularly in Germany—and are using the socio-ecological approach. Besides the definitions and understandings of resilience in academia, it is very important to also consider how practitioners interpret resilience. Practitioners and policy makers are a central part of the resilience-transformation process. Therefore, it is remarkable that the term resilience is interpreted in a much wider range of ways by practitioners than by academia [13].

Adaptation measures are implemented in different sectors of the city system. Since cities are complex and multifaceted systems, which in turn contain other systems, measuring the success of resilience-increasing activities poses a particular challenge. However, measurement is of great importance in order to be able to govern and steer the adaptation and transformation process. Every city has its specific context and needs, and its exposure to risk and vulnerability is dynamic and changes over time [8].

However, it is important to develop measurable indicators for different reasons. Indicators enable monitoring of the resilience-building process, as they provide regular and impartial feedback. They build an evidence base and make resilience more tangible for decision and policy makers as well as society at large. Furthermore, indicators can help to govern and steer the transformation process because they help to structure the new field of urban climate resilience. Clear indicators are not only important for the general measurement of resilience, but also for the analysis of whether adaptation measures were effective and whether the expected results were achieved [14]. Indicators also contribute to the credibility, transparency and accountability of the measures implemented. This in turn is very important for local policy makers to support further adaptation measures.

However, the development of indicators in this context poses particular challenges. In addition to the conceptual challenges of urban climate resilience, context specificity represents another challenge for the development of resilience indicators. Consequently, it is very important to consider how to include context specificity in the indicator set. Another fundamental consideration is in regard to the context-specific, dynamic and ever-changing nature of risk and vulnerability [8].

MONARES (monitoring of adaptation measures and climate resilience in cities), a project funded by the German Federal Ministry of Education and Research (BMBF), was initiated in order to address the main challenges of (1) developing a consistent understanding of resilience for both practitioners and academia, (2) shaping the adaptation and transformation process into a transparent process of governing and steering and (3) the use of resilience and adaptation measurements. The aim of MONARES is to create application-oriented methodologies for monitoring and evaluating local adaptation measures. As we are focusing on the special needs for cities in Germany, we are working together with 14 other projects of the funding initiative "Climate resilience through action in cities and regions" of the BMBF, who are focusing on climate change adaptation measures and urban resilience, as well as doing on-the-ground research in municipalities across Germany. These projects and cities differ considerably concerning scale (street, district, city, suburbs and region), inhabitants and type of adaptation measure (e.g., planning, physical infrastructure, capacity building or greening). Important commonalities of the projects are their interdisciplinary approach, the aim to enhance urban climate resilience and that they conduct on-the-ground research. However, the projects test many different pathways to improve resilience, and MONARES is focusing on how to measure the success and impact of these different projects and activities with a common set of indicators. In order to ensure applicability, we began to involve the projects at an early stage of our research. The first key step (Figure 1 Phase 1) before developing the indicators was to develop a framework [15] to describe urban resilience. Based on 19 frameworks described in the literature [16–34], our first draft was developed, which then was modified together with the projects. This process was indispensable as it resulted in a definition of urban resilience that is suitable for all projects so that there was agreement on common basic principles.

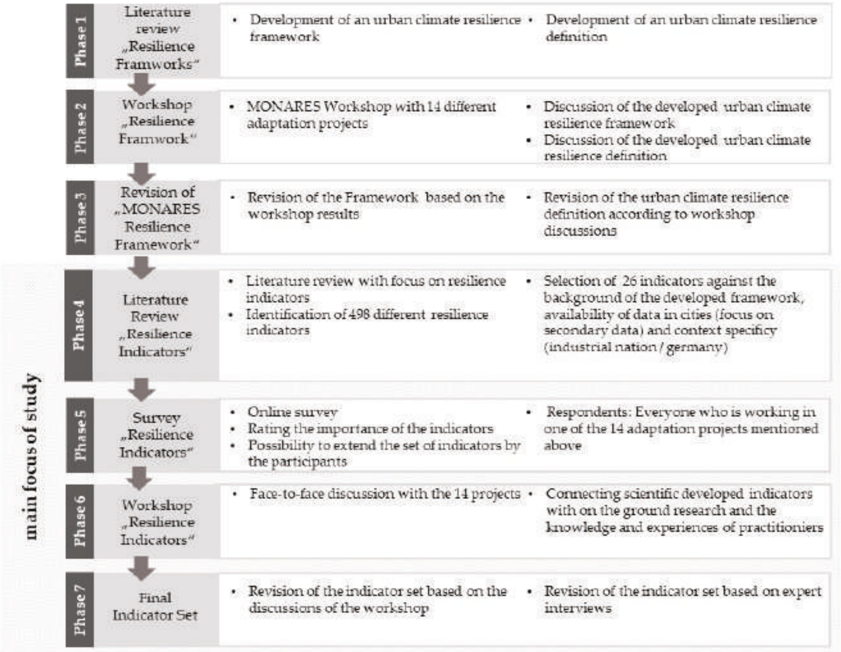

Figure 1. MONARES—research process.

Based on steps 1 to 3 as shown in Figure 1, the final definition of urban resilience in MONARES is as follows:

The climate resilience of a city depends on the ability of its sub-systems to anticipate the consequences of extreme weather and climate change, to resist the negative consequences of these events and to recover essential functions after disturbance quickly, as well as to learn from these events and to adapt to the consequences of climate change in the short and medium term, and transform in the long term. The more pronounced these abilities are, the more resilient a city is to the consequences of climate change. All abilities are important.

Based on this preliminary work, a four-step mixed-method approach (Figure 1 Phases 4–7) was designed to develop the indicators for urban climate resilience on which this paper focuses.

2. Materials and Methods

The exponential growth of literature concerning urban resilience contains a multitude of approaches, indicators and methods stressing the resistance of an urban system. The development of the method of this paper was guided by the questions: resilience for whom, for what and where [35]. A reflexive approach of input and feedback loops was developed in order to adapt and validate international indicators. A main challenge was to adapt the indicators to the specific context of German communities in the face of climate change.

2.1. Literature Review: "Resilience Indicators"

The selected frameworks (see Figure 1 Phase 1) were identified through an extensive literature review using the key search terms "resilience", "urban resilience", "climate resilience", "adaptive capacity + urban/city", "resistibility + urban" and "learning capacity + urban/city" (in German and English). Based on these frameworks and their operationalisation of resilience, an extensive list of indicators was deduced. These indicators were matched with the MONARES framework, developed in steps 1–3, which consists of dimensions and action fields (see Table 1).

Table 1. Dimensions and action field of the resilience framework.

Dimension	Action Field
Environment	Soil and green spaces
	Water bodies
	Biodiversity
	Air
Infrastructure	Settlement structure
	Energy
	Telecommunication
	Traffic
	Drinking and wastewater
Economy	Innovation
	Business
	Economic structure
Society	Research
	Knowledge and risk competence
	Healthcare
	Socio-demographic structure
	Civil society
	Civil protection
Governance	Participation
	Municipal budget
	Strategy, plans and environment
	Administration

As we have the aim to develop a user-friendly, applicable and transparent indicator set, we firstly reduced the indicators to two indicators per action-field. The two most important selection criteria were (1) context specificity of industrial nations, especially Germany, and (2) data availability. Context specificity is important because many of the indicators in the literature are suitable for the context of the Global South but not for the Global North, and even indicators that might be suitable for the Global North might not be suitable in the German context. The second criteria—data availability—is therefore important because municipalities have, on the one hand, good access to a lot of data but have, on the other hand, resource problems regarding time, finances and human resources. Action fields without literature-based indicators required the development of new ideas within the project. Given the available data, some action fields were difficult to measure without significantly neglecting the complexity of the action field.

2.2. Survey to Assimilate the Indicators for Context Specificity

Based on the literature review (see Figure 1 Phase 4) and the described selection process, an online-survey was developed (see Figure 1 Phase 5). The survey was used because, given that the indicators should be transparent and user-friendly, not only the scientific background is important, but a clear understanding of the indicators in the broad community is important also. The survey was sent to all persons who are working in one of the 14 projects mentioned above. 39 people answered the survey.

The main aim of the survey was to measure how participants assess the different indicators. They were requested to rate the importance of every indicator regarding urban climate resilience on a scale from one (low importance) to five (high importance). Each action field was represented by at least one indicator (Table 1). Besides the rating of indicators, the survey consisted of four chapters: First, some general background; Second, the context of urban climate resilience; Thirdly, the indicators; Fourthly, the possibility of extending the set of indicators by indicators without existing data sources, and some final remarks.

2.3. Workshop Following the Survey

As mentioned previously, the explanatory power of an indicator set of urban climate resilience is hugely dependent on the context, and therefore we discussed the results of the survey again with the 14 projects (see. Figure 1 Phase 6). Moreover, this feedback loop increases the transparency of the process and the robustness of the results. The workshop started with presenting the survey results and then the participants were split into two groups in order to create two independent feedback loops and cross-validation of the indicator set. For each group, a poster was prepared, listing all indicators included in the survey. The indicators that were ranked lower in the survey were written on the poster in light grey (compared to black), for an improved visualization of the survey results. Hence, both groups had the visual results to discuss and were asked to compare each pair in detail and find explanations for the survey results. In addition, the overall set remained visible, which allowed participants to keep the important question of the overall themes in mind. Therefore, indicators could be moved across the set or could become more important if they were deemed a missing piece in the mosaic. The guiding questions for this phase of the workshop were: (1) Are there enough indicators? (2) How many indicators are needed and sufficient? (3) Are the selected indicators the right ones or should they be changed? And (4) are there important gaps in the set that are yet to be filled?

2.4. Finalizing the Indicators Set

In Step 7 (see Figure 1) we analyzed the results of the workshop. Furthermore, expert interviews with practitioners were conducted with the aim to develop indicators in action fields where neither the literature review nor survey and workshop produced results. On this basis, we finalized the urban resilience indicator set.

3. Results

In our review of the academic literature, 19 indicator-based resilience frameworks were analyzed. Based on the indicators of these frameworks a list of 498 indicators (including duplicates) was generated. The indicator list was used as an important starting point for developing the MONARES Indicator Set (MIS). After screening the indicators through the lens of the MONARES-framework, some action fields remained empty and were filled by proposed indicators of the MONARES project-team. One to four indicators were selected per action field in order to cover all topics and include sufficient redundancy. Table 2 shows the selected and proposed indicators.

Table 2. Delineated indicators and action fields.

Dimension	Action Field	Indicator	Code	Literature
Environment	Soil and green spaces	Degree of soil sealing	A_a_1	[31]
		Land consumption	A_a_2	[21]
		Recreational area	A_a_3	[21]
	Water bodies	Share of water bodies	A_b_1	[36]
		State of water bodies	A_b_2	[23]
	Biodiversity	Share of nature conservation and protection areas	A_c_1	[23]
		Wetlands and retention areas	A_c_2	[36]
	Air	Cold air parcels	A_d_1	[23]
Infrastructure	Settlement structure	Density of buildings	B_a_1	[37]
		Accessibility of green spaces	B_a_2	[38]
	Energy	Share renewable energy	B_b_1	[18]
		Diversity renewable energy	B_b_2	[18]
	Telecommunication	Broadband access	B_c_1	[37]
	Traffic	Concept for sustainable traffic	B_d_1	[21]
	Drinking and wastewater	Number of springs	B_e_1	[8]
Economy	Innovation	Innovation index	C_a_1	[37]
	Business	Ratio of insolvencies to start-ups	C_b_1	[22]
	Economic structure	Share of employees in largest sector	C_c_1	[39]
		Employees in research intensive companies	C_c_2	[40]
Society	Research	Number of research projects	D_a_1	[18]
	Knowledge and risk competence	Citizen information about heat, heavy rain and flooding	D_b_1	[37]
		Experience with extreme events in last five years	D_b_2	[37]
	Health care	Accessibility of hospitals	D_c_1	[41]
		Doctors per 10,000 citizens	D_c_2	[40]
	Socio-demographic structure	Share of citizens ABV6/U65	D_d_1	[42]
		Share of employees	D_d_2	[30]
	Civil society	Voter turnout	D_e_1	[42]
		Number of associations	D_e_2	[42]
	Civil protection	Fire brigade	D_f_1	[37]
		Citizens in honorary positions	D_f_2	[31]
Governance	Participation	Number of participation processes	E_a_1	[37]
		Contact point for participation	E_a_2	[37]
	Municipal budget	Depth per citizen	E_b_1	[21]
		Tax income	E_b_2	[21]
	Strategy, plans and environment	Risk and vulnerability analysis	E_c_1	[26]
		Strategies against heavy rain and heat in plans	E_c_2	[26]
		Landscape plan legally binding	E_c_3	[37]
		Climate change adaptation part of urban development plan	E_c_4	[30]
	Administration	Inter-office working group regarding risk, climate change and resilience	E_d_1	[37]
		Climate manager	E_d_2	[37]

3.1. Survey about Resilience Indicators

The survey was structured based on the results of Phase 4. The survey (Figure 1 Phase 5) was filled out by 39 respondents within the funding initiative "Climate resilience through action in cities and regions" of the BMBF. The overall mean perceived importance of the indicators was 3.63 within the complete range from one to five. Considering the complexity of the urban system and the interdisciplinary character of the indicator set, this rating was regarded as high. The median of four was also high. The standard deviation of 1.17 together with the entire evaluation range reflected the diversity of interpretations. Nevertheless, despite this diversity, these core numbers show that the indicators were overall judged as important. Splitting the indicators into the five main dimensions (Figure 2), the median shows that only the indicators within the dimension of economy were rated less important, they are rated in the middle of the range, which might indicate a slight indecisiveness. Several reasons could explain this, such as that the indicators selected were not covering the dimension in a satisfactory manner or that the dimension is perceived as unrelated to urban climate resilience. Those questions were discussed in the workshop (Figure 1 Phase 6) in detail.

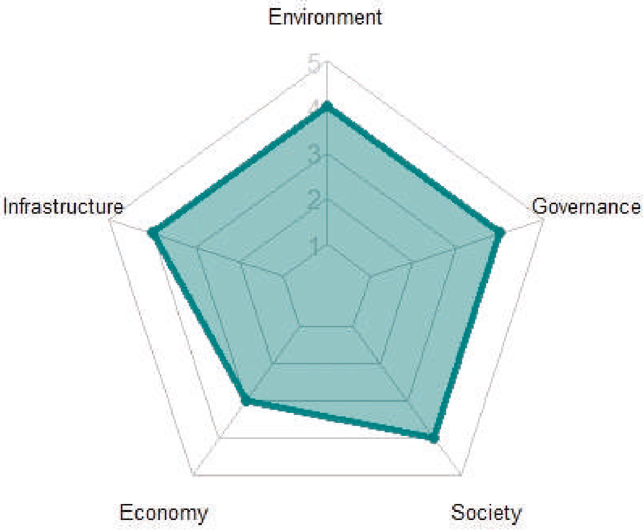

Figure 2. Median importance of indicators grouped into five dimensions.

All top five ranked indicators had a median rating of 5. The mean values ranged from 4.4 to 4.6. Only two respectively three respondents did not rate the indicators, showing the general agreement regarding the importance. Nevertheless, regarding the minimum values, all had a large range from 2 to 5.

The set of five indicators in Table 3 shows that the three dimensions *environment*, *governance* and *society* were seen as particular important. The indicator rated as the most important was the environment indicator *cold air parcels*. Second and fourth ranked were *governance* indicators, namely *inter-offices working groups regarding risk, climate change and resilience* and *strategies against heavy rain and heat in plans*. Third and fifth ranked were two indicators from the dimension *society*. The respondents saw the importance of *experience with extreme events in the last five years* and *citizen information about heat, heavy rain and flooding* as particularly crucial for building urban resilience.

Table 3. The five indicators rated as most important in the survey.

Dimension	Action field	Indicator	Min.	1st Quartile	Median	Mean	3rd Quartile	Max	N/A
Environment	Air	Cold air parcels	2	4	5	4.6	5	5	3
Governance	Administration	Inter-offices working group regarding risk, climate change and resilience	2	4	5	4.5	5	5	2
Society	Knowledge and competence	Experience with extreme events in last five years	3	4	5	4.5	5	5	3
Governance	Strategy, planned and environment	Strategies against heavy rain and heat in plans	2	4	5	4.5	5	5	3
Society	Knowledge and competence	Citizen information about heat, heavy rain and flooding	2	4	5	4.4	5	5	2

Table 4 displays the five lowest ranked indicators in context of their relevance related to urban climate resilience. The overall lowest rated indicators were both from the *society* dimension, namely *voter turnout* and *number of associations*. The respondents did not think that they were relevant for measuring and monitoring urban resilience. The third lowest indicator was the *infrastructure* indicator *broadband access*. Fourth and fifth were two *economic* indicators measuring *ratio insolvencies to start-ups* and *share employees in largest sector*.

Table 4. Five lowest rated indicators.

Dimension	Action field	Indicator	Min.	1st Quartile	Median	Mean	3rd Quartile	Max	N/A
Society	Civil society	Voter turnout	1	2	3	2.4	3	4	1
Society	Civil society	Number of associations	1	2	3	2.6	3	4	2
Infrastructur	Telecommunication	Broadband access	1	2	3	2.8	4	5	3
Economy	Business	Ration insolvencies to start-ups	1	2	3	2.8	3.5	5	4
Economy	Economic structure	Share Employees in largest sector	1	2	3	2.8	3	4	6

Figure 3 displays boxplots of all indicators. The main tendency has already been shown in a more condensed form previously in Figure 2. *Share of nature conservation and protection areas (A_c_1)* was the lowest ranking in the dimension *environment*. The second indicator of the action field *biodiversity*, however, received high approval, which emphasised the perceived importance of *biodiversity* considerations for climate resilience in the urban context. *Settlement structure* (B_a_1&2) was seen as vital for structural climate change adaptation, similar to the first action fields of *soil and green spaces* (A_a_1-3).

Energy (B_b_1&2) indicators, in contrast, not only ranged from a rating of one to five, but the quartiles of the boxplot also show a comparably high range around the middle of the scale.

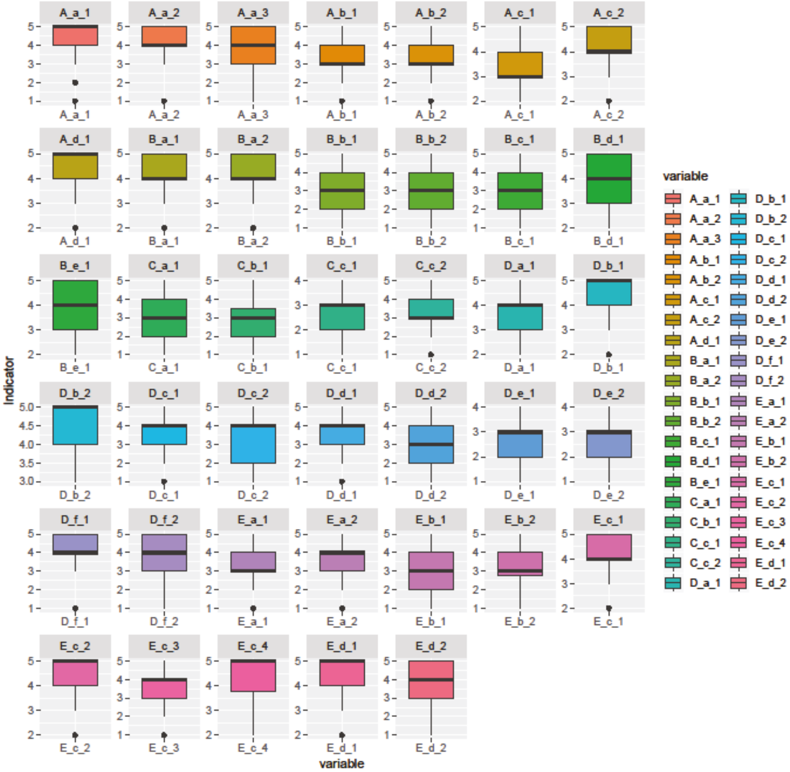

Figure 3. Box-plots of all indicators included in the survey (see Table 2 for indicator codes).

3.2. General Workshop Results Regarding the MIS

The discussion of the indicators during two discussion groups yielded important feedback on the overarching attributes and requirements of the MIS. They were mentioned several times from different persons and related to different indicators. Firstly, one important aspect was the size of the municipality and hence the scaling of the indicator. No universal scaling was found appropriate, since the different units and scales required indicator-specific scaling. Nevertheless, the scaling was seen as an important factor in order to reach the goal of acquiring indicators for municipalities and therefore an interpretable result on this level of administrative organization.

The overall discussion about applicability and feasibility was touched on in many ways from different angles, most prominently regarding data availability, numbers of indicators and total effort needed. The balancing of the loss of information related to simpler indicators or vice versa with more complex indicators with higher explanatory power but with an infeasibility to be handled by the target group was seen as a key challenge. Therefore, the participants agreed that the indicators should be based solely on existing data, thereby reducing the overall effort and simplifying the calculations and data management.

The idea of detailed factsheets describing the data source and calculation of the indicator and helping with the interpretation of the result was raised by participants and received wide support. Factsheets also help to communicate the meaning of an indicator to uninitiated persons, which was also mentioned as a crucial aspect.

The total number of indicators to be feasible was seen at around 25. Certain gaps were identified during the workshop due to the fact that specific expertise related to certain action fields was missing in the room, specifically regarding the action fields *energy, wastewater* and *civil protection*. Here, single expert interviews were carried out after the workshop to fill in the gaps.

3.3. Indicator Specific Workshop Results

Table 5 summarizes the process of indicator development during the three phases of the survey, the workshop and ending in the final set of indicators. The indicators highlighted in grey are those of the initial indicator set that were seen as important by survey respondents and therefore stayed on the list. The indicators highlighted in orange were updated or modified as a result of the survey and/or workshop. The yellow indicators were moved from one action field to another. The indicator *degree of soil sealing* was inverted to *degree of unsealed ground*, as sealing is not per se negative, even may even be desirable or unavoidable in urban areas. The *cold air parcels* was seen as an important factor of resilience but should be updated, adding cold air streams to the indicators. *Biodiversity* was discussed in contradictory ways, as it was not clear to the participants how it is related to climate hazards. Hence, the workshop resulted in representing urban biodiversity with the indicator *wetland and retention areas* in order to include flood protection arguments into the indicator of biodiversity.

Infrastructure was seen undoubtedly as a key area for achieving urban climate resilience, but also related to secondary data and its inherent complexity most difficult to quantify currently. *Accessibility of green spaces* was rather seen as an indicator of social justice and less as a settlement structural indicator and hence the second indicator *building density*, slightly lower ranked in the survey, was included instead. The *share of renewable energy* indicator focused strongly on climate protection and less on resilience factors, such as robustness and redundancy. These factors were seen to be better covered by the *diversity of renewable energy sources*. However, it was also argued that even conventional energy should be included in the indicator. This observation was followed by the consideration that no climate resilience can be achieved without climate protection in the long term. Therefore conventional energy sources cannot be regarded as a positive contribution to climate resilience in the long term. The action field of *telecommunication* was deleted in accordance with the participants' perception of this as being less important than the other action fields, lacking data and having low to no influence of the municipality. Instead, the action field *wastewater treatment* was included, as there was agreement on its importance additionally to the supply side. No specific indicator was defined in the workshop due to missing competence in this regard. *Transportation* was discussed as an important action field for municipalities, but participants agreed that its complexity cannot be covered by one indicator. Therefore, the action field remained as an action field of the framework, reminding of the importance of the topic and urging municipalities to consider and discuss it qualitatively.

The discussion around the *economic* dimension reflected the lower ranking of its indicators in the survey. The dimensions *environment* and *infrastructure* were seen to be more naturally linked to resilience than the *economic* dimension. Nevertheless, discussing the importance of a resilient economy for an urban system generated acceptance for the dimension and its components. This example illustrates one very important lesson of the workshop: the need for explanation and building a common understanding. *Innovation* was seen to be covered best by the *number of employees in research intensive companies* not by the *innovation index*. The *tax income from companies* was considered an important resource for the financial ability of the municipality to adapt. This indicator was part of the action field *municipal budget* in the survey and has since been moved to *business*. Similar to *energy,* a *diverse economy* was considered more robust, flexible and redundant when facing uncertainty of climate impacts. It was also discussed whether there might be sectors with crucial or higher relevance than others, but the group agreed that no single sector could be selected.

There was a general agreement on the importance and contribution of *society* to urban climate resilience, but less agreement on how to measure it quantitatively. Literature shows that the experience with extreme events contributes positively to citizens' resilience. In addition, *citizen information about heat, heavy rain and flooding* (Table 3) was amongst the top five rated indicators. However, regarding the spatial scale of municipalities, it was argued that information is not only provided by the local authority and therefore the indicator was not further considered. *Civil society* started an intense discussion on how to measure it and if the proposed indicators were adequate. In contrast to the survey, where the indicator *voter turnout* ranked higher, the workshop participants disliked this indicator, arguing that *voter turnout* nowadays cannot be seen as a proxy indicator for solidarity and community in Germany. The indicator *associations* was also critically reflected upon as being unable to capture *civil society* entirely. Still, the participants were in favour of the imperfect indicator *associations* instead of deleting the action field. In the survey, the dimension *governance* and its indicators were ranked high, and this result was confirmed in the workshop. Only one change was decided: replacing the *contact point for participation processes* with the *number of conducted participation processes*. Both were ranked very close in the survey with a mean of 3.3 and 3.4, respectively.

Table 5. Indicator set after the survey, workshop and final set.

Dimension	Action Field	Survey Result	Workshop	MIS
Environment	Soil and green spaces	Degree of unsealed ground	Degree of unsealed ground	Degree of unsealed ground
	Water bodies	State of water bodies	State of water bodies	State of water bodies
	Biodiversity	Wetlands and retention areas	Wetlands and retention areas	Nature conservation and protection areas
	Air	Cold air parcels	Cold air parcels and flows	Ventilation status
Infrastructure	Settlement structure	Accessibility of green spaces	Building density	Building density
	Energy	Share renewable energy	Diversity of renewable energy	Diversity of renewable energy
			Per capita energy consumption	Per capita energy consumption
	Water supply and wastewater treatment	Number of springs	Number of springs	Number of springs
			(Including wastewater indicator)	Adapted sewer system
Economy	Innovation	Innovation index	Employees in research intensive companies	Employees in research intensive companies
	Business	Ration insolvencies to start-ups	Commercial tax per capita	Commercial tax per capita
	Economic structure	Employees in research intensive companies	Diversity of business	Diversity of business
Society	Research	Number of research projects	Number of research projects	Number of research projects
	Knowledge and risk competence	History with extreme events	History with extreme events	History with extreme events
	Health care	Accessibility of hospitals	Accessibility of hospitals	Number of doctors
	Sociodemographic structure	Share of citizens ABV6/U65	Share of citizens ABV6/U65	Share of citizens ABV6/U65
	Civil society	Voter turnout	Associations per 10000 capita	Associations per 10000 capita
	Civil protection	Fire brigade	Fire brigade	Fire brigade volunteers
Governance	Participation	Contact point for participation	Number of participation processes	Number of participation processes
	Municipal budget	Depth per citizen	Depth per citizen	Depth per citizen
	Strategy, plans and environment	Risk and vulnerability analsysis	Risk and vulnerability analsysis	Risk and vulnerability analsysis
		Strategies against heavy rain and heat in plans	Strategies against heavy rain and heat in plans	Strategies against heavy rain and heat in plans
	Administration	Inter-offices working group regarding risk, climate change and resilience	Inter-offices working group regarding risk, climate change and resilience	Inter-offices working group regarding risk, climate change and resilience
		updated	switched action field	no change

3.4. Urban Climate Resilience Indicator Set

Since even the diverse group of participants of the workshop did not cover all topics of the indicator set, experts were interviewed. Furthermore, the results of the survey and the results of the workshop were summarized and merged.

The final set of indicators is shown in Table 5 in the column MIS. Compared with the workshop set, the action field of *biodiversity* was seen crucial in its own right and better approximated by the indicator *nature conservation and protection areas*. Moreover, wetlands and retention areas were already covered by the *state of the water bodies* in line with the European Water Framework Directive regarding good ecological and chemical status. Hence, in order to create a balanced set of indicators, it was seen that the latter indicator added thematically more information and another aspect to the overall set. Secondly, the *air* action field was further developed, as *cold air parcels and flows* was difficult to interpret. The simple number or share of cold air parcels and streams were not clearly related to resulting air status. The *ventilation status* including the effects of air streams and cold air production parcels was therefore selected. For the *wastewater* action field introduced by the workshop, an expert interview recommended the indicator *share of adopted sewer system*. Another interview was conducted with the lower civil protection agency. The interviewee stressed the importance of volunteers across organizations, but as no data were gathered assessing the total numbers of volunteers, the most important one of the fire brigade was considered. Moreover, the municipality may have to consider this important topic even more in the future, as the principle of volunteers may be endangered due to demographic development. Finally, yet importantly, the *accessibility of hospitals* was interchanged with the *density of doctors*.

4. Discussion

The results from the work on indicators for monitoring urban climate resilience presented above yields a number of important insights and implications—with respect to previous studies but also for future research and for practitioners in this field.

Existing indicator sets are a good starting point, but adapting and extending them for the context at hand is crucial. There are numerous indicator sets for urban resilience; these provided a good basis from which the MONARES indicator set could be developed. However, many of the indicators analysed in the literature review were aimed at the context of developing countries. To adapt indicators identified in the review for the German context, four steps were important: (A) Disregarding indicators that do not allow sufficient distinction between cities, e.g., literacy rate is favoured as an indicator in many sources, but in Germany the literacy rate is rather high and differences between cities are marginal. (B) Disregarding indicators for which the data availability was rather limited in Germany. (C) Adding new indicators for action fields that are deemed important in the context of MONARES but which were not touched upon in the literature. (D) Focusing on municipalities as the key player for climate change adaptation. These level of municipalities require the set to be manageable in terms of data availability as well as size and complexity of the calculations.

Step A did not pose any major difficulties. Further, step B based on research concerning data availability did not cause problems. However, step C and D need to be examined in more detail.

First, the workshop clearly stated here the conflicting goals when discussing single action fields. It was felt that one indicator does not reflect the entirety of the topic, but at the same time all action fields were considered important and the total number of indicators should not exceed around 20, in order to stay manageable, which is far less than the proposed 52 indicators by the City Resilience Index (CRI) [22] and comparable to the core of 14 by the project Building Resilience Amongst Communities in Europe (embrace) [37] or Cutter's [43] core of 22. Since researchers, as well as practitioners, participated in our workshop, we had the impression that researchers tended to prefer larger, encompassing indicator sets. Compared with the scientists, practitioners were more in favour of concise and compact sets. The discussions in the workshop showed that persons with a research background had numerous ideas for new indicators for all dimensions, and advocated for their inclusion. During the workshop and its aftermath, practitioners working in municipalities displayed a different tendency—their perspective tended to focus more on how to handle the indicators in practice. Hence, what some researchers considered a concise indicator set was perceived by practitioners as overwhelming and too extensive. In order to find an adequate balance between a broad coverage and good usability in practice, it is important to involve both researchers and practitioners in the development of an indicator set. This finding is consistent with the literature and is one strength of the current study. Meerow and

Stults [13], for example, stress the need for including practitioners in the process. Consequently, the trade-off between practicability and completeness had to be balanced, leading to the fact that some indicators that were considered important were still sorted out in order to cover all action fields and still achieve a manageable amount of indicators.

Second, it was mentioned that the indicators just by title were not clear in terms of their effect on and relation to urban climate resilience, and were consequently rated around the middle. This fact was considered while developing the survey, but an in-depth explanation of indicators was removed from the survey in favour of including more indicators covering all action fields and in consideration of the time needed to fill out the survey. However, this lack of explanations meant that the disciplinary background of respondents affected the ratings.

Third, indicators from the dimension *environment* were met with relatively high consensus while indicators from the dimension *economy* were faced with more diverging opinions. The indicator selection was dependent on the conceptualization of urban resilience and the urban context. The results contribute to the gap between the understanding of urban resilience by scholars and practitioners [13]. This became apparent both in the survey and the workshop and shows that more research is warranted on what characterizes a climate resilience urban economy. Supporting evidence for this can be taken from the fact that much more has been published on climate resilience and environmental issues than on climate resilience and economic issues. Moreover, this discussion displayed the importance of a negotiation-focused approach for defining place-specific attributes of urban resilience and its measures [44].

Fourth, secondary data was seen as crucial for monitoring purposes in order to reduce resource expenditure by the administration. In other words, "The best indicator is inoperable if there is no feasible way to obtain the required data." [37]. Moreover, there was a strong request from the local administrations for more provision of data from the higher administrations. They argued that data handling, data collection and finances for these activities are lacking. They stressed the need for data provision to be handled at the higher level of administration to avoid scaling and data comparability issues. Hence, data availability for indicators on a municipal level is a strong limiting factor, especially when it comes to indicators concerning infrastructure and social aspects [45]. Parts of the infrastructure related to energy, transport and communication are owned or organized by entities on a higher administrative level, such as the national government or by private entities. This tends to lead to limited data availability when it comes to data with a sufficient resolution on a municipal level. Here it would be favourable if entities in charge of the respective infrastructure made access to data easier and provided data with a resolution that is suitable for analyses on a municipal level. Moreover, the discussion centred around technical measures and physical impacts and less about social drivers and demographic changes. The latter are seen as core aspects of the community's ability to resist unforeseen threats. Nevertheless, the intense discussion around the proxies suggested by literature displayed vividly the intricacy of social dynamics. New data and methods from the higher administration or crowd-sourced databases are needed to better understand and monitor the indicators [43].

Fifth, it is important to mention that a conflict of goals among indicators can arise and can lead to a competition for the scarce resources. These reciprocal processes cannot be completely avoided. For example: impervious surfaces are seen negative regarding heavy rain, fresh air and heat island effects, but they are necessary for a redundant infrastructure and other urban functions. Another example is provided by Meerow and Newell [35] who analysed the negative correlation of park access and stormwater management goals, concluding that resilience measures create winners and losers. This also requires transparency of the data and the method of the indicator definition to understand the root causes of the conflicting goals and find adequate solutions. Here the Rockefeller [22] approach seems like a black box because it is difficult to deduce what adaptation measures are used as a data basis, and indicator calculations are unclear. During the workshop, several practitioners mentioned consequently the necessity of transparency and the need for precise communication and non-scientific language.

Sixth, following the previous point, many indicator approaches are used to build a composite index for resilience [19,22,45–47], vulnerability [18,48–52] or risk [53–55]. Specifically, at the scale of urban resilience, indexing across the multitude of action fields was discussed critically. The different scales, topics and units appeared to not be logically linkable. Moreover, a combined index value was seen to not tell much about the level of resilience. It was seen as more important to see the contribution of each action field to the overall resilience. Also, considering the next step of adaptation measures, it is more relevant to have a resilience profile displaying specific topics to be addressed in the municipal context.

Working at the science-policy interface was challenging for all sides. The mixed method approach proved invaluable in finding a common language, tolerance and understanding. This created an environment that allowed for constructive criticism, which is indispensable for finding a compromise.

5. Conclusions

In this study, we developed an indicator set to measure and monitor urban climate resilience for municipalities, thereby assessing the requirements of indicators and implementing a method for adapting global approaches to the local context.

The mixed method approach proved to be essential for the process of indicator development. It provided an adequate frame and time to develop a mutual understanding across disciplines, researchers and practitioners, which is needed in order to select indicators or accept indicators from different fields of expertise. Transparency in the process and the inclusion of feedback builds acceptance and trust. The concept of resilience provided the required assembly hall and saw climate change as the imperative. Even the often-criticized ambiguity of the resilience concept was helpful as it created room for discussion. The number of 24 indicators based on secondary data balanced as well as possible the diverging interests. Amongst the indicators, conflict of goals is unavoidable. Making the conflicts visible is a helpful basis for making informed decisions, which is a strength of this indicator set. In general, the softer and more qualitative aspects of resilience are challenging. They were seen as crucial but very hard to assess by quantitative proxies based on secondary data. Still, representative surveys to cover them in more detail on a regular basis were rejected by municipalities as too expensive and labour-intensive.

Developing an indicator set tends to be easier than assessing the significance or validity of an indicator over time and it requires an extended period of observations to be able to make statements about the significance of a certain indicator. Nevertheless, in order to advance this field of research, it is necessary to pursue this path and start inquiries into the significance or validity of the numerous indicators that are permeating the ongoing discussions. In further research, the indicators need to be tested in reality, and there needs to be more research that addresses the validation of the indicators.

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The Multi-Risk Assessment Approach as a Basis for the Territorial Resilience

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Abstract: The deep modifications to climate are currently provoking risks of increasing impact, that can cause unexpected consequences, interacting with other risks. However, the available planning regulations and instruments appear inadequate to face this challenge, most of all at a local scale. This paper presents a semi-quantitative methodology for the assessment of multiple risks, developed for the direct use of the municipality technicians, in order to increase their awareness towards multiple risks and unexpected events that could hit their territory. The methodology is based on the assignation of rates to the risks, and on a simple calculation of the binary interactions. It was tested on two Italian case studies, revealing a good feasibility in the results obtained for the interactions, and highlighting some problems neglected in the sectorial risk plans. The methodology is a background knowledge of the 'Responsible Risk Resilience Center' (R3C) of Politecnico di Torino, and it was furtherly developed through an in-depth analysis of the territorial vulnerabilities. This paper introduces two new indicators of sensitivity towards external risks, related to fire and flood risks, proposed for the application at a local scale. The indicators belong to a wider R3C framework in the phase of development to operationalize resilience.

Keywords: multi-risk; vulnerability; flood; fire; indicators

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1. Introduction

The methodology for the semi-quantitative assessment of multiple risks at a local scale constitutes the background employed for the development of the framework and theories of the multidisciplinary research center of Politecnico di Torino 'R3C'—Responsible Risk Resilience Center. The R3C Project aims at designing and operationalizing an interdisciplinary research methodology to implement resilience in regional and urban systems. Within the project, an in-depth discussion around the epistemological meaning of resilience in different fields of application has been set up, comparing the theoretical approaches and their practical applications derived from the operational research carried out by urban and regional planners, social scientists, anthropologists, engineers, historicists, and ecologists [1].

The R3C group adheres to the definition of resilience as "the capacity of the system—and of all its socio-ecological, technical, and infrastructural components—to preserve or rapidly return to basic functionalities, responding to turbulence and/or shocks, of adaptation to climate change, and to transform the subset of components which limit the present and/or the future evolution capacity" [2]. In particular, the emerging idea of "territorial resilience" is introduced, as a concept capable of supporting the decision-making process, together with the tool needed for identifying vulnerabilities and guiding the transformation of socio-geographical areas [3]. In order to operationalize the "territorial resilience", it is essential to develop a framework for the measurement of the resilience itself. Measurement is strictly related to the management of the risks impinging on an area, integrating the approaches of multi-risk assessment with climate modelling and the qualitative study of governance models [1].

The methodology described in this paper aimed at overcoming the common approach to risk analysis for single hazard factors [1], through the proposition of a multi-risk approach able to represent the mutual interaction of natural and anthropic stressors for the territory in a more useful view, for the development of an "operational resilience approach". The methodology was expressly developed and tested for the application at a local scale, because local authorities are on the front-line in facing the consequences of shocks and territorial changes, and often they do not have adequate instruments to cope with them. In fact, in Italy, as an example, the land use planning is delegated to municipalities, that are responsible both for the emergency planning and land use strategies. The operative tools available to the municipalities are the City Plan and the Municipal Emergency Plan. The first one aims at regulating urban and land functions, adapting the needs of urban development to the natural specificities of the territory (geomorphological, hydrological, etc.). The second one sets up the operational activities, the materials, capacities, and means to deal with possible emergencies, on the basis of the existing sectorial risk analysis. Both the plans implement and apply planning measures derived from the superordinate sectorial plans (seismic, flood, etc.), but, even if they share the same basic indications, they are not mutually linked in terms of long-term risk management, adaptation, and increase of resilience [4].

As a consequence of this planning structure, municipalities currently deal with multiple risks, but they merely implement contents from superior plans, without analyzing or correlating them in a systemic way. Additionally, the management of risks in a separate way, with different procedures, timings, and methodologies, makes it difficult for the municipalities to have a clear and updated concept of the actual hazards that threaten their territories, most of all for those deriving from the mutual influence and interaction between risks.

Till now, no mandatory rules require municipalities to evaluate the combined effects of risks; but the increasing effects of the climate change, together with the lack of resources for preventive and protective interventions, highlights the need of advanced approaches and tools for the identification of the areas more exposed to risks and risk interactions, to optimize and better address the use of resources, and to improve the actions related to adaptation and mitigation strategies.

However, the available methodologies for multi-risk assessment could present some problems for the application at a local scale (see [5] for a complete literature review). On one side, they still suffer some criticalities that need to be settled out, for example, as highlighted by Garcia-Aristizabal and Marzocchi [6], there are huge difficulties on the definition of a common metric for loss assessment, and the weighting of the different categories of exposed elements. On the other side, sometimes "specialists in various fields studying risks have failed to produce results in a form that could be useful to planners" [7]. Many methodologies for multiple risks are based on quantitative techniques for risk analysis; even if this mathematically rigorous approach can seem the most reliable one, the application to real cases usually require great simplifications, mainly related to the difficulties in obtaining the detailed information needed. Additionally, the high specialization level of this type of methodologies makes them hardly manageable for local administrations, that can have a limited technical preparation, and in many cases cannot afford the expenses for detailed risk investigations.

In order to address the problems above-mentioned, multi-risk projects like MATRIX [8] adopted a multi-level strategy, introducing the most technical phase of the methodology only after a first simpler phase. Analogously, the objective of the authors was the implementation of an easy-to-use risk screening instrument, based on a simplified methodology like an index approach, to allow the municipalities to directly evaluate the risks and possible risk interactions that affect their territory. After this, the Municipalities could define possible further actions, including the adoption of more specific risk-assessment procedures, in accordance with superior local authorities (provinces, regions).

The following paragraph presents the methodology proposed for this screening path. This approach was adopted as a baseline for the identification of the vulnerabilities of the territorial system and the measure of its resilience. As discussed in Section 3, a set of indicators of resilience are under development, able to estimate territorial vulnerabilities, and some of them are introduced in this paper.

2. Materials and Methods

2.1. A Semi-Quantitative Methodology at a Local Scale

The proposed methodology considers, in an integrated framework, the main risks on the territory and their possible interactions, in order to better orient further in-depth studies and interventions related to land use planning and emergency. Since the methodology was intended for a direct use from the municipalities' technicians, it recovered the simplified scheme adopted for the Italian plans related to the industrial risk, called E.R.I.R.—Elaborato Tecnico per il Rischio di Incidente Rilevante (Technical Plan for Major Risk accidents), composed by:

1. Characterization of risks;
2. Characterization of the territorial and environmental vulnerable elements;
3. Assessment of the compatibility;
4. Planning phase (development of further studies and adaptation strategies).

The risks to be taken into account were chosen following the concept of the "spatial relevance" stated in the ESPON project [9]: only risks that regularly or irregularly interest the same territorial area should be take into account, disregarding those that could take place everywhere. The methodology was developed for the risks more diffused in Italy: industrial, flood, and seismic risk, and, given the recent increase in extreme climatic events—violent rains, windstorms etc.—a climate related factor was also included. Each municipality should clearly consider also its main territorial criticalities, other than those included in the main model (i.e., volcanic risk, avalanches, wildfires, etc.).

A semi-quantitative approach was adopted, introducing a rating system common for all the main risks present on the territory. This type of approach, already employed in European projects [7] or regional methodologies [10], was chosen for its simplicity, which could allow its use also with low economical resources and technical skills. The adopted rating scale assumes different scores related to the possible impact of the risk/risks analyzed:

- $0 < I \leq 0.99$: Negligible;
- $1 < I \leq 1.99$: From low to moderate;
- $2 < I \leq 2.99$: From moderate to high;
- $I \geq 3$ onwards: From high to very high.

2.2. Characterization of the Risks

The first step of the proposed methodology consists of an in-depth analysis of the main territorial risks that insist on the territory of the municipality. An in-depth data collection has to be developed on the basis of existing sectorial plans, emergency plans, and through a direct investigation of the territory. In order to better understand and address the description of each risk, the risk characterization was based on three macro-categories, aimed at highlighting the characteristics of the analyzed risk which could mostly influence its dangerousness and its possible interaction with other events. The categories are:

1. SE—strengthening effects: Local characteristics able to increase the dangerousness (i.e., in case of seismic risk, the type of soil);
2. HE—historical and recent events: All the events related to the specific risk should be taken into account, to evaluate if the return times expressed by the overall plans are reliable;
3. PM—protection measures: The presence of protection and preventive measures could reduce the impact of the risk analyzed.

The ratings defined in Section 2.1 were assigned to each risk based on these three macro-categories; a guideline for the assignation of the scores was defined. Climate related events were introduced and rated, but they were evaluated through a simplified approach, related to the global tendencies, because an analysis of the local trends could present difficulties related to the data collection and interpretation. Table 1 below shows the guide for flood risk; it analyzes the functioning of individual regulatory subsystems or elements, such as water intakes, pumping stations, the water distribution network [11,12], and the events that occurred on the territory, both those reported in the flood plans through probabilistic approach, and the recent occurred ones.

Table 1. Guiding table for the assignation of the ratings to the flood risk.

Macro-Category	**Rating**		
	1 < I ≤ 1.99	**2 < I ≤ 2.99**	**I ≥ 3 Onwards**
SE: Strengthening effects	Interaction with other rivers/creeks with low or reduced criticalities; hydraulic devices in good state; no or few critical points (crossing and bridges with insufficient flow section; eroding or sliding banks/levees; sudden section variations, etc.	Interaction with other rivers/creeks and hydraulic control devices with moderate criticalities; identified critical points (see precedent column); the river/creek/etc. analyzed contains key element for the safeguarding of the general safety of the system.	Problematic interaction points with other rivers/creeks, recognized high critical areas, reported in flood plans (i.e., throttling points, areas interested by erosion etc.). Hydraulic devices in bad conditions, with recognized criticalities.
HE: Historical events	Rare main flood events return time of flood management plans is confirmed (zones classified as C, Em, or Cn if recent events do not evidence different distributions/timing of the floods).	Floods of moderate impact, and/or in areas not included in plans, with a short return time (≥50 years) (zones classified as B, Eb, or Cp if recent events do not evidence different distributions/timing of the floods).	Events with return time > than that of the flood management plan worst zone (zones classified as A, Ee, or Ca if recent events do not evidence different distributions/timing of the floods).
PM: Protection measures	No water regulation artefacts/systems or insufficient number/way. Criticalities and inadequate safety level.	Water network/river/creek is properly controlled, the artefacts do not show relevant criticalities.	The management of the water network/river/creek is well coordinated, evidencing no criticalities.

2.3. Risks Interactions

The macro-categories SE, HE, and PM are the basis to assess the possible impact of risk interaction, because they determine the risk role in a possible risk interaction and provide useful indications on the possible plausible effects. However, the macro-categories have different levels of influence on the interaction, and different reliability in terms of data; therefore, different weights were attributed to express this variability. The weights (HE = 2, SE = 1, and PM = 0.5) were designed to obtain results in line with the general scale employed in the methodology (see Section 2.1.) and were validated through experts' judgement.

The binary risk interaction, intended as the impact a hazard factor could have on another one, should be assessed in the area of risk overlaying, where vulnerable environmental or territorial elements are present. The binary risk interaction is calculated through a weighted average of the values assigned to each category of the different risks, shown in Equation (1).

$$I = [(HE_{risk1} + HE_{risk2}) * 2 + (SE_{risk1} + SE_{risk2}) * 1 + (PM_{risk1} + PM_{risk2}) * 0.5]/6 \quad (1)$$

A dedicated binary interaction table was developed in order to simplify the assessment of the possible interactions: the values assumed by each risk macro-categories in the analyzed point of the territory are reported in the table; when a possible risk correlation was encountered, the formula of Equation (1) was applied.

The values of interaction obtained through the Table can be also assessed directly through a GIS (Geographic Information System): each risk factor can be represented on a single layer; then, it is possible to directly obtain the georeferenced value of the integrated risk intersecting the risk layers and making use of the "calculator" field.

Table 2 shows an example of an interaction table: in this case, on the territory under study, a major risk chemical plant (I) was present and flood (F), earthquake (E), and extreme climate events (C) could occur. The table shows the values assigned to each macro-category and it returns the results of the mutual interaction between the risks, where relevant. In the specific case, interactions with moderate effects could occur; in fact, despite the high dangerousness of the Seveso plant (due to the huge quantity of substances stored, presence of vulnerable items, etc. (SE = 3)), the natural risks had quite low values. The seismic risk was unlikely in the area (HE = 1), even if the poor quality of soil could enhance the SEISMIC EFFECTS (SE = 2), while the flood risk had been dramatically reduced through an effective system of protection (PM = −3); as a consequence, the possible binary interactions obtained a low value, tending towards moderate.

Table 2. Example of binary interaction table.

Impact →			**E**			**F**			**I**			**C**		
			SE	**HE**	**PM**	**SE**	**HE**	**PM**	**SE**	**HE**	**PM**	**SE**	**HE**	**PM**
			2	**1**	**0**	**1.5**	**1**	**−3**	**3**	**2**	**−1**	**2**	**1**	**0**
E	**SE** **HE** **PM**	**2** **1** **0**	No interaction			0.92			1.75			No interaction		
F	**SE** **HE** **PM**	**1.5** **1** **−3**	No interaction			No interaction			1.42			No interaction		
I	**SE** **HE** **PM**	**3** **2** **−1**	No interaction			No interaction			No interaction			No interaction		
C	**SE** **HE** **PM**	**2** **1** **0**	No interaction			0.92			1.75			No interaction		

2.4. Vulnerability and Compatibility Assessment

The assessment of territorial and environmental vulnerabilities was based on the legislative indications of Ministerial Decree 09/05/2001 [13] and of D.G.R. 17/377 [14] for E.R.I.R. plan—plan for the safe planning of the areas around major risk plants. According to [13,14], the vulnerability is mainly identified as "exposure to the risks in terms of population"; the possible factors of sensitivity and coping capacity of the analyzed elements are not taken into account.

The proposed methodology recovered the classification of urban functions and strategic buildings in six different categories (see Table 3), assigned on the basis of the people density and mobility.

Table 3. DM 09/05/2001 territorial vulnerabilities.

Category	Vulnerable Elements
A	1. Residential areas, with building ratio index >4.5 m^3/m^2
	2. Buildings hosting people with limited mobility (more than 100 people or 25 hospital beds); hospitals, hospices, nursery schools
	3. Outdoor places interested by a high presence of people, like markets or other commercial functions (more than 500 people)
B	1. Residential areas, with building ratio index from 1.5 to 4.5 m^3/m^2
	2. Buildings hosting people with limited mobility (up to 100 people or 25 hospital beds); hospitals, hospices, nursery schools
	3. Outdoor places interested by a high presence of people, like markets or other commercial functions (up to 500 people)
	4. Indoor places interested by a high presence of people, like shopping centers, business districts, hotels, universities, high schools, etc. (more than 500 people)
	5. Places interested in limited periods by a high presence of people, for example, places for public entertainment and for cultural, sporting, and religious activities (more than 100 people for outdoor places, more than 1000 people for indoor places)
	6. Railway stations (more than 1000 passengers by day).
C	1. Residential areas, with building ratio index from 1 to 1.5 m^3/m^2
	2. Indoor places interested by a high presence of people, like shopping centers, business districts, hotels, universities, high schools, etc. (up to 500 people)
	3. Places interested in limited periods by a high presence of people, for example, places for public entertainment and for cultural, sporting, and religious activities (up to 100 people for outdoor places, up to 1000 people for indoor places)
	4. Railway stations (up to 1000 passengers by day).
D	1. Residential areas, with building ratio index from 0.5 to 1.5 m^3/m^2
	2. Places interested by high presence of people once a month (e.g., local fairs, flea markets, events, cemeteries, etc.)
E	1. Residential areas, with building ratio index <0.5 m^3/m^2
	2. Industrial, artisan, agricultural, and livestock activities
F	1. Area inside the plant boundaries

However, the assessment of the compatibility differed from that indicated by [13,14], because multiple risks had to be considered. Therefore, the assessment was based on a threshold of 2.5, corresponding to a medium impact tending towards high: If the ratings of risk interactions and of macro-categories SE and HE overcome the threshold in areas where A and B elements are included, a potential incompatibility is detected. This is a signal for the municipality that a further investigation on the area is needed, to prove the incompatibility and verify possible preventive and protective measures.

2.5. Planning

The last step of the methodology is dedicated to the studies and actions to be carried out to face possible incompatibilities. Two levels of actions are foreseen: The first step is an analysis in detail of the potential incompatible situations, both as far as it concerns the hazards and the vulnerabilities. If the incompatibility is confirmed, the second step, based on possible prevention and protection measures and interventions, could be prepared; in this last phase, the municipality will have to involve and cooperate with experts of several fields.

Some existing manuals and guidelines, diffused by the government or other public authorities [15–23] or settled by research groups [24–26], already provide useful indications for in-depth analysis and actions, but in many cases, they do not have binding value, and; therefore, are little known and applied. These indications were collected in dedicated tables, that can guide the municipalities in the choice of a correct approach to face problems related to multiple risks. Table 4 below reports an example of further investigations that can be carried on related to flood and seismic risk, here referred to as Italian regulations and guidelines.

Table 4. Guide for the definition of further investigations to be carried on depending on risks.

RISK	**Measures**	
	In Presence of: Punctual/Areal Elements and Infrastructure Cat. A, B	**In Presence of: Environmental Elements Subjected to a High Influence**
Earthquake	Draft of data sheets related to the constructive and seismic characteristics of the building [15], starting from the public buildings and infrastructures classified as A.	For the archaeological and historical monuments, and protected landscapes: development of an in-depth analysis of structural and non-structural elements in compliance with [16].
Flood	For the buildings classified A and B, the characteristics of the pavement, walls etc. should be analyzed on the basis of the indication of [17]: i.e., ground level should be higher than that of the reference flood or levee height. For the bridges (linear element), it is recommended the compilation of the vulnerability sheet proposed by [18], an Operative manual on the hydraulic vulnerability of bridges.	Case by case assessment of the specific vulnerabilities for the elements subjected to high influence
Interactions	The interactions between risks could cause an increase of the effects; in case the threshold of interaction is higher than 2.5, it could be useful to proceed with an in-depth analysis related to the probability of occurrence and the assessment of the spatial distributions of the possible effects. Involvement of experts with skills in matter of Seismic/flood and other hazards.	

2.6. A Step towards a Measure for the Resilience: The Definition of Vulnerabilites

As remarked in Section 2.4, the characterization of the vulnerabilities for the proposed methodology followed the simplified approach proposed by the Ministerial Decree 09/05/2001 [13]. This classification does not explore in-depth the intrinsic characteristics of the vulnerable element that contribute to its sensitivity or capacity to react and recover towards an external event, therefore the further investigation on the vulnerable elements were transferred to the last step of the methodology, the Planning.

The awareness of the need to develop a more detailed investigation on vulnerability was considered and developed in the wider context of the framework for the 'Operationalization of resilience' by R3C research Centre. In fact, one of the ongoing projects within the Centre refers to measuring the resilience of a territory, and its first step is the identification of indicators able to spatially describe the vulnerability of the territorial and urban system.

Indicators were defined for three main components of the system (Environment, Urban system, Population). With reference to the indicators related to Urban systems and building, general indicators able to express the sensitivity towards external pressure and events were settled, i.e., in relation to quality, function and age of the buildings.

In this context, the authors proposed specific risk-oriented indicators, developed to test the peculiar sensitivity towards the risks more recurrent in a determined territory. One of the guiding principles for the selection of these indicators was the availability and reliability of the data, in order to be able to provide quick elaborations and quick responses. In fact, the survey of specific vulnerability towards risks is often based on a deep level of investigation on site, that requires the compilation of data-sheets, the involvement of owners etc.; these long procedures sometimes can obstacle or even stop the correct application of plans and legislation. In example in Italy, the compilation of the basic level of the seismic vulnerability data-sheets required by [15] for the strategic public buildings required ten years more than those foreseen.

As far as it concerns Flood, a valid help to identify the factors of increment of the sensitivity was found in [17,27,28], that provide detailed lists of technical indications on the best characteristics that buildings should have to resist to a flood. However, these indications were rarely translatable into helpful indicators at a local scale; firstly, they usually referred to new buildings, and not existing ones; secondly, they required a level of information too punctual (i.e., material composing pavements, presence of interspaces, specific use of the underground spaces, etc.), very difficult to be acquired in a reasonable period and without the cooperation of the building owners.

For this reason, only one possible parameter was selected from these literature resources and converted into an indicator: the height of the ground floor compared to the flood height. The expected flood height is usually known from the existing flood plans and the surveys of the events occurred, while the ground floor height is easily verifiable through Google street-view. Exposure being equal, this indicator of sensitivity can provide an essential information on the vulnerability of built landscape, because a ground floor used for residential purposes located under the max flood height is deeply more vulnerable with respect to other types of buildings and functions.

The second indicator here presented is related to Fire risks; in this case, the vulnerability towards a fire strictly depends on the characteristics of the building and of the vegetation cover in its close surrounds. An index considering 4 different factors of vulnerability towards risks is defined by [29], like i.e., type of materials employed for the roof and coating of the building, and some of these factors can be found also in [27,28].

The parameters most suitable to be applied at a local scale, because of the availability of information and spatial data, were the so-called 'defensive space' around the buildings and the slope. The defensive space is an area of 10 m around the building in which only grass should be present; if trees or bushes are included in it, they can increase the sensitivity of the building towards fire. The slope should be minor of 40%. Spatial data related to vegetation cover and slopes are available in regional archives.

3. Results

The proposed semiquantitative methodology, as described from Sections 2.1–2.5 was tested and applied to two Italian case studies that returned positive results in terms of soundness of the interactions detected, highlighting possible problems that were not clearly signaled or neglected by the risk sectorial plans.

I.e., one of the case studies considered was Mantua: on the Mincio river, in front of the ancient city that is an Unesco site, an important industrial hub rose in 1950. Two plants are still active and relevant for their dimensions and quantities of stored hazardous substances: a petrochemical plant and a warehouse of gasoline and diesel fuels. During the years, both the plants produced a serious situation of pollution, but despite of the proximity to the river, and the unexpected earthquake of 2012, the possible effects of the interactions between the industries and natural events were not taken into account in the official planning instruments of the city. The methodology was applied to find out if the risk-interactions could produce damages not analyzed in Mantua E.R.I.R. The values of interaction obtained through the interaction tables resulted between low and moderate (see Table 2, referred to the petrochemical plant), because of the initial low levels of the natural risk. These values were therefore employed to settle simulations of industrial damages with ALOHA® and HSSM®, that revealed possible criticalities both for the environment and the population. On one side, due to the quality of the soil, even a very small damage to the tanks caused by an external event could cause the penetration of pollutants in the underground aquifer, confirming why the pollution under Mantua plants is still ongoing today. On the other side, despite of the several protections adopted by the petrochemical plant and the warehouse, unexpected consequences could come from minor damages to the rail-tankers that bring the products to the plants; as shown by Figure 1 below, possible toxic releases could interest residential areas located alongside the railway.

Figure 1. Possible toxic releases of acrylonitrile or benzene due to a hole of 3 cm in the rail tanker, following a seismic event. The release can interest residential areas along the railway.

The second case study was related to a small city in Piedmont; it was repeatedly interested by floods due to a minor hydrographic network, not reported and analyzed in the regional Flood plan. Some Seveso plants were located in the town (see Figure 2), so that it was important to verify possible risk interactions.

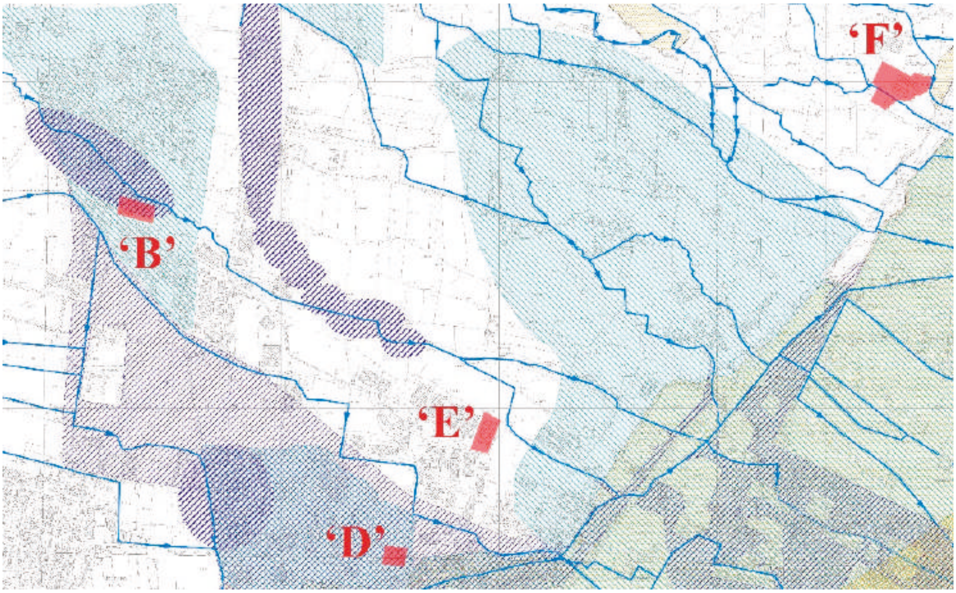

Figure 2. Position of the plants and areas interested by floods (blue and light blue).

The following two tables (Tables 5 and 6) report the analysis developed for Plant B, a plant detaining an amount of hazardous substances that overcame the Seveso thresholds, but that was not compliant with the Seveso regulations. Plant B was hit by Flood in 1994, 2000 and 2008; the flood events however had a moderate impact, reaching the maximum height of 1 m. This initial moderate value of the flood risk, combined with low value adopted for the Industrial macro-category H.E. in absence of certain information, produced a low interaction risk tending to medium (1.98).

Table 5. Plant B binary Interaction table.

Impact →			**Flood**			**Industry**			**Climate**		
			SE **3**	**HE** **2**	**PM** **0**	**SE** **2.8**	**HE** **1.5**	**PM** **−1.8**	**SE** **2**	**HE** **1**	**PM** **0**
F	**SE** **HE** **PM**	**3** **2** **0**	No interaction			1.98			No interaction		
I	**SE** **HE** **PM**	**2.8** **1.5** **−1.8**	No interaction			-			No interaction		
C	**SE** **HE** **PM**	**2** **1** **0**	1.83			1.48			No interaction		

Even if the Interaction values were moderate, the ratings assigned to some risk macro-categories overcame the threshold of 2.5, therefore the Compatibility analysis was carried out:

Table 6. Plant 'B' Compatibility and planning actions.

Ratings.	**Territorial Vulnerabilities Inside 500 m.**	**Environmental Vulnerabilities Inside 500 m.**
Interaction	(1) C residential areas. 2 productive areas (E) destined for reconversion to commercial function, whose transformation should be monitored. (2) 2 punctual elements in B (commercial centre/bowling; church) (3) Energetic lines	RV—water table depth < 3 m. Presence of a canal for irrigation adjacent to the northern of the plant
1.98		
Industrial risk		
SE 2.8, HE 1.5		
Flood risk		
SE 3, HE 2		
Judgement of compatibility & possible further steps	**Territorial compatibility**	**Environmental compatibility**
	Potential incompatibility in case of toxic release with the two punctual elements classified as B (threshold for S.E. > 2.5). *An in-depth analysis is recommended for: (1) the specific activities of the 2 vulnerable elements classified as B; (2) the storage methods and protection and preventive measures of the substances classified as TOXIC (H2)*	The plant, detaining toxic substances and substances dangerous for the environment, is not compatible. S.E. = 2.8 overcomes the compatibility threshold; the interaction with flood events, even if connoted by a low-medium value (1.98), could enhance the threat. *Further analysis on the possible pollution scenarios and prevention and protective measures against flood should be carried out.*

Even starting from low level impact risks, some problematics related to the environment were identified (as shown by Table 6). The Municipality in this case should develop some further in-depth investigations.

The proposed approach provides the Municipalities with a quick and easy to use tool that can be developed almost completely with internal resources; the application of the methodology can be done by a work team composed by Municipal technicians and members of superior authorities or institutes (like Regions, Agencies for the Protection of the Environment, etc.). The work team proceed with the assignation of ratings, exploiting the major direct knowledge of the territory that usually the Municipality has, and then assess the risk interactions and the possible incompatibilities. The methodology aims at filling a gap in the existing planning and risk instruments, helping local planners in find out the unexpected effects of multiple risks and providing an important indication on the priority areas to which address technical studies and financial resources.

The methodology constituted an important background for the development of the "R3C" framework, whose development is at an initial stage: The R3C research group is focusing on the development of spatial indicators able to describe the vulnerability of a territory, in order then to test and develop effective solutions to increase resilience and adaptation. In particular, the research group is currently working on the definition of indicators of vulnerability that are spatially meaningful and able to usefully describe the local vulnerability. The experience with the above-mentioned multi-risk methodology guided the authors in the definition of indicators of sensitivity strictly related to risks.

The indicators proposed in the context of R3C were identified and tested for the experimental case-study of Moncalieri, a town of medium dimensions nearby Turin, that constitutes an interesting case-study for its peculiarities. In fact, it presents both hilly and flat areas, crossed by the Po river and its tributaries, it owns an important historical heritage together with extensive industrial areas, and it is crossed by important transport and energy infrastructures.

The indicator "*Height of the ground floor compared to the flood height*", mentioned in Section 2.6., was investigated and identified for the experimental case study of Moncalieri, that in 2016 was interested by a huge flood event that overcame the limits reported in the flood plan for catastrophic events. Following the rupture of a levee, the flood hit some quarters of Moncalieri never reached by floods, connoted by residential cottages of maximum of two floors. These areas were accurately investigated to identify all the buildings more sensitive to the flood because of the height of their ground floor. Figure 3 below shows the superimposition between the flooded areas and the residential building whose ground floor was below the flood height (1 m).

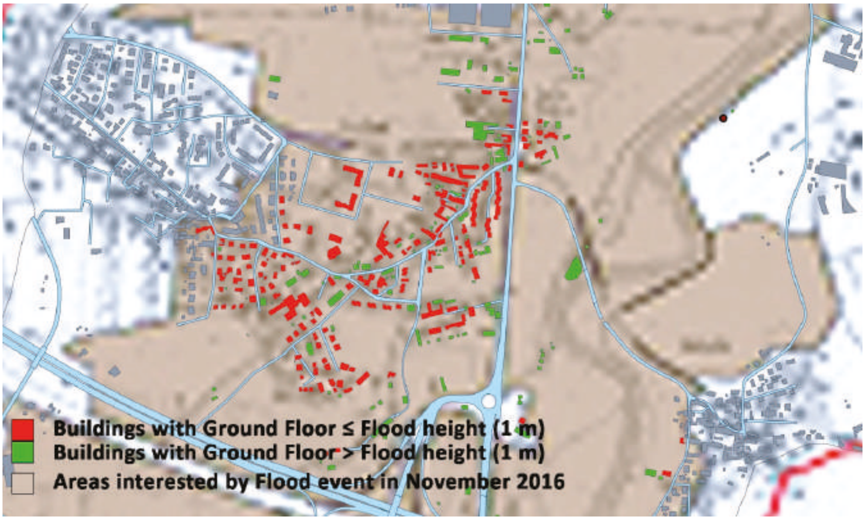

Figure 3. Indicator of vulnerability towards flood events: Red buildings are more sensitive because of the height of their ground floor.

As far as it concerns the indicator related to fire risk, the area of Moncalieri more exposed is the hilly one: the defensive space of the buildings here located was investigated to identify the presence of trees or bushes. This data was spatially obtained though GIS, using the thematic regional map of the vegetable cover and verifying, for each building, a buffer zone of 10 m. The result of the investigation is shown in Figure 4.

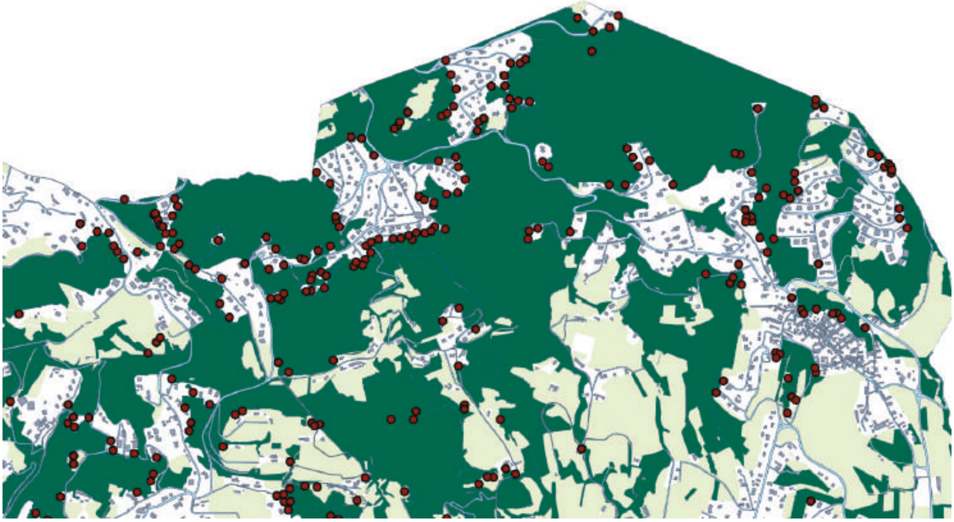

Figure 4. Indicator of vulnerability towards fire: Red points signal buildings whose defensive space include trees or bushes. These buildings are more sensitive in the case of fires.

The indicators for sensitivity here presented could be valid not only to highlight the vulnerability of residential buildings, but they could be applicable also to industrial buildings. However, in this case, a further investigation on the type of substances detained should be indispensable to verify possible effects and unexpected consequences of the impact of flood or fire.

A process of weighting will be soon carried out for all the R3C spatial indicators of vulnerability, in order to properly use them to give priorities to the most vulnerable areas.

4. Discussion and Conclusions

R3C adopted the concept of territorial resilience as the focus and objective of its research work: It expresses a novel concept of resilience, aimed at reconnecting the theoretical knowledge to a factual translation into spatial plans and projects. The implementation of resilience in a territorial system means reduction of vulnerability, the pursuit of social and institutional learning capacity, and the achievement of better territorial governance that increase the adaptation ability and reduce vulnerabilities [1]. The R3C research group is composed of several contributors, coming from different disciplines, both related to risks and land use planning; it promotes a multi-disciplinary approach that should generate feedback between assessment and territorial government, indicating and selecting sites where specific actions of mitigation, adaptation, risk reduction, or transformations should be implemented to reduce the vulnerability of the system.

This paper presents, on one side, a background contribution to the research carried out by R3C, and, on the other side, one of the outputs of R3C's first stage—the research of feasible indicators of vulnerability for urban systems. The proposed semi-quantitative methodology for multi-risk pre-screening produced interesting results for the analyzed case-studies, evidencing possible negative events deriving from risk interactions; however, since the methodology requires a phase of in-depth studies to confirm and prove the consistency of the results, wider investigations on the vulnerabilities of the territorial system should be carried out. As mentioned in Section 2.4, at the moment the vulnerabilities are evaluated according to the Ministerial decree 09/05/2001 [13], but further analyses on the risk-specific sensitivity were needed: two indicators were proposed to quickly evaluate the vulnerability of buildings towards flood and fire. They identify important aspects of sensitivity towards external risks, and, at the same time, are quite reliable in terms of available information and spatial data. The insertion of specific indicators of sensitivity related to risks in a wider approach aimed at influencing the current practices of land use planning could represent an important advancement to obtain major preparedness and awareness at a local scale, obviously keeping in mind the final objective of increasing "territorial resilience".

Beside the indicators here presented, the authors are currently working to develop indicators of sensitivity more strictly related to industrial areas and strategic infrastructures on the territory. Both these elements are connoted by a dual nature: On one side they are vulnerable towards external natural events, but at the same time, they can provoke damages to the population and urban functioning in case of failure and damage. For this reason, the authors are in the development phase of specific indicators related to: (1) the type of production and items correlated for industries; and (2) accessibility and redundancy for strategic infrastructures.

As far as it concerns the methodology for rapid risk pre-screening, some further refinements are in progress; in particular, a sensitivity test was carried out to verify the impact of subjectivity in the phase of the rating attributions, and possible corrective actions were proposed. The sensitivity test made clear that the interaction values that are more susceptible to variations consequent to the assignation of the rating are those closer to the limits between the intervals of the scale adopted ("low", "medium", "high"). In fact, in these cases, the variation of only one parameter of the risk macro-categories can determine an interval change; therefore, it can be said that these interaction values are those more exposed to discretion risks. In order to compensate for this result, a variation was proposed for the application of the methodology: In the case of interaction values near to the limit of the intervals, an attention threshold of ±0.25 could be adopted. This means that, for example, if the interaction value is 1.75, or 2.25, the user should know that this value could be particularly sensitive to uncertainties and thus discretion occurred during the rating phase; therefore, the results of the interaction tables could need some in-depth analyses [30].

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Mapping Urban Resilience for Spatial Planning—A First Attempt to Measure the Vulnerability of the System

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Abstract: The concept of 'resilience' breaks down silos by providing a 'conceptual umbrella' under which different disciplines come together to tackle complex problems with more holistic interventions. Acknowledging the complexity of Davoudi's approach (2012) means to recognize that 'spatial resilience' is influenced by many phenomena that are difficult to measure: the adaptation and transformation of a co-evolutive system. This paper introduces a pioneering approach that is propaedeutic to the spatial measure of urban resilience assuming that it is possible to define a system as being intrinsically vulnerable to stress and shocks and minimally resilient, as described by Folke in 2006. In this sense, vulnerability is counterpoised to resilience, even if they act simultaneously: the first includes the exposure to a specific hazard, whereas the second emerges from the characteristics of a complex socio-ecological and technical system. Here we present a Geographic Information System-based vulnerability matrix performed in ESRI ArcGIS 10.6 environment as an output of the spatial interaction between sensitivities, shocks, and linear pressures of the urban system. The vulnerability is the first step of measuring the resilience of the system by a semi-quantitative approach. The spatial interaction of these measures is useful to define the interventions essential to designing and building the adaptation of the built environment by planning governance. Results demonstrate how mapping resilience aids the spatial planning decision-making processes, indicating where and what interventions are necessary to adapt and transform the system.

Keywords: urban resilience; spatial planning; vulnerability; measuring; mapping; decision-making

1. Introduction

If we look at the international scientific debate around the concept of resilience and its relation with urban planning, also considering some practical experiences, the term creates a "conceptual umbrella" that provides a flourishing perspective for urban planning with a slippery and ambiguous definition [1,2]. This is the limit but also the strength of this concept that represents a metaphor to develop spatial policies of mitigation, adaptation, and transformation to the turbulences of the system [3]. As to what concerns the most cited approaches on urban resilience, two concepts emerge as paradigmatic: the co-evolutive perspective [4] and the multidisciplinary integration of knowledge that is necessary to assess the vulnerable and resilient capacity of a system [5]. Both approaches share the common assumption that urban resilience is a driver capable of steering the policies and the urban agenda of institutions, organizations, and social groups [6,7] towards a multi-level governance of urban systems to a long-period perspective.

The evolutionary definition of resilience provided by Davoudi (2012) is the one that explicitly refers to a co-evolutive condition of a system, and a challenge for planning. Therefore, the dynamic non-equilibrium of a system is an opportunity to create knowledge and intelligence through learning capacity, robustness, adaptation, and transformation [8,9].

Particularly, the perspective of dynamic co-evolution is an approach derived from social sciences [10], which considers the resilience of a complex system as an evolutionary process of adaptation [11]. The implication of this definition in the urban planning agenda is that resilience becomes a normative concept for territorial systems and mainly refers to how a new approach to spatial development supporting the adaptation and transformation of the system could be traced. At the same time, spatial resilience implies that territorial systems continually self-organize and adapt in the face of ongoing and unpredicted changes [12].

In this view, a recent reflection on the theoretical development of a common background on the meaning of spatial resilience in planning has been deepened in the paper written by the Responsible Risk Resilience Centre (R3C) research group of Politecnico di Torino (the manuscript—in press—is entitled "Territorial Resilience: Toward a Proactive Meaning for Spatial Planning"). The work concludes that "territorial resilience" is an emerging concept that supports the decision-making process, identifying vulnerabilities while improving the development of urban transformations coupled with nature-based solutions [13].

It is agreed that urban resilience is characterized by a co-evolution, self-adaptiveness, and learning capacity; the question on how to operationalize the concept into urban planning procedures remains unsolved to the lack of empirical knowledge of how to measure the degree of resilience in a specific context [14,15].

This paper wants to move a step forward from these theoretical works in the operationalization of this concept, and particularly it works toward the application of a pioneering empirical model to measure the degree of vulnerability in a specific study. The assumption here is that measuring urban resilience is necessary in order to operationalize the concept into a more normative approach for urban planning that shifts from the pure descriptive/analytical assessment to the definition of a spatial support system that aids the definition of the transformation of the system in a long-term and co-evolutive manner. Main findings are referred to the capacity to construct a spatial and measurable knowledge of the vulnerable dimension of territorial systems to design land use plans that generate a resilient adaptation [16]. Results indicate that a composite assessment can indicate 'where' and 'what' kind of urban planning measures are suitable to reduce the vulnerability achieving the resilience of the system. Urban transformations range from 'grey' to 'green' infrastructures, adopting an integrated view of nature-based and technological solutions [17,18] according to contemporary resilience frameworks [19].

2. Measuring Vulnerability as a First Step to Resilience

Urban resilience has been measured both quantitatively and qualitatively with a predominance of indicator-based measurements that constitute the most considerable part of the research framework [3,20–22].

Measurement is mainly grounded on pre-emptive assessment, with an integration of multi-risk analysis and the qualitative study of governance models [23,24]. This specific knowledge is constructed in a GIS environment that creates local datasets to deliver maps of climate and risk vulnerabilities accounting for social, environmental, and economic components of the system [24–26].

In attempting to understand the spatial distribution of vulnerability in a system, a set of indicators were chosen as a proxy of the different group of variables (e.g., environment, land use, economy, and society) [27]. We approached structuring the GIS project to map vulnerabilities, taking into account the numerous limitations of an indicator based on quantitative or semi-qualitative measurements of a resilient system:

- Oftentimes, resilience is measured as the counter position of vulnerabilities and therefore the indicator-based quantitative methods do not lend to capturing intangible elements such as the social capital, power relations, partnership, and self-sufficiency that contradistinguish urban resilience;

- even when vulnerability is measured with different methodologies, indicators of the state of the system are mixed up with an indicator of response (coping capacity), generating confusion and misleading interpretations;
- the neglecting of a more self-adapting and governance capacity of the system in a proper measurement approach, namely 'resilience', may lead to ignoring the most important determinants factors that can lower the vulnerability of a system;
- indicators are, in the vast majority of cases, non-spatial but purely statistical and therefore useful for a cross-comparative analysis of different urban areas but unhelpful to construct a spatial support system that steers the urban agenda of local institutions.

However, even with the abovementioned limitations, quantitative approaches offer a systematic and reliable way to measure the different dimensions of resilience. Therefore, the methodology hereafter synthesized is composed with some warnings in mind.

First of all, vulnerability and resilience should be measured with different approaches since vulnerability is the predisposition of exposed elements to being impacted by hazard events [27]. While resilience includes the governance of the system, including planning regulation at different levels and the decision-making framework [28,29]. Resilience also deals with education and early communication: a well-educated and informed population could react coping with the disaster risk while using and disseminating the knowledge of hazardous effects [30].

Currently, in a great number of studies, 'vulnerability' overlaps with 'resilience' where the 'resilience' refers to what is properly claimed to be the coping capacity. Such an approach creates confusion and misleading interpretations since the resilience is not an endogenous character of the system (like the coping capacity) and is instead a dynamic and co-evolutive character that depends on the post-disaster effects on socio-ecological and technological systems (SETS) [16]. On the other side, what in most resilience frameworks is properly called 'vulnerability', is the sum of a linear or nonlinear relation between sensitivity, exposure, and the coping capacity. Independently of which indicator is, or is not, present in a spatial evaluation of the vulnerable dimension of the system, what emerges is that vulnerability is the product of a systematic analysis of the state and pressures of the system, while the resilience is a condition that is influenced by the vulnerable dimension but it is not a part of it.

This is why vulnerability and resilience should be measured separately, taking into account that a resilient system is one where vulnerable elements are less present and the adaptive capacity is strongly acknowledged. Therefore, methodologies of measurement should consider this theoretical distinction. If vulnerability is much more prone to be measured with semi-quantitative indicators using spatial indexes, the measurement of resilience should account for a more qualitative and documental-based approach mixed up with a certain knowledge of the governance and barriers that make the system capable of adapting and transforming the territory in an effective manner.

Secondly, vulnerability has to be spatially measured including the sensitivity, where sensitivity is the predisposition of the system's components to be affected by potential damages suffering harm as a consequence of endogenous conditions [15,31,32].

In this paper, a first attempt into the spatial measurement of vulnerability is presented using a GIS-based framework performed in ESRI ArcGIS 10.6 (Environmental System Research Institute, Redlands, CA, USA) environment as an output of the spatial interaction between sensitivities, shocks, and linear pressures of the urban system. The area of investigation is the Municipality of Moncalieri, Turin (Italy) that represents an optimal context for this study.

The spatial assessment of vulnerability is considered just the first step of measuring resilience of the system by a semi-quantitative approach. The spatial interaction of these measures is useful to define the interventions essential to building the adaptation of the built environment by planning procedures [1,19,33]. In the second chapter of this paper, the methodology of measurement is presented along with the kind of indicators used, while the Discussion and Conclusion sections present the significant findings and implication of this study.

3. Materials and Methods

The spatial assessment of vulnerability is the product of an interaction between sensitivities, disturbances, and shocks analyzed by three different components of the system (environment and ecosystem services; land use, infrastructures and heritage; economy and population). Indicators are mapped by the spatial representation of composite values by raster images with pixel values of sensitivities, disturbances and shocks (see the list of indicators in the Table 1).

Table 1. List of indicators of vulnerability.

State of the System					
Sensitivity					
	Indicator	**Structure**	**Source**	**Year**	**Unit**
IMP	Imperviousness	Impermeable surface/pixel	Existent	2012	%
IFI	Ecological Fragmentation	Infrastructure length * weight/pixel	R3C	2016	%
HQ	Habitat Quality	Value habitat/pixel	(InVEST)	2010	%
CS	Carbon Sequestration	Tons C02/pixel	(InVEST)	2010	num
WY	Water Yield	Mm * year/pixel	(InVEST)	2010	num
SH	Landscape Diversity	n.patches * area/pixel	R3C	2010	%
Pressures on the System					
Disturbances					
NDR	Nutrient Contamination	Kg nutrients * pixel/year	(InVEST)	2010	num converted in %
SDR	Erosion	Tons eroded * pixel/year	(InVEST)	2010	num converted in %
CDS	Land Take	Built up areas between 1990 and 2016	R3C	2016	%
Shocks					
IBO	Fires	Buildings near forested areas/pixel	R3C	2010	%
ALU	Flooding	Flooding risk/pixel	R3C	2006	%
ALA	Flows	Run-off/pixel	(InVEST)	2010	%

The categorization of indicators into groups of ‘components’ follows what has been done by previously published works on territorial resilience. From its definition [34] to its practical implementation in planning [35] the measurement of the vulnerability of the system has been analyzed using different criteria. To our knowledge, indicators are grouped in ‘components’ when referring to the main categories of social, economic and environment [36], into ‘resources’ when referring to capacities to react of the system (connections, services, natural resources, physical assets, economic assets, environmental assets, human assets, and social assets) [37], whilst ‘dimension’ and ‘sub-dimensions’ refer to analytical criteria existing on the system (environmental, social and economic, and their sub-dimensions of dynamism, robustness, efficiency, transport, and urban design) [38]. Within this background, our choice was to develop a simple and easy-to-comprehend framework composed of at least three main components that cover the abovementioned fields. Therefore, we optimize these approaches using a pragmatic categorization that matches the most essential ‘dimension’ of SETS: social aspects including economy, technological aspects including the infrastructures and the built-up heritage, and the environmental ones including the ecosystem service provisioning of the system.

The work here conducted focuses on a single component of vulnerability that is environment and ecosystem services. This decision is the effect of a sharp selection of a specific component of the system that is the ones linked with the ecological and environmental characteristics of the selected urban area.

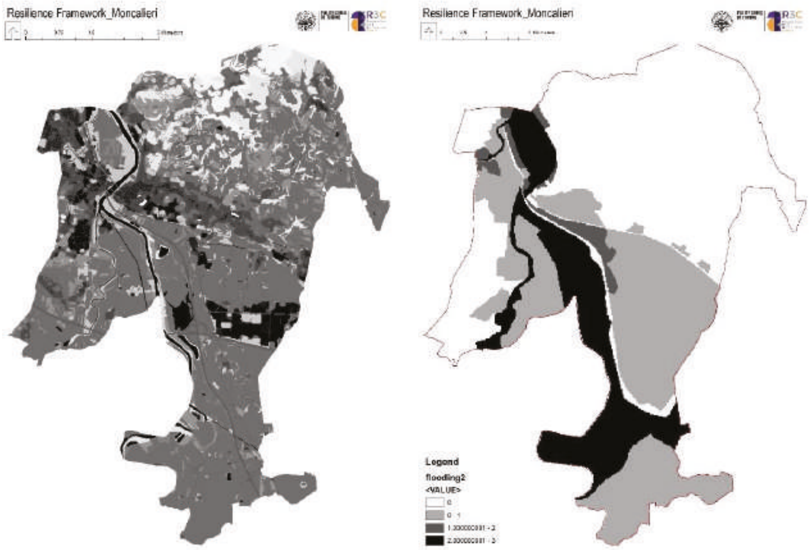
The selection of the indicators has been the output of an accurate study of the two main operational references of resilience framework. The first is the “100 Resilient Cities” program of the Rockefeller Foundation that aims to measure urban resilience working across government departments; the second is the “Smart Mature Resilience” framework that directs all available resources toward well-defined goals to ensure city resilience development and planning. Both programs provide working reports and documents with the list of indicators used to measure the resilience of the system.

At this stage, since the interaction between the components of the system are not well defined, it was decided to develop a simple and understandable methodology that links together different spatial indicators. Moreover, since the interaction between different groups of indicators is not codified by a standard algorithm, the selection of a few indicators was necessary to reach a comprehension of the framework.

As early mentioned, indicators are grouped into three categories: sensitivity (state of the system), disturbances, and shocks (pressures in the system).

Sensitivities are constituted by the spatial distribution of indicators (index or absolute values) in each part of the territory that are randomly distributed and describe the actual condition of the environment and ecosystem services.

The pressures of the system (divided into disturbances and shocks) are constituted by the areas that are affected by external agents of the environment the determined its slow or sudden modification under linear circumstances (land take) or unpredicted events (shocks such as floods or fires) (see Figure 1).



(**a**) State (**b**) Pressures

Figure 1. Visualization of the cartographic representation of spatial indicators: (**a**) State indicator covers all the system indicating existing sensitivities (municipality); (**b**) Pressure indicators are distributes where the system is subjected to hazards, in that case from light grey to black there are the areas subjected to flooding events.

The spatial assessment of vulnerability is a product of an unweighted overlay (ESRI ArcGIS) of sensitivities, disturbances, and shocks.

The presented indicators (Table 1) refers to the component of natural asset (environment and resources) [38] that includes ecosystem services monitoring, the quality of landscape, and ecological resources. Here, the most common and diffuse supporting and regulative services are mapped [39] (HQ, CS, WY) while a sharp selection of landscape ecology indicators is provided (IMP, IFI, SH). The selection includes the different threats to which these resources are affected by: NDR, SDR, and CDS for linear disturbances and IBO, ALU, and ALA to shocks. The selection of every single indicator follows the recent approach proposed by McPherson [40,41] which indicates the pathway to apply the ecosystem service mapping approach to design resilient cities. The selected indicators resulted in the available work conducted on ecosystem service mapping done by InVEST, and the available GIS vector material shared with the technical office of the municipality.

In the sections that follow the structure of each indicator is deepened.

Indicators are the output of three different kinds of elaborations:

- "R3C" elaborations, when indicators are autonomously created by the Research Group of the Responsible Risk Resilience Centre, Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino (This work is the first output of the project "Measuring Resilience" initiated in early 2018, which aims to develop an operational framework to address urban resilience. The R3C Project aims at design and operationalize an interdisciplinary research methodology to implement resilience in regional and urban systems. The project has been used to set up an in-depth discussion around the epistemological knowledge of resilience by different theoretical scientific approaches and their practical applications through the operational research carried out by urban and regional planners, social scientists, anthropologists, engineers, historicist and ecologists);
- "Existent" indicators, that are the ones that were applied to the context without any kind of elaboration (despite clipping the pixel value in the context of analysis);
- Indicators that are the output of other mapping software, and particularly Integrated Evaluation of Ecosystem Services and their trade-off—"InVEST, ver. 3.4.4" of the Natural Capital Project.

3.1. Context of the Study

The City of Moncalieri, directly south from Turin, is part of the Metropolitan area of Turin (northwest Italy—See Figure 2). The municipality is located in the south-east axis that from the main town follows the Po river course along both the Turin-Piacenza-Brescia and Liguria directions, in line with Alessandria and Genoa. The town has a population of 57,234 inhabitants (ISTAT, 2017) and consists of about 6200 buildings (as pointed out by the BDTre Digital Topographical Database of Piedmont Region). The city has been chosen for two main reasons: the proximity respect to Turin (which is bordering Moncalieri in the north-west side) which has influenced the development of this district of the metropolitan area that is not an isolated and autonomous system but a dense conurbation of approximately 60 thousand inhabitants, and the topography of the city, which is composed by a heterogeneous hilly topography with particular flat part subject to flooding.

Moncalieri territory has a quite diverse orography and consists of a flat part that develops mainly in the southern and western sectors of the municipal boundaries, and of the Po river basin that from the City of Moncalieri enters in Turin along the Turin hill ridge [42]. The settlement system has developed transversely to the north–south axis of the river, approaching to the hill that contradistinguish the city of Turin. However, Moncalieri has also extensively expanded in the sloping northern part of the municipal territory, where settlements mainly distribute along the main streets that provide access to the Turin hill, also with high-density land uses [43]. This high accessibility and infrastructure level is precisely what determines Moncalieri peculiarity: the city is located at the entrance of the northern-Italian highway system and directly linked to the Turin beltway network. For this reason, the city has historically seen the development of large industrial areas, as the Vadò quarter, one of the largest in the metropolitan area. On the other hand, the Po River has historically represented a limit to the development of settlements. Thus, in summary, the geological, morphological, and hydrographic characteristics of Moncalieri make its municipal territory naturally susceptible to high levels of vulnerability.

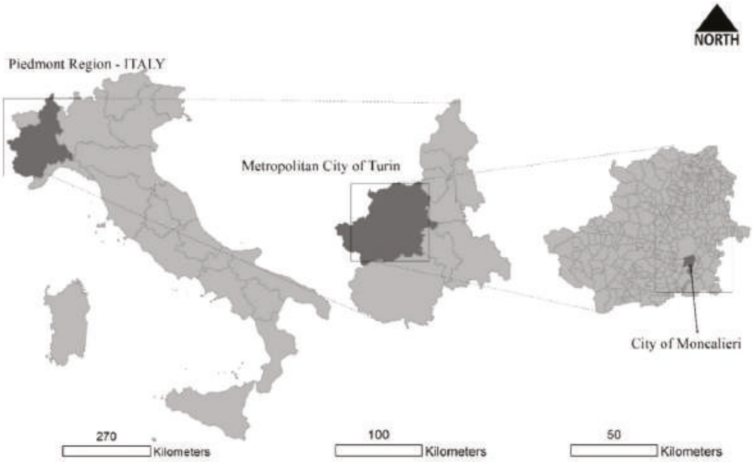


Figure 2. Location of the context of study.

The analysis on the macro categories of land use, according to the regional digital topographic database of 2018 (see Table 2), indicates that 34% of the territory consists of the anthropic system (including urban green spaces and urban free spaces), 39% comprises agricultural land, while the woodland occupies 14% of the territory. A remaining part of extra-urban green areas covers the 4% of the territory; the infrastructure system occupies the 6% while bodies of water represent the remaining 3%. The anthropic system, although not representing the majority of land uses, covers a significant ecological and landscape impact. The rate of impermeable soil, calculated with the spatial interpolation of data from the high-resolution database built up area imperviousness (2012), is about 26%, but the comparison with the anthropic system (permeability index of anthropic soil), shows that approximately 78% of urban land is impermeable. This percentage expresses a remarkable critical level considering that in the stock of 1638 hectares of urban land almost the 80% consists of impermeable material and therefore it is exposed to complete soil degradation, the consequent increase in hydrogeological risk and surface run-off, depletion of ecosystem functions, and an increase of heat islands. The current urban plan (approved in 1997 and upgraded with several variations until the 2016 final version) is an instrument that has almost finished its building capacity. As the document review shows, the urban plan still has few zones that need to be completed, either through direct interventions with built-up permissions, or through new built-up expansion zones to design with new masterplans.

Table 2. Land use composition in Moncalieri

	Land Use/Cover Type	**Surface (ha)**	**Land Use Index (%)**
Land Use	Antropic	1638.87	34.48%
	Agricultural	1838.60	38.68%
	Natural and Seminatural	654.44	13.77%
	Other (green)	173.21	3.64%
	Infrastructures	294.33	6.19%
	Water	153.54	3.23%
		4752.99	100.00%
Land cover	Impermeable	1276.94	26.87%
	Permeable	3476.05	73.13%
		4752.99	100.00%

3.2. Sensitivity

As introduced earlier, sensitivities are made up of indicators that range from the landscape ecology to ecosystem services. Notably, in this work, six different indicators were selected:

- three indicators refer to the landscape ecology approach on environmental planning (IMP, IFI, and SH);
- three indicators refer to ecosystem services dimension (HQ, CS, WY);

Sensitivity here is calculated as the predisposition of environment and ecosystem services to be sensible to events due to intrinsic conditions that lead the inclination to suffer if the available resource will be destroyed. Therefore, values increase where the environment presents a good quality (thus it can be damaged by disturbances and shocks) and its ecosystemic functions are well-provisioned, too (Figure 3).

3.3. Normalization of Variables

Each indicator has been normalized in values that range from 0 to 1 and distributed in a homogeneous spatial unit of a pixel (210 sqm) using the ArcGIS Create Fishnet (Data Management Tool) of the local digital topographic database. Each indicator has been homogenized statistically and stylistically harmonized with the same range of colors form low to a high value.

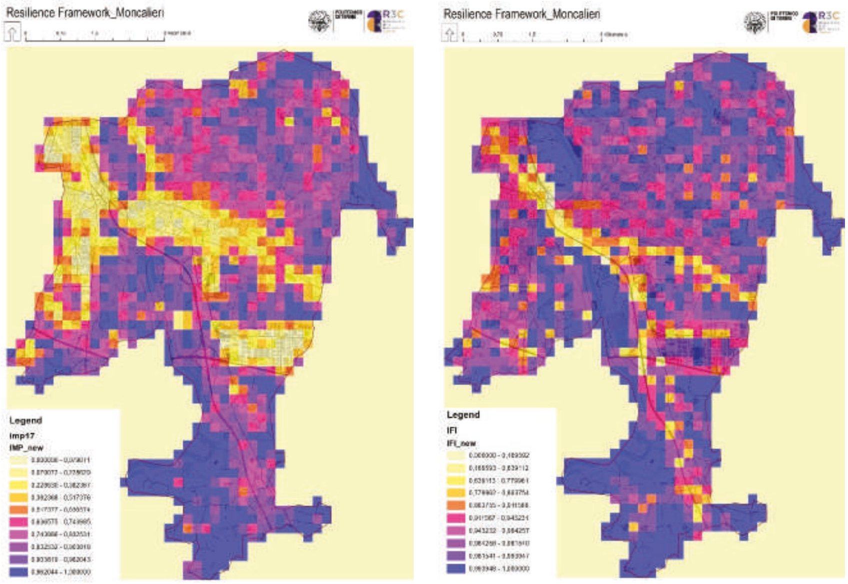
3.3.1. Environment (IMP, IFI, SH)

IMP—Impermeabilization, that is the permanent sealing of topsoil due by asphalt, concrete, and other non-permeable construction materials, is the most diffuse and degrading effect of the urbanization process [44,45]. The impermeable surface of an urban area does not correspond to its entire dimension since urban areas are not completely sealed, therefore some urban systems are more sustainable of others since the permeability of urban areas can be considered a good proxy for the environmental condition of a built-up system. For this indicator, it has been employed the national sealing map available at www.consumosuolo.isprambiente.it that is the result of Copernicus High-Resolution Layer-Imperviousness Degree (2012) data. The indicator distributes in a pixel area of 5 m the information of land cover, where pixels with 1 value indicates a sealed area, while pixels with 0 value indicates an unsealed area.

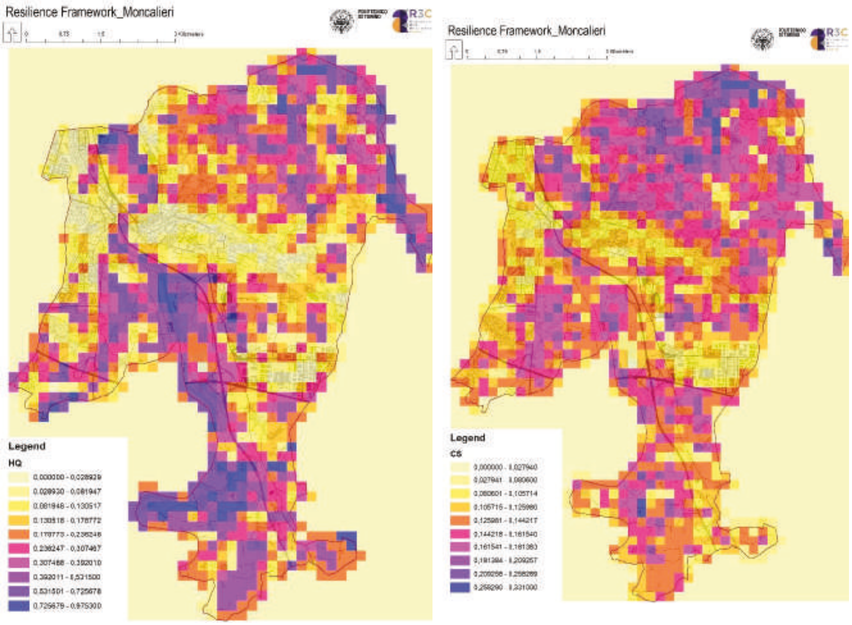
IFI—Ecological fragmentation is an important indicator of the healthy condition of the ecological system since the isolation and the creation of patches into the ecological mosaic is one of the prominent threats for the ecological processes that regulate the environment [46]. IFI has been conceived, assuming that there is a spatial well-detailed knowledge of the network system that cuts the landscape continuity interrupting or degrading the potential connectivity. The fragmentation caused by the road network can be weighted according to the magnitude of the road system, generating a spatial index that displays the effective fragmentation of the ecomosaic.

Sensitivity

IMP IFI



HQ CS



WY SH

Figure 3. *Cont.*

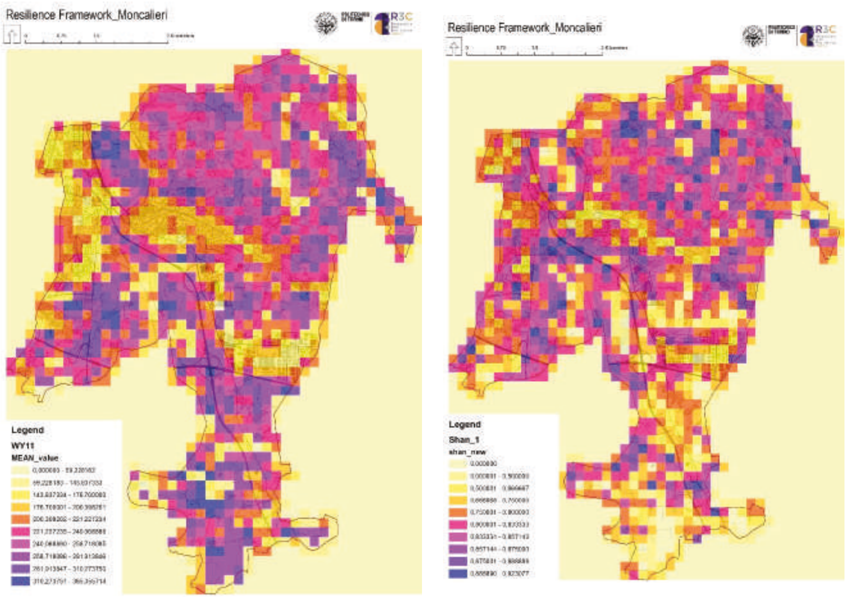


Figure 3. Spatial per-pixel representation of each indicator of sensitivities.

IFI has been calculated as follows

$$\text{IFI} = \frac{\sum(L_i \times O_i)}{AU} \quad (1)$$

where

L_i = length of the infrastructure).

O_i = coefficient of ecosystemic occlusion according to road ranking.

AU = surface unit (pixel surface 210 sqm).

The coefficient O_i has been set according with some national references in the field, giving higher weights to highways and motorways and lower values to local streets:

This coefficient allows to obtain the weighted occlusion of infrastructures.

O_1 = 1 Highways, motorways, and railways

O_2 = 0.7 national and regional streets

O_3 = 0.5 urban streets

O_4 = 0.3 local streets

This indicator has been autonomously created by the research group distributing the IFI value in the minimum spatial unit of a pixel and using the two layers 001156_el_str_2016, 001156_el_fer_2016 of the local digital topographic database.

SH—The landscape diversity index reflects how many different kinds of land uses there are in a minimum detected unit (pixel of 220 sqm), providing a distribution of the different components of the landscape where higher values reflect a richer heterogeneity of landscape patches in the observed unit [47,48]. This indicator is heavily used in landscape ecology to assess the species diversity or the ecological diversity in a specific area of investigation. It reflects how the landscape is composed of different patches that correspond to the land use polygons. The assumption here is that a mixed composition of the land uses that includes also anthropic areas helps to increase the quality of the landscape in general.

Land uses where analyzed using the Land Cover Piemonte of 2010, and the pixel calculation of the index has been done using the ArcGiS dissolve function (coverage tool).

3.3.2. Ecosystem Services (HQ, CS, WY)

As introduced, ES sensitivity has been evaluated using supporting and regulative ES [39,49]

HQ—The map of habitat quality has been employed as a proxy of biodiversity since high quality of habitats supports the development of all ecological functions [50].

The supporting ES of habitat quality has been produced using InVEST software. Habitat quality combines information on LULC and threats to generate maps that includes the degradations due to sources of habitat disturbances.

The model works assuming three input data:

- the spatial representation of the Land Use Land Cover distribution, that is a GIS raster map which includes the area of analysis, as well as a buffer zone that include potential threats;
- the spatial distribution of intensity of each individual threat in a GIS raster file with values between 0 and 1;
- a .csv table with threats data. This table contains all threats considered in the landscape weighting their impact;
- a .csv table of the sensitivity of LULC to threats. This table contains the specific sensitivity of each habitat to the considered threats.

Concerning the threats, they have been considered as a source of disturbance to the anthropic system, agricultural areas and road network, with a weighting factor for different kinds of streets: principal, secondary, and local.

The output of this model is a relative index (0–1) of the habitat quality in each LULC pixel. This model has been then transformed into a sensitivity map where higher sensitivities correspond to the area where habitat quality is higher and therefore most vulnerable to potential damages.

CS—The carbon sequestration is an ES related to the capacity of the soil of storing in the biomass and dead mass above and below ground to store CO_2. Ones that soil is sealed it lost its capacity to store the atmospheric carbon and therefore the storing capacity of soil influences the quantity of carbon that is present in the atmosphere. This ES has been mapped to model carbon storage and sequestration of InVEST that maps carbon storage densities to a different kind of LULC. The model maps the quantity of carbon sequestration that are produced by a csv. table of the four carbon pools: above ground, below ground, necromass, and the litter. Input data were based on the Italian National Inventory of Forests and Carbon Pools (INFC).

The output is a map where each LULC pixel contains the absolute amount of carbon stored per pixel.

WY—The water yield is an ES that refers to the water storing capacity depending on the structure and the physical structure of the ground and the aboveground vegetation. Changes of land use profoundly affect hydrological cycles affecting the evapotranspiration that is a primary function that modifies the water availability and microclimate conditions.

Moreover, the water yield is of primary importance for run-off regulation since this ES influences the capacity of the landscape to retain water from the surface, subsurface, and baseflow, determining the amount of pixel's run-off calculated as the precipitation less the fraction of the evapontranspired water.

Inputs of this model are:

- Root restricting layer depth: the land capability classification took soil depth data with a scale of representation of 150,000.
- Precipitation: data were collected from the regional department for environmental protection (ARPA Piemonte. http://www.arpa.piemonte.it/rischinaturali/tematismi/clima/confronti-storici/precipitazioni/introduzione.html)

- Plant available water content: data comes from the SPAW Model for Agricultural Field and Pond Hydrologic Simulation. To obtain the specific data required by the SPAW Model the original land capability map was integrated with additional soil texture information provided by The Regional Institute for Plant and Environment (IPLA) at a reference scale of 1:250,000.
- Average annual reference evapotranspiration: values for each watershed were collected from the regional department for the environmental protection (watershed boundary dataset) http://www.scia.isprambiente.it/Documentazione/report2006.pdf Watersheds:
- The biophysical values in the attributes table were taken from references collected in the InVEST user's guide and supervised by the National Institute for Environmental research and Protection—ISPRA.

The output used in this model is the annual average evapotranspiration per pixel in the landscape.

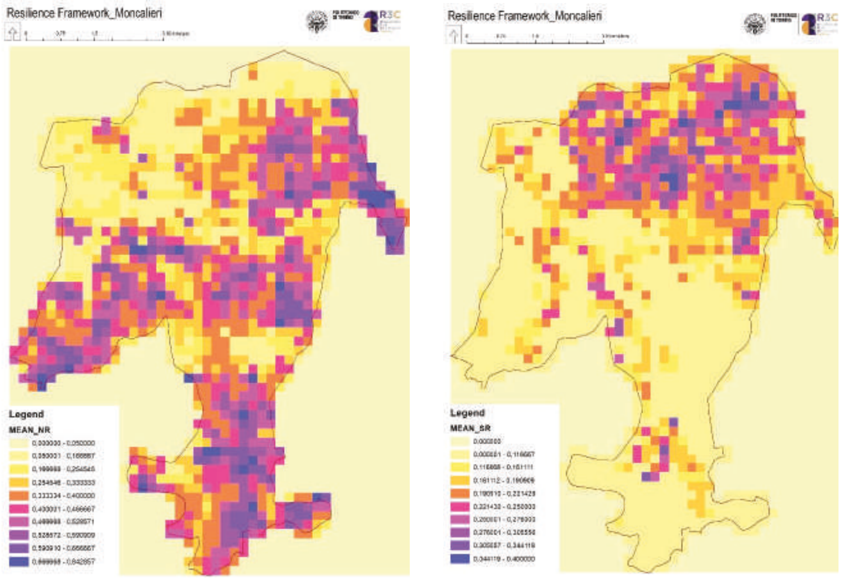
3.4. Pressures on the System: Disturbances

Disturbances are linear and predictable trends that affects the system gradually altering its condition. Therefore, are areas of the system that are affected by slow modification due to particular processes that affect sensitivities (Figure 4). As to what concerns the component of Environment and Ecosystem Services, the selected disturbances are composed by three indicators:

- Two indicators depend on soil ES: nutrient contamination—NDR that is an output of the model nutrient retention of InVEST; and the Erosion—SDR, that is an output of the model sediment retention of InVEST;
- One indicator refers to the landscape transformation due by the process of urbanization: the land take indicator—CDS represents the areas where the process of urbanization has been concentrated in the last years.

Disturbances

NDR SDR



CDS

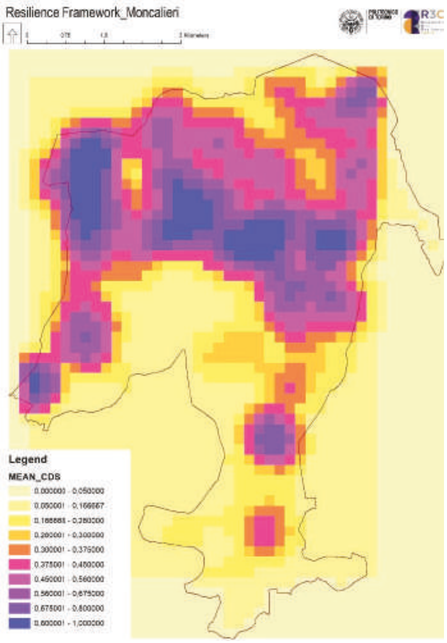


Figure 4. Spatial per-pixel representation of each indicator of disturbances.

NDR—the nutrient retention model of InVEST calculates the areas where diffuse pollutants flow into streams. The model routes the nutrients path along the environment. Mapping nutrient retention make clear the effects of anthropic activities on water quality [51].

Concerning inputs, this model shares the vast majority of inputs with the nutrient delivery model, plus the following:

- Average annual precipitation was calculated using the regional climate report of ARPA;
- Digital elevation model (DEM) is a raster file provided by Regione Piemonte by aerophoto Ice 2009–2011. The DTM covers the entire regional territory and it has a 25 sqm grid resolution.

SDR—Sediment retention model works towards the interaction of the digital elevation model and the soil characteristics computing the amount of the annual soil loss in each pixel, therefore calculating the soil loss that reaches the stream. This ES is pivotal since its account for one of the most dangerous and pervasive kinds of degradations that affect soils at different scales. This model has been used to map one of the most influent systemic pressures on the system since Moncalieri is partially built-up in the Turin Hill and has experienced in the last years some debris flows events due to intense rainfalls.

This model shares the vast majority of inputs with the nutrient delivery model. The rainfall erosivity index (R) indexes in the attributes table of the software were calculated using the biophysical values computed using the references parameters collected in the InVEST user's guide [50] and supervised by the National Institute for Environmental research and Protection—ISPRA.

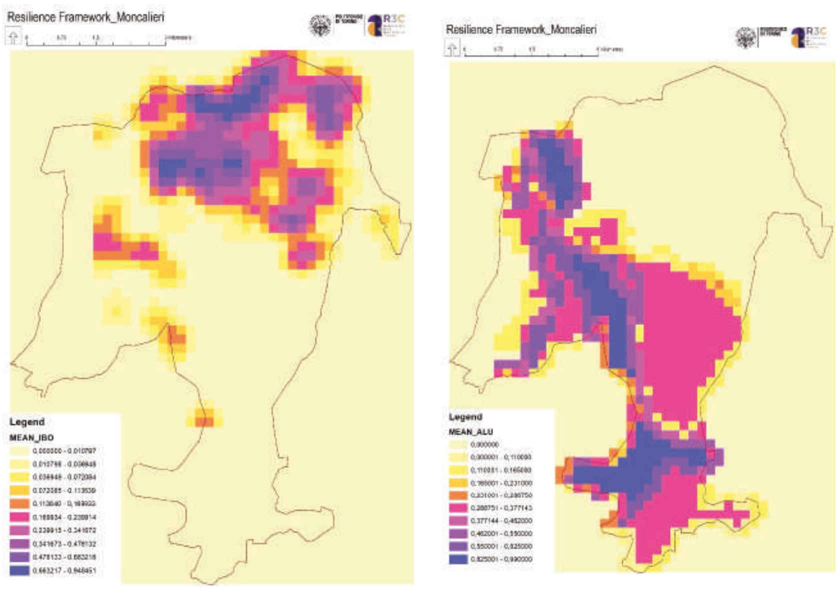
CDS—The land take indicator indicates the amount of new impermeable surfaces due to new urban areas [52,53]. This phenomenon is associated to the loss of the non-renewable resource of soil that is caused by the substitution of agricultural and natural/seminatural land to artificial land. This process generates ne expansion areas in the landscape degrading the landscape and generating several environmental consequences [54–56].

The indicator has been autonomously elaborated by the diachronic comparison of different built-up layers in the Municipality of Moncalieri. The addition of new buildings has been monitored from 1990 to 2015, each building has been transformed into a point file, and using the ArcGis kernel density function (Spatial Analyst) (Tool).

3.5. Pressures on the System: Shocks

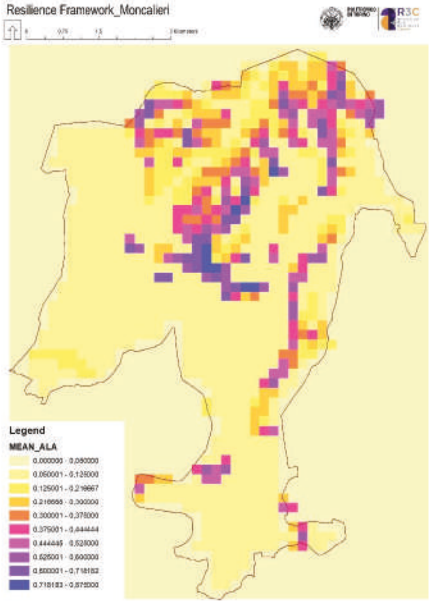
Shocks are unpredictable and dangerous events that threaten the system occasionally and with high impact for the environment, settlements, and populations. Shocks are intended as the major catastrophic events that the system has to absorb in case of adverse conditions. Shocks are unpredictable since their occurrence is viewed in a long-time period and, moreover, their effect is unpredictable too. To provide a spatial distribution of shocks, auxiliary maps of the public administration were consulted (flooded areas of 2016 and the map of fire risk taken by the civil protection plan) in order to obtain updated information (Figure 5).

Shocks



IBO

ALU



ALA

Figure 5. Spatial per-pixel representation of each indicator of shocks.

Shocks are composed by three indicators:

- An indicator refers to the risk of fire IBO;

- Two indicators ALU and ALA refer to meteo-hydrological related risks. ALU represent the spatial distribution of flooded areas in case of a catastrophic event while ALA represents the areas that are threatened by high run-off processes and therefore are affected by debris flows.

IBO—The spatial distribution of fires risk has been obtained by an autonomous elaboration that has been conducted using the methodological requirements of the Italian Civil Protection that is the selection of areas where buildings are less than 10 m from a forested area. This condition is evaluated as potentially dangerous in case of fire since these buildings are highly exposed to flames. The indicator has been created by ArcGIS Kernel Density (Spatial Analyst Tool) with a degree of risk that increases as much as there is a concentration of exposed buildings.

ALU—This indicator has been calculated using the ancillary map of the flooded areas of the event that occurred in 2016 that has been considered 'catastrophic' since the flooding overcomes for large parts the maximum exposed areas that the hydrological plan was originally considering. This event showed that the traditional single risk maps underestimate the potential effect of a natural hazard where the accumulation of causes generates a highly dangerous condition. Flooded areas were mapped by ranking the catastrophic effect of the flooding, thus the indicator maintains the scoring from 0 to 1 of the potential dangerousness in each pixel.

ALA—This indicator differs from the previous since the phenomena of intense rainfall can generate in the medium period a flood peak in the existent streams, but at the same time in the short period, the run-off along sloping areas often causes debris flows where the soil reaches the point of saturation. This is the case of hilly areas, but also the plain areas in low drainage soils that reach the saturation in case of heavy rain. This indicator has been created using the InVEST Nutrient Retention model that generates a preliminary intermediate output where each pixel of the landscape is affected by a run-off index. The upstream areas where selected and evaluated by a 0–1 indicator alongside the run-off streams.

3.6. Mapping the Vulnerability of the System

Once the sensitivities, disturbances, and shocks were mapped with the same parcel units the spatial overlay of each component has been employed to generate a final index of the overall evaluation of variables, where the vulnerability here is intended as the unweighted sum of sensitivities with the disturbances and shocks.

The map is the product of the per-pixel formula that follows

$$Vul = Sen + D + S \tag{2}$$

where

Vul = vulnerability of the system

Sen = sensitivity composed by a composite unweighted sum of IMP + IFI + HQ + CS + WY + SH

D = disturbances composed by a composite unweighted sum of NDR + SDR + CDS

S = shocks composed by a composite unweighted sum of IBO + ALU + ALA

The dark violet areas are the ones where the highly sensible pixels interact (are exposed to) linear pressures and unpredictable shocks (see Figure 4). Therefore, it is highly probable that from an environmental and ecosystem perspective, the system is subjected to disruptive effects in that parts, both in case of unpredictable natural hazards or long-time exposures to linear pressures that modify the state of the system. The probability that the environment will be threatened by climate-change-driven consequences in the violet areas is a piece of valuable information since it gives the possibility to comprehend the extent to which this system is vulnerable spatially and to which degree. This represents the first step into the experimental spatial measurement of the resilience of the system whereas the system is considered more resilient when is less vulnerable in a first attempt. In this view, resilience is the product of a combined reduction of vulnerability with and augment of adapting and coping capacity.

It is relevant to state that the Vulnerability is here produced by an unweighted overlay of indicators, meaning that there is no priority between the variables that are summed up to define the vulnerable parts of the system. We acknowledge that this is an essential limitation of this first empirical exercise, but we are opening the debate around this issue that is relevant to the final utilization of this pioneer and partial approach.

4. Discussion and Conclusions

4.1. Designing Adaptation: Where?

As demonstrated in the boxplot distribution of the composite sum of sensitivity, disturbances, and shocks (see Figure 6), values ranging from 0 to 1 (some outliers in shocks and disturbances are present due to unaccounted decimal values during normalization) displays how the average value of sensitivity is a decimal value above the disturbances and more than three decimal values above the shocks. This depends on the fact that disturbances and shock are concentrated in some parts of the municipality while sensitivities are spread in all the system, with lower clustering zones. The system, in that case, is generally sensible by itself without external factors that affect its condition. The dark violet vulnerable areas are the ones where the Vul value overcomes the 1.40 value and therefore a compresence of Sens values over 0.7 overlays D over 0.65 and S over 0.4.

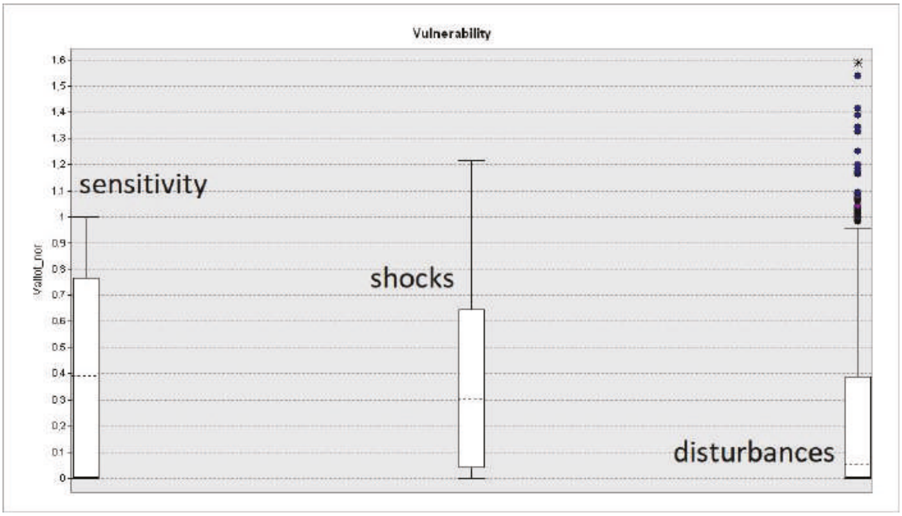


Figure 6. Boxplot of sensitivities, disturbances, and shocks.

The production of a composite overlaid map of vulnerabilities, as a product of the spatial interpolation of different indicators grouped as sensitivities, disturbances, and shocks, turned out to be significant for the following considerations and their relevance to better design the adaptation/transformation measures increasing the resilience of the system.

The distribution of dark violet areas is mainly concentrated in four priority areas (Figure 7):

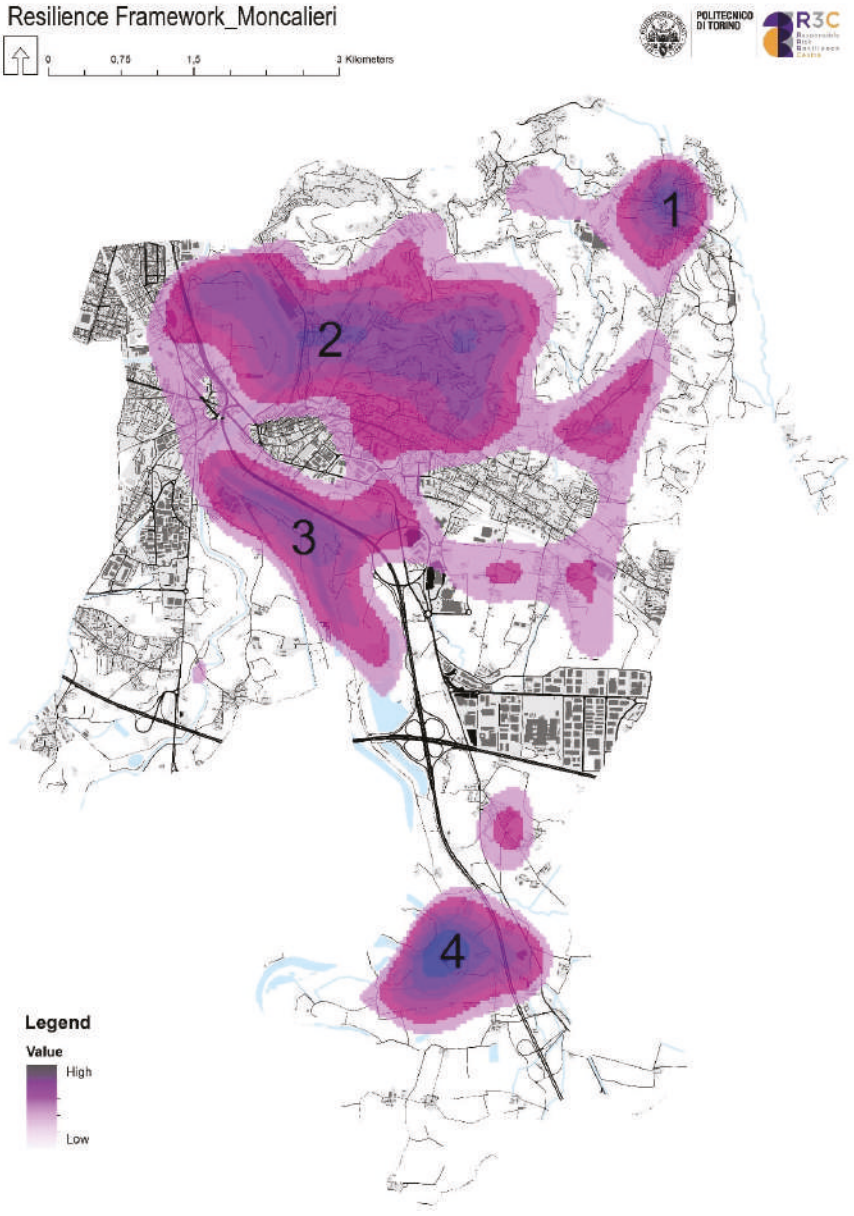


Figure 7. Vulnerable areas.

The hilly development of Revigliasco (area 1) which comprises the landscape of natural and seminatural forested areas with the disperse and fragmented settlement system that is developed along the historical track, namely "Strada della Maddalena". Here, a high vulnerability is particularly due to the probability that an event (fire) occurs destroying the rural and natural environment characterized by the presence of human settlements that are composed by detached and semi-detached houses with a high landscape and scenic quality.

The upper town development (area 2) along the panoramic routes that provides accessibility to the hilly semi-detached development that forms a continuum with the dense and highly developed ancient town center. This part of the system is characterized by high promiscuity between the natural landscape and the built-up system made up by villas and big private gardens and parks. In these areas, the development of the real-estate market for upper-class development of the city has been historically polarized and the vulnerability is characterized by the predominance of the land take disturbance over these areas;

The rural Po riverbed (areas 3 and 4) that is constrained between the A6 Highway Torino-Savona, the national ancient street that connects Torino (Nichelino) and Carignano, the railway, and the national road to Carmagnola. This part of the landscape preserves the character of a humid ecosystem only along the stripped riverbanks because it has historically subjected to a high process of urbanization and hydraulic regulation. The landscape comprises intensive seminative fields with dispersed settlements on the west side with orchards and some formerly productive sites. Here, the vulnerability is mainly due to shocks (flooding) that compromises the environmental and ecosystem integrity of the system and to highly sensitive parts of these areas that are sensitive to hydrological regimes.

The clustering analysis is a first attempt to define where specific actions to develop mitigation and compensation measure to pursue the adaptation of the system should be planned.

4.2. Designing Adaptation: What?

Resilient approaches rose to attention and became pivotal to introduce the vulnerable dimension of the system during the land use planning process. Nonetheless, they remain a weak approach if there is not an operational integration of the vast quantity of information that frames the assessment to support effective land use planning [57–59].

The above-presented spatial measurement of vulnerability of the system in a selected case-of-study area represents a first tentative to prioritize area of intervention to implement the transformation and the adaptation of the system.

The spatial measure of the vulnerability wants to overcome the analytical approaches that aim to define lists of city-performance indicators, thus becoming a tool that indicates where the system is vulnerable to potential hazards. The implication of this finding is that this measure should be implemented in the local analysis as a step towards the implementation of resilience, whereas resilience is further characterized by an additional capacity to cope with hazards by innovative governance solutions, adaptive and learning capacity, and adaptation.

The utilization of the map is crucial to define the kind (what) of interventions in urban areas that are necessary to lower the vulnerability of the system. Intervention ranges from the most commonly used 'green' nature-based solutions [60] to infrastructural 'grey' interventions. The bullet point that follows results from a first recognition of interventions categories that spans across a multitude of potential possible measures.

To what concern Moncalieri, some actions should be developed in vulnerable areas. In areas 3 and 4, preferable actions range from different measures to achieve flow regulation:

- planting green roofs or green walls to intercept rainfall;
- creating rain gardens/plaza reducing run-off;
- create underground water storage that increase the absorption capacity of urban areas;
- urban catchment forestry to retrofit sustainable urban tree cover to reduce flood risk;
- floodable parks to absorb flood peaks.

While the hill (areas 1 and 2) should pursue a de-sealing process with a rational regulation of the interconnection between natural areas and the built-up system.

- creating landscape connections with urban green space—trees, alleys, hedges, riparian vegetation;
- increase biodiversity within green areas, paying particular attention to the distance between forested areas and settlements to cope with fire risk;

- urban catchment forestry to retrofit sustainable urban tree cover to improve water supply;
- natural wastewater treatment to reduce drinking water consumption for irrigation.

These measures are just some of the solutions provided by the national guidelines to define the Adaptation to Climate Change—according to the Italian National Plan of Adaptation to Climate Change (PNCC, 2016)—that we purpose here as an operational methodology that links the assessment of vulnerability to the definition of a selected target of transformative measures. The selection mainly depends on two factors: the location of the vulnerability respect to the system and the kind of vulnerability that affects the system (see Section 4.1). Grey interventions, suggested in the plan, should be developed where technological, civil, and architectural projects are designed to retrofit, refresh, substitute, or re-develop the built-up system achieving a more efficient, sustainable, and resilient anthropic environment. Here, the National Adaptation Plan suggests implementing structural solutions in highly sealed contexts referring to the capacity of using the available technology to increase the ability of the built-up system to be more efficient in terms of energy consumption also absorbing the potential effects of common natural hazards such as flooding, heat islands, or earthquakes. Grey measures also include public interventions concerning sewage, electrical, and telecommunication systems, in order to augment the capacity of absorbing shocks providing an adequate communication system even in case of profound damages on buildings. On the other side, nature-based solutions are recommendable in peri-urban, rural, and hilly parts of the system where the greening and de-sealing are necessary actions to provide a higher regulative capacity of ecosystems to regenerate the environmental functions. Both green and grey interventions range from mitigative to long term adaptive solutions that transform the system to reach a measurable resilient condition.

5. Conclusions

The first step to achieve resilience is to reduce the vulnerability. In this study, a parcel-based analysis of the vulnerability has been spatially mapped in GIS environment using ArcGis ver.10.6 as the output of a spatial overlay interaction between many variables.

The design of a parcel-level composite index [61] introduces a significate step forward to developing urban policies aimed at incorporating the measure of vulnerability increasing the resilience of the system [62–64]. Composite indexes support the spatial development of sustainable policies, achieving a long-term benefit for people by connecting environmental values with socio-cultural and economic values [63,65,66]. Nonetheless, communicability of technical maps during the decision-making process remains a critical issue and if planners are not able to represent their information in a spatial and simplistic way [59,67–69] the utilization of the scientific assessment is weak.

This empirical study demonstrated that measuring the vulnerability of the system helped in the preliminary definition of a normative list of priorities in the urban agenda of the Public Administration of Moncalieri. The acknowledgment of the vulnerable dimension in the system provides a keen awareness that citizens are exposed to potential damages in the next years if some adaptations and transformation measures are not considered. Within the study, a first attempt to provide a scientific background in the definition of public interventions to increase the resilience of the system has been obtained. We are aware that this is a preliminary study and that the adaptation of the system includes measures of preparedness and response capacity that are not included in the list of actions here proposed. Nonetheless, we aim at integrating this study including the 'soft' measures that are the ones which are not referred to the physical transformation of the territory but depends on the innovation, governance, and self-adaptation of society to the vulnerable dimensions. Regarding this point, the first draft of action was considered to augment the resilience of the environment and ecosystem services:

- as regards the governance system, introducing local prescriptions that lead to propose natural parks and environmental protection zones in high habitat quality areas should be considered. Moreover, the re-design of the ecological network should consider much more the connections between primary ecological zones and the built-up environment. Strategic environmental assessment

for plans and projects should include the evaluation of ecosystem services and the efficiency of buildings and infrastructures introducing a monitoring system that provide an ongoing adaptation of policies and environmental strategies;
- regarding associations, fire vulnerability sheds light on the need to consider the activation of an inter-municipal consortium of forested areas that also includes active associations and citizens to promote conservation, monitoring, and emergency coordination in case of dangerous events;
- regarding the population, awareness, learning capacity, and innovation, the need to increase the perception of natural capital is an asset to develop and promote a diffuse preparation and the spread of initiatives aimed at improving the value of the territory and the needs to understand the vulnerability of the system. Teaching classes in primary schools while providing evening courses for workers and seniors are, among others, channels to promote knowledge of the territory that is fundamental to increasing the social resilience and the capacity of adaptability to dangerous events.

The experience here presented shows how to provide a first attempt to achieve the resilience of the system by increasing the knowledge of the spatial distribution of vulnerabilities. Such an approach includes the visualization of a final multilayered indicator [70–73] that is the product of a geostatistical procedure made by GIS analysis. Maps of sensitivities, disturbances, and shocks were used to overlay every single value and generate a spatial representation of vulnerabilities at parcel-level scale. The methodology has been conceived to be replicated in another context in the future since it has been structured by grouping different indicators in different components of the system. This means that, independently from the utilization of the same indicators (which depends on availability of data and the practicability of measures), the relation between sensitivities, pressures, and shocks measured in a GIS-spatial-gridded environment with an unweighted overlay procedure can produce a spatial representation of the vulnerable dimension of the system, aiding decision-making for applying resilience measures.

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Breaking the Black-Box of Regional Resilience: A Taxonomy Using a Dynamic Cumulative Shift-Share Occupational Approach

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Abstract: In the European literature on the regional and local development, the concept of resilience has progressively gained momentum, eventually overcoming that of competitiveness and posing a critical challenge for the future of territorial studies and the territorialisation of the policy discourse. In the current economic turmoil, the success of an urban and regional economy relies more and more on its capacity to react to sudden shocks in a positive and evolutionary perspective, i.e., in its resilience. Nevertheless, as a recent analysis of the employment dynamics of Italian metro-regions in the period before and after 2008 has demonstrated that the existing taxonomies may be distant from reality and hardly communicable. The paper proposes a taxonomy of regional resilience based on the consideration of the region's capacity of both improving its employment rate during the pre-crisis period and overcoming the concurrent performance of the nation. Via a shift-share analysis of the employment in Italian metro-regions, the paper investigates the contribution of the sectoral structure of the local labour market in terms of economic resilience. The result is twofold: a geography of the dynamism of the territorial systems in Italy that diverges from some "classic" interpretative frameworks; a novel taxonomic approach to regional resilience.

Keywords: regional resilience; shift-share analysis; employment dynamics; sector composition; metro-regions

1. Introduction

The paper investigates how the conceptualisation of economic resilience can affect the design of territorial research methods and the building of regional taxonomies. From a geographical and regional perspective, this aim is meaningful because, for a long time, taxonomies have proven to be useful tools to detect territorial development trends and factors [1,2]. In regional studies, the identification of recursive evidence among territories can help the achievement of several goals, such as [3]: the up-scaling of assumptions and findings, the stratifying of samples of population and resources, the discovery of a selection of representative sites, and the framing of policies and reporting. Thus, taxonomic practices are an essential part of the work of academics [4].

Regarding the taxonomies of European regions, a preliminary overview of the literature is enough to realise how numerous they are [3]. They are recurrent above all in the studies that investigate the territorial patterns of competitiveness. For instance, in the realm of the innovation literature, regional scientists [5–7] and international territorial organisations such as the Organisation for Economic Co-operation and Development (OECD) [8] and the European Commission [9] contributed significantly to the construction of regional taxonomies. While, in the context of a more holistic approach to regional competitiveness [10–12], emblematic taxonomies have been produced within the European Observation Network for Territorial Development and Cohesion (ESPON) initiative [13,14] with reference to different types of territorial attributes [3].

The aim of all these taxonomies is to divide the European territory into “convenient” groups of regions, connoted by homogeneity with respect to a given property (e.g., richness, competitiveness, innovation etc.). Some of them have also inspired important funding decisions by the public policies, becoming familiar to the broad society. The European Union (EU) Structural Funds, for instance, since the 1988 reform, used to classify the European regions of levels NUTS II and NUTS III according to their eligibility to a selection of priority objectives. More specifically, in the funding periods 1989–1993 and 1994–1999, four of the seven Structural Funds’ objectives were reserved to selected regions: Objective 1, targeted to economic adaptation in regions lagging behind in economic development, was eligible only by NUTS II level regions with GDP per capita in PPP (purchasing power parity) below 75% of the Community average; Objective 2, dedicated to assist regions suffering from industrial restructuring, was reserved to NUTS III level (and smaller) regions with: unemployment rate above the Community average, a percentage share of Industry employment higher than the Community average, and a decline in the employment level of the Industry sector; Objective 5b, aimed at assisting rural regions with development problems, was addressed to the units smaller than NUTS III level with a low GDP per capita and two of the following statuses: high share of agricultural employment, low level of agricultural income, low population density and/or significant depopulation trend; Objective 6 concerned regions with very low population density of eight inhabitants per km^2 or less.

From a policy point of view, successful taxonomies are robust in method and broad in coverage, but also simple in conception and cross-analysis with other variables [3]. Ideally, the taxonomic exercise produces typologies that are neither too similar, nor conflicting. It mixes the rigorousness of the classification process with the clarity and transparency of the objectives and the capacity to substantiate the results of the analysis with the “experiential world” [1].

Often, however, the methods implemented to construct the taxonomies tend to be too sophisticated and biased by the context of the analysis and the availability of data [4]. It also happens in the studies on regional resilience, with some peculiarities.

In the resilience discourse, the need for a flexible adjustment to an increased number of emerging global challenges replaces that “survival of the strongest” approach that has characterised a large portion of the regional and urban discourse [15] since the first decades of the 20th century.

After the 2008 global economic crisis (and, more recently, as a consequence of the COVID-19 emergency), the world economy has profoundly changed. In a period characterised by frequent and dramatic turmoil, the success of the regional economy does not rely any longer on the search for techno-economic innovation, but also on the development of a mixed capacity of resistance, adaptation and creative exploitation of changes. The most important task has become the generation of a “fit-for-purpose” reaction, based on what Toynbee defined a “challenge and response” strategy [16]. Yet, this is also a definition of resilience. So, the concept of resilience increasingly accompanies that of competitiveness in the analysis of territorial development [17].

Secondly, as a consequence of the diffusion of an evolutionary approach to the conceptualisation of economic resilience [18–21], procedures of dynamic decomposition of the regional economic performance started gaining more and more attention [22,23]. In this conceptualisation, shocks represent acute modifications in the factors that regulate the functioning of the regional economic system, which are deeply contextualised in time and space. The idea is that shocks intertwine with the unfolding of broader processes of change and cause long-run adjustments [24] readable via the concepts of resilience and its corollaries (sensitivity, recoverability, resistance, antifragility). Table 1 identifies five renowned types of regions’ reaction to shocks suggested by the literature, which have proved useful to classify the regional economies.

Table 1. Some main concepts of regional resilience and other forms of reaction to shocks.

References	Typologies	Approach
Martin (2012) [22]	Resistant, Recovered, Re-orientated, Renewed	Evolutionary
Sensier et al. (2016) [25]	Resistant, Recovered, Not recovered in upturn, Not recovered not in upturn	Evolutionary
Martin et al. (2016) [23]	Most resilient (resistant and recovering), Least resilient (not resistant nor recovering)	Evolutionary
Blečić, Cecchini (2020) [26]	Resistant, Resilient, Antifragile	Planning
Equihua et al. (2020) [27]	Integer, Resilient, Antifragile	Ecosystemic

Source: authors' elaboration.

The concepts listed in the first row of Table 1 derive from Martin's article "Regional economic resilience, hysteresis and recessionary shocks" [22]. Martin introduced the distinction between "resistance" (i.e., the capacity to contrast the adverse effects of the shock), "recovery" (i.e., the bouncing back from the immediate effects of the shock), "re-orientation" (i.e., region's structural realignment or adaptation) and "renewal" (i.e., when the growth path resumes to a pre-shock level). The second row refers to the results of a detailed analysis by Sensier et al., developed for the ESPON project "Economic Crisis: Resilience of Regions". According to these authors, some years after the occurrence of a crisis, the reaction of the regional economy can be of four types [25]: "resistant" if the region keeps on growing despite the shock; "recovered" if it overcomes rapidly from the effects of an initial contraction; "not recovered, in upturn", if the contraction produced by the crisis has already got to the trough and the region has started to grow again; "not recovered, downturn", if the trough still has to be reached. Similarly, the third taxonomy reported in Table 1, developed by Martin et al. [23], defines different typologies of regions based on the stage of the economic cycle experienced after the crisis (see Figure 1).

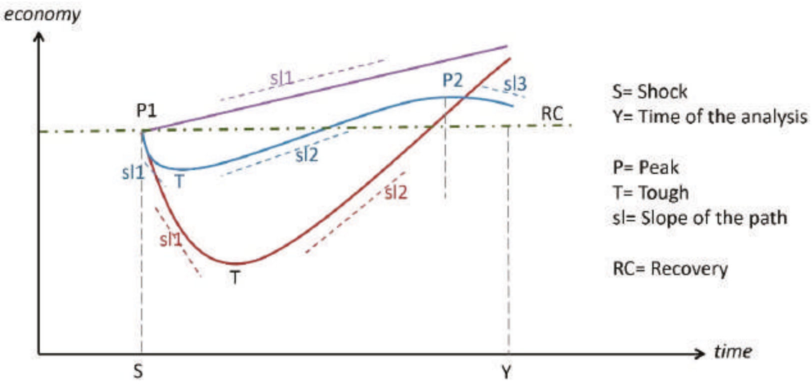


Figure 1. Stylised economic cycles after a shock. Source: authors' elaboration from Sensier et al. [25] p. 137.

The two taxonomies reported at the bottom of Table 1 report the region's reactiveness within a hierarchical discourse. Blečić and Cecchini [26], in particular, define "resilience" as a complement of a more comprehensive condition of regional recovery called "antifragility". The ability to withstand the adverse events determined by the shock, without being damaged disproportionately, is instead considered a complement of the resilience, described as "robustness". The study by Equihua et al. [28] too deals with the category of antifragility, but in reason of its being a substitute (not an attribute) of robustness and resilience. In the authors' words: "while resilient/robust systems are merely perturbation-resistant, antifragile structures not only withstand stress but also benefit from it".

As we can see, the taxonomies underlying an evolutionary approach pay specific attention to the capacity of regions to start growing again and recover past economic performance. The concepts concerning a planning and ecosystemic approach, instead, describe the status of the region at the time of the analysis. All the cases listed in Table 1, however, show a common trait in evaluating regional resilience in absolute terms, i.e., without considering what occurs out of the borders of the region. In this paper, we adhere to an evolutionary perspective, recognising, however, more attention to the way the regions perform with respect to the other regions. The amplitude and the duration of the recovery are not significant per se, but to the extent that they overcome in size and pace the average/aggregate recovery. How the crisis impacts on the national economy, in particular, is recognised to have a dramatic influence on the resilience, resistance or antifragility of regions.

Consistent with this, we differentiate the concept of resilience according to an absolute and relative dimension. Absolute resilience refers to the capacity of the region to safeguard its initial economic performance, i.e., the performance it had before the crisis. Relative resilience compares the type and intensity of the reaction of the region to the reaction of the nation. In a perspective of absolute resilience, the most crucial information is the direction and slope of the growth path (see Figure 1). The scholars that follow this approach thus tend to have little consideration for resistance and sensitivity as dimensions of resilience [25,29]. Conversely, in a perspective of relative resilience, which also considers the sign of the national trend before and after the crisis, regional resilience results in the capacity of either avoiding sub-optimal growth rates or starting a path of growth better than the national one [28].

Following Martin et al. [23], our impression is that the reactions to the 2008 crisis are so complex and diverse that a shift away is required from territorial typologies uniquely based on the criteria under and over the national threshold. These typologies can appreciate the contribution of the structural and local conditions just loosely [30–34]. For this task, there is the need for a different taxonomy, capable of interpreting the different economic cycles that follow the shock (see Figure 1) in the light of the possible combinations of local conditions, ultimately highlighting different territorial patterns of resilience. It is mostly on these patterns that regional policies can act to create and reinforce regional resilience processes [35]; yet, their identification remains a controversial and challenging task, especially with respect to the already existing territorial typologies and the perceived state of the art of the relations among regions.

The rationale of the paper refers to this open issue. It aims at building an easy-to-use methodology of regional analysis, based on the concept of resilience and coherent with the complexity [36] and the actual dynamism of territories [30].

Our study contributes to this end by proposing a novel taxonomy based on an original methodology in which the different territorial patterns of resilience emerge from the consideration of the regional economic performance compared with the national one, as well as the overall capacity of the region to maintain the employment levels, and the sectoral composition of the regional economy. For some authors, sectors have proven to play an essential role in influencing the different sensitivity levels demonstrated by countries and regions of the world concerning the global economic crisis of 2008 [29,37]; i.e., they contribute to the moulding of different territorial patterns of resilience [32,38–40].

The paper aims to construct a taxonomy of the regional patterns of economic resilience and to empirically identify them regarding the response of Italian metro-regions to the 2008 crisis.

Section 2 describes the data and methodology of the analysis. Section 3 illustrates the proposed taxonomies of resilience to the crisis. Section 4 completes the discussion with the case of Italian metro-regions and develops the concluding remarks.

2. Materials and Methods

2.1. A Three-Step Taxonomic Approach

In line with evolutionary theories, regional resilience is considered here as a continuous process of self-adjustment through feedback and learning mechanisms, which do not allow the achievement of a stable equilibrium condition [18,19,41–45].

The first methodological consequence of this approach is the necessity of a long-term perspective. According to Boschma [20], this is essential to reconstruct the region's ability to reconfigure its industrial, technological and institutional structure. However, there is no agreement on the physiological duration of the recovery of a regional economy. According to Hill, four years are enough for the regional self-organising response in order to emerge [21]. Here, we prefer to consider a larger timespan, consisting of the eight years before and after the starting of the crisis in 2008.

The second methodological consequence concerns the spatial scale of analysis. Resilience studies are conducted at almost all the territorial units. Here, we have assumed the metro-regional scale of analysis to be as in the literature; it has proven to be highly functional to discern development gaps among and within the European territories, measured using the employment variable [30,35,46]. The third and last methodological consequence regards the influence of local conditions on the region's ability to create autonomous responses to shocks [47]. Evolutionary theories underline the role played by place and context in creating a specific system of cultural, social and institutional contingencies, which limit the options of regional development within a range of possibilities not too far from the initial trajectory [20]. This condition of path-dependency explains why, in the face of the shock, some economies renew themselves, while others decline [48]. A path-dependent approach, claiming for considering the influence that the sector composition of the economy exerts on regional resilience, has thus become customary in the literature [18,23,25,38,49]. Following these examples, the paper identifies in the dynamic cumulative calculation of the shift-share effects on employment the best technique to distinguish (and quantify) the contribution given by the regional sectors, and by the regional competitive advantage, to the deviation of the regional growth path from the national one. See Lahr and Ferreira [50] for a discussion of the potentialities of shift-share. The methodology proposed here uses the annual employment growth rate as the basic variable to measure regional resilience and entails three complementary steps:

- The calculation of the regions' trends in employment before and after the crisis, and in comparison with the national one;
- The classification of the regions according to six territorial typologies of resilience that reflect: whether the employment rates in the pre-crisis and post-crisis periods were over or below the national ones; whether the number of employees increased or not after 2008;
- The quantification of the influence of the sectoral distribution of employment, via a dynamic formulation of the shift-share methodology.

2.2. The First Step: Using Regional Trends and Occupational Capacity to Propose a New Taxonomy

The first phase, inspired by the sensitivity index proposed by Martin [22,24,51], estimates the regional trends in employment, both before and after the crisis, and compares them to the national trend. In particular, we calculated the trends with the expression:

$$(E_{ir}{}^{t_{0+h}} - E_{ir}{}^{t_0})/E_{ir}{}^{t_0} \tag{1}$$

where $E_{ir}{}^{t_0}$ indicates the employment of sector i and region r and t_0 and t_{0+h} are the initial and final year of the chosen interval of time.

Martin's sensitivity index is calculated as a ratio between percentage variation in employment in a region and the respective variation in the country as a whole, as expressed by the following expression:

$$\beta_r = (\Delta E_r/E_r)/(\Delta E_r/E_r) \quad (2)$$

where $\Delta E_r/E_r$ is the percentage variation in employment of region r and β is the "sensitivity index". Differently, in our model, the employment trends before and after the crisis are plotted on a Cartesian graph: period 2000–2008 on the x-axis; period 2008–2016 on the y-axis. Since the focus is on relative economic performance of regions, i.e., their performing either better or worse than the nation in terms of employees growth, the origin of the graph, where the axes x and y intersect, is not placed on (0, 0), but corresponds to the national values.

To capture the information of the yearly variation of the regional employment, which does not emerge from the calculation of the average trend, two more metrics are introduced, called *absolute occupational capacity* and *relative occupational capacity*. As explained further in Appendix B, from a mathematical point of view, the absolute occupational capacity for the period between year t_0 and t_{0+h} represents the discrete version of the integral of the cumulative sum defined in Equation (5). The *absolute* occupational capacity thus sums, for each year of the time interval, the difference of employees with respect to year t_0. To facilitate the comparison between regions, we expressed this new metric in percentage terms, dividing it by ${E_{ir}}^{t_0}$ (the number of the employees at year t_0).

The relative occupational capacity of a region is calculated as the difference between its absolute occupational capacity and the occupational capacity of the nation.

The regional relative occupational capacities of metro-regions, for the entire period 2000–2016, are reported on the Cartesian graph (see Section 3.1) as circles of different magnitudes and colours.

2.3. The Second Step: A New Taxonomy of Regional Response to the Crisis

As the second phase of our study, we have developed a methodology based on the Cartesian diagram built in the first step. The schemes in Figure 2 exemplify the criteria adopted in the setting up of the taxonomic methodology. From a graphic point of view, the deviation from the y-axis registers the distance of the regional growth rate from the national one in the post-crisis period.

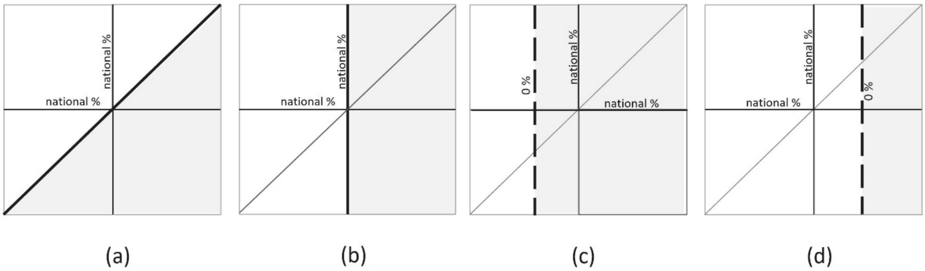


Figure 2. The setting up of the taxonomic methodology. In grey are the sectors meeting the conditions: (**a**) regional post-crisis rates above the regional pre-crisis ones; (**b**) regional post-crisis rates above the national post-crisis ones; (**c**) positive post-crisis regional rates, in a context of positive national rate; (**d**) positive post-crisis regional rates in a context of a negative national rate. Axes x and y report the regional trends in employment in the post- and pre-crisis periods, respectively, while the dashed line represents the value of zero growth in the post-crisis period. The horizontal dashed line, indicating the value of zero growth in the pre-crisis period, is not represented in the graphs, as it is not utilised for the construction of the taxonomy.

In order to distinguish different territorial typologies of resilience, we consider the following conditions:

(1) The region has improved its relative performance (calculated as trends in employment) in the post-crisis period. This condition corresponds to the portion of the graph on the right of the main diagonal (see Figure 2a);
(2) The region has performed better than the nation in the post-crisis period. This condition corresponds to the portion of the graph on the right of the y-axis (see Figure 2b);
(3) The region has registered in the post-crisis period a positive variation of its employment levels (growth). This condition corresponds to the portion of the graph on the right of the dashed line representing the value of zero growth in the post-crisis period. This line can occupy a different position in the Cartesian scheme according to the fact that, in the same period, the nation has gained or lost employment (see the dashed line in Figure 2c,d, respectively).

The joint consideration of the first two criteria allows for the identification of six types of response to the crisis, graphically corresponding to the six areas identified in Figure 3:

- The first type (1) corresponds to the regions characterised by solid economies, fuelled by employment rates that are higher than the national one, both in the pre-crisis and in the post-crisis period, and that improve their performance in the period 2008–2016.
- The second type (2) identifies the regions whose employment rates are higher than the nation in both of the considered periods, although resized in the passage to the post-crisis period.
- The third type (3) contains regions characterised by growth rates that are worse than the national one in the pre-crisis period and better in the post-crisis one. These regions have also improved their performance in the post-crisis period, eventually emerging for their capacity to react to the crisis proactively.
- The fourth type (4) corresponds to the top left sector of the graph. The regions of this group are fragile and vulnerable as they failed in maintaining the comparative advantage, they held in the pre-crisis period in terms of employment dynamism. In the period 2008–2016, their occupational capacity decreased to a level lower than the national one.
- The fifth type (5) corresponds to the portion of the bottom left sector, right of the diagonal. The regions in this area are characterised by weak economies, with employment trends lower than the national average both in the pre-crisis and in the post-crisis period. Nevertheless, their employment trends improved after 2008, signalling a certain capacity of reaction.
- The sixth type (6) embraces the regions that fall in the bottom left sector, left of the diagonal. This area experienced the worst situation of all, i.e., employment rates that are always below the national average and resize in the passage to the post-crisis period.

However, the identification of these six types of response to the crisis is not the final stage of our taxonomy. In order to take into account the complete information available, also the third criterion (shown in Figure 2c,d) has to be considered. The fulfilment of all the three criteria is obtained by the superposition of the six types of response to the crisis shown in Figure 3 with the schemes of Figure 2c (if the nation has gained employment in the post-crisis period) and Figure 2d (if the nation has lost employment in the post-crisis period). The results of such a superposition lead to the identification of the taxonomies of regional resilience shown in Figure 4. The former of the two graphs in the figure refers to the hypothesis that the variation of the national employment in 2008–2016 is positive; the latter to the case it is negative variation. To the best of our knowledge, these schemes provide a novel, practical, and easy to reproduce tool for the identification of the resilient regions.

We outline that the use of this third additional condition allows one to depict the territorial reactions to the crisis better. More specifically, the regions that stand on the right of both the y-axis and the dashed line emerge as endowed with an additional attribute, that, following Martin et al. [23], can be defined as *resistance*: the property of a region of maintaining positive growth rates of the economic variables, despite the crisis.

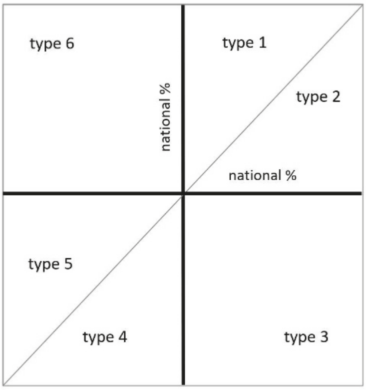
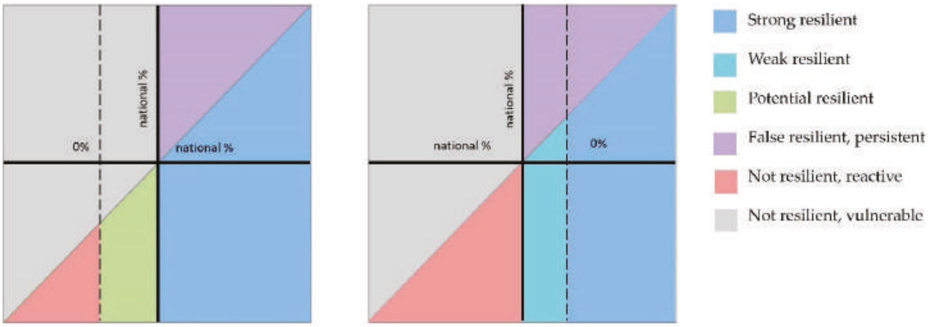


Figure 3. The six types of the regional response to the crisis that derive from the joint use of conditions 1 and 2 (see the beginning of Section 2.3). Axes x and y report the regional trends in employment in the post- and pre-crisis periods, respectively.



(a) (b)

Figure 4. The taxonomy identifies the typologies of regional resilience in cases where the variation of the national employment levels in the post-crisis period is either positive (**a**) or negative (**b**). Axes x and y report the national rates in the post- and pre-crisis periods, respectively, while the dashed line represents the value of zero growth in the post-crisis period. As mentioned regarding Figure 2, the horizontal dashed line, indicating the value of zero growth in the pre-crisis period, is not represented as it is not utilised for the construction of the taxonomy.

As a final result, the proposed taxonomy identifies six different typologies of a regional response to the crisis (see Figure 4a,b):

- *Strong resilient*. These regions present growth rates higher than the national ones, both in the pre-crisis and in the post-crisis periods. In addition, they register an improvement in absolute terms of the occupational performance in the post-crisis period, which can be evidence of reaction. Finally, their economy shows clear features of resistance, as demonstrated by the fact that the growth rate in the post-crisis period is positive in sign.
- *Weak resilient*. These regions have growth rates higher than the national ones in the pre-crisis period as well as in the post-crisis one, and they register in the post-crisis improvement of their performance in absolute terms, which can be considered evidence of dynamism/reaction capacity. However, concerning the strong resilient, these regions present a negative growth rate of the occupational performance, so as they are defined as weak resilient.

- *Potential resilient*. These regions improve in the post-crisis period their performance in absolute terms, which can be a clue of dynamism, and they can also rely on a good resistance to the crisis that allows them to maintain positive growth rates. Nevertheless, in the post-crisis period, their performance is negative and below the national one, so they cannot be defined as fully resilient, but just as potentially resilient.
- *False resilient, persistent*. These regions are characterised by economic resistance. They register positive relative performance in both the pre-crisis and the post-crisis period (since located in the upper-right sector), and their growth rates are always higher than the national average (since located to the right of the vertical dashed line). Nevertheless, the occurrence of declining performances in time (since located to the left of the diagonal) suggests a condition of poor reaction.
- *Not resilient, reactive*. What characterises these regions is the fact that, despite being economically fragile (growth rates are negative and lower than the national ones in all the considered periods), they are located to the right of the diagonal, which means they had a positive reaction to the crisis.
- *Not resilient, vulnerable*. In this sector, regions do not meet any of the criteria of resilience: both in the pre-crisis and in the post-crisis periods, they present growth rates worse than the national ones, and worsen their occupational performance after 2008; therefore, they are considered not resilient in a vulnerable way.

2.4. The Third Step: The Quantification of the Sectoral Influence on Resilience

The third phase of the study aimed at investigating why the regions faced the 2008 economic crisis differently. In this phase, we analysed the contribution of the different economic sectors to the emergence of a specific condition of regional resilience or fragility. The method we adopted is a dynamic formulation of the well-known shift-share methodology [52–54] that allows one to describe the economic behaviour of a sample of local systems (in this study the metro-regions defined by Eurostat), comparing them to the national dynamic.

Considering the variation in time of a given economic variable (the employment), the dynamic and cumulative equation of the shift-share decomposes it into some partial effects. Applied separately for the years before and after the onset of a shock, it provides a substantial help for the detections of similar territorial patterns of reaction, based on the observed recurrences and similarities.

In our study, the dynamic-cumulative method described and already used in Bagliani et al., 2020 [30,55], for the analysis of the competitiveness of Italian metro-regions, is proposed in order to build an innovative taxonomy based on the concept of resilience. Our methodology originates from the Esteban-Marquillas formulation of the shift-share [53], that, considering a given time period between year t_0 and t_{0+h}, splits the variation of occupation E into four different effects, according to the equation:

$$\Delta E_{ir}{}^{t_0} = E_{ir}{}^{t_{0+h}} - E_{ir}{}^{t_0} = NGE_{ir}{}^{t_0} + IME_{ir}{}^{t_0} + CSE_{ir}{}^{t_0} + AE_{ir}{}^{t_0} \tag{3}$$

where i indicates the economic sector, and r the region. The effects are defined by the following expressions:

$$\begin{aligned} NGE_{ir}{}^{t_0} &= E^*_{ir}{}^{t_0}\, g_{iN}{}^{t_0} \\ IME_{ir}{}^{t_0} &= (E_{ir}{}^{t_0} - E^*_{ir}{}^{t_0}) g_{iN}{}^{t_0} \\ CSE_{ir}{}^{t_0} &= E^*_{ir}{}^{t_0}\, (g_{ir}{}^{t_0} - g_{iN}{}^{t_0}) \\ AE_{ir}{}^{t_0} &= (E_{ir}{}^{t_0} - E^*_{ir}{}^{t_0})\, (g_{ir}{}^{t_0} - g_{iN}{}^{t_0}) \end{aligned} \tag{4}$$

where the subscript N indicates the national value and:

$E^*_{ir}{}^{t_0} = (E_r{}^{t_0})(E_{iN}{}^{t_0}/E_N{}^{t_0})$ designates homothetic employment, i.e., the number of employees that region r would register in sector i if it had the same national sector composition;
$g_{iN}{}^{t_0} = (E_{iN}{}^{t_{0+h}} - E_{iN}{}^{t_0})/E_{iN}{}^{t_0}$ indicates the growth rate of sector i at the national level, in the period between year t_0 and year t_{0+h};

$g_{ir}{}^{t_0} = (E_{ir}{}^{t_{0+h}} - E_{ir}{}^{t_0})/E_{ir}{}^{t_0}$ describes the growth rate of sector i for region r in the period between year t_0 and year t_{0+h};
$E_r{}^{t_0} = \Sigma_i\, E_{ir}{}^{t_0}$ and $E_N{}^{t_0} = \Sigma_i\, E_{iN}{}^{t_0}$, respectively, indicate the total number of employees in region r and in the nation.

Consistent with the established use, we identify the four effects that follow [52–54]:

- The *National Growth Effect* (*NGE*) quantifies the growth that the region would have registered if it had the same national sectoral composition and grew at the average national rates. It represents the term that allows the comparison of the dynamics observed by the region with the national average;
- The *Industry Mix Effect* (*IME*) indicates the contribution of the sectoral composition of the region compared to the national one. It estimates whether the region is specialised in sectors that, on a national scale, are experiencing a phase of growth or crisis;
- The *Competitive Share Effect* (*CSE*) measures the different capacity of regional sectors to create employment compared to that of the same sector at the national level;
- The *Allocative Effect* (*AE*) indicates the competitive efficiency of national sectors, that is, whether regional specialisation is more distributed in sectors that are more or less efficient than the national average in creating new jobs.

To allow a more detailed examination of the temporal variation of the four effects, we used the dynamic-cumulative formulation of the shift-share, proposed and discussed in Bagliani et al. [30]. Considering the above-mentioned interval of h years between t_0 and t_{0+h}, we calculate, for each year k included in the interval, the quantity $CS_{ir}{}^{t_0 - t_{0+k}}$ representing the *cumulative sum* from t_0 to t_{0+k}, of the annual shift-share effects obtained by Equation (3). The corresponding formula is:

$$CS_{ir}{}^{t_0 - t_{0+k}} = \Sigma_m\, \Delta E_{ir}{}^{m} = \Sigma_m\, (E_{ir}{}^{m+1} - E_{ir}{}^{m}) = \Sigma_m\, NGE_{ir}{}^{m} + \Sigma_m\, IME_{ir}{}^{m} + \Sigma_m\, CSE_{ir}{}^{m} + \Sigma_m\, AE_{ir}{}^{m} \quad (5)$$

where k can assume values between 1 and h and indicates in which year, after t_0, the sum stops, while m varies between t_0 and t_{0+k}. This cumulative sum accounts for the total amount of employees added or lost during the time interval between t_0 and t_{0+k}, with respect to year t_0 (see also Appendix B). Thanks to this methodology, it is possible to analyse the development over time of the shift-share effects and not just the sum over the whole interval, as the original shift-share formulation does [53].

Again, in order to make the comparisons between regions easier and more meaningful, we express the cumulative sum in percentage values dividing Equation (5) by $E_{ir}{}^{t0}$. Percentage cumulative sum is used to assess, in Sections 3.2–3.5 the sectoral influence on resilience.

The number of sectors in the shift-share analysis is not a priori determined. Martin et al. [23], for instance, run a fine-tuned 25-sector disaggregation. Artige and van Neuss [56] in their analysis of the Belgian manufacture used data from 14 sub-sectors. In this study, we propose to consider 11 economic sectors, resulting from the NACE codes listed in Appendix A.

3. Results

3.1. Territorial Patterns of the Resilience of the Italian Metro-Regions

This section describes the results of the application of the taxonomic procedure described in Section 2 to the Italian metro-regions. More specifically, we consider the 21 metro-regions identified in Italy by Eurostat (see Appendix C).

Following the methodology described in the first and second step of the procedure (see Sections 2.2 and 2.3) we obtain the graph of Figure 5, that allows for the identification of the regional typologies of resilience via the taxonomy proposed in Section 2.3. Figure 5 reports the relative economic performance of the Italian metro-regions in the 2000–2008 period (y-axis) and the 2008–2016 period (x-axis), and the regional relative occupational capacity. The variable of relative occupational capacity, in particular, is represented by the symbol of a sphere, whose size and colour are representative of the value and the sign of the variable, respectively. Furthermore, the vertical dashed line indicates the value of zero growth in the post-crisis period.

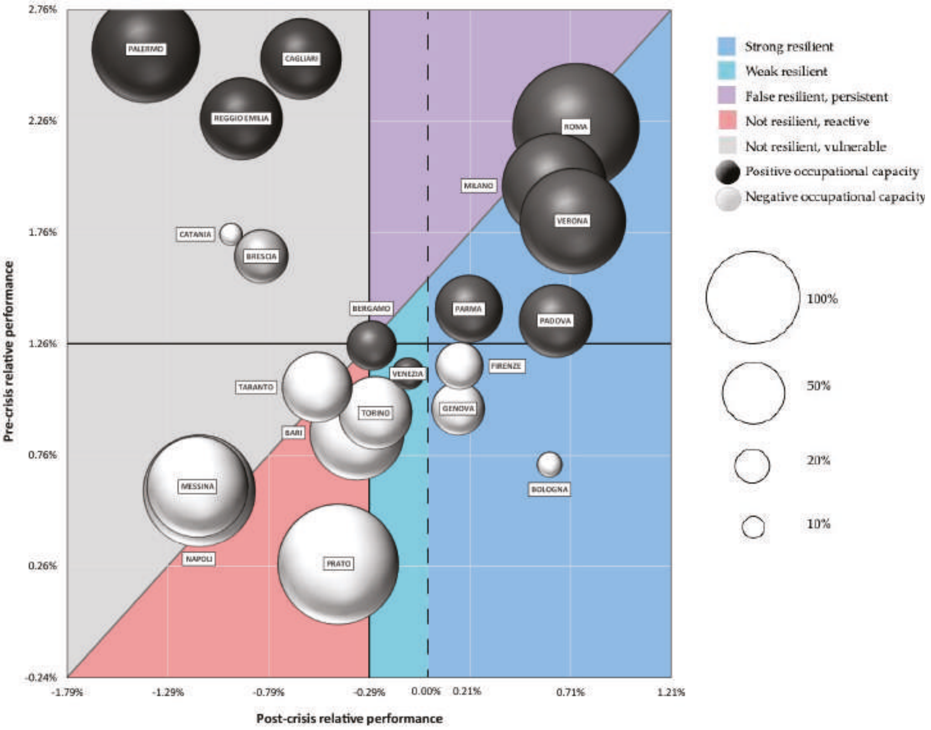


Figure 5. Italian metro-regions and their position concerning the trend in employment in the 2000–2008 period (y-axis) and the 2008–2016 period (x-axis). The intersection of the axes is not placed on (0, 0) but on the national values of the post- and pre-crisis periods. The dashed line represents the value of zero growth in the post-crisis period. The circles of different magnitudes and colours represent the relative occupational capacity of the regions (see Section 2.2).

The analysis of the Italian case shows an average national growth rate negative in the post-crisis. This means that our case study falls in the typology described by Figure 4b.

The results draw a novel geography of the economic performances of the Italian territories. Following the scheme of Figure 4b, we identify eight *strong resilient* metro-regions (Bologna, Firenze, Genova, Milano, Padova, Parma, Roma, and Verona) and three *weak resilient* metro-regions (Bergamo, Torino and Venezia). None of the analysed cases falls into the typology of the *persistent* regions, while two of them result *not resilient, but reactive* (Bari and Prato). The remaining eight metro-regions are classified as *vulnerable* (Brescia, Cagliari, Catania, Messina, Napoli, Palermo, Reggio Emilia, and Taranto). In addition, the spheres of Figure 5 also report the information of the relative occupational capacity, from which we can further distinguish the metro-regions, according to the way their resilience combines with the pre-crisis employment levels. For instance, Roma and Milano belong to the group of the strong resilient and are also characterized by a positive consistent occupational capacity. Conversely, the occupational capacity of Firenze, Genova and Bologna is negative, despite their resilience. Among the weak resilient metro-regions, Venezia and Bergamo have a positive occupational capacity, while Torino has a negative one. Additionally, in the group of the vulnerable metro-regions, the results for this variable are diversified:

Palermo, Reggio Emilia and Cagliari register a positive performance; Catania and Brescia slightly negative; Taranto, Bari, Napoli and Messina highly negative.

About the third step, for practical reasons, the shift-share analysis with the detail of the sectoral contribution to the occupational rates is not reported in a yearly time series, but as the partial sum of the whole pre-crisis (2000–2008) and post-crisis (2008–2016) periods.

In the following sections, the metro-regions of each typology are described according to the results of the shift-share analysis of the employees for each economic sector in the periods 2000–2008 and 2008–2016, as calculated by Equation (A1) in Appendix A. The aim is to point out recurrences and divergences in the way the economic sectors influence the resilience of the Italian metro-regions.

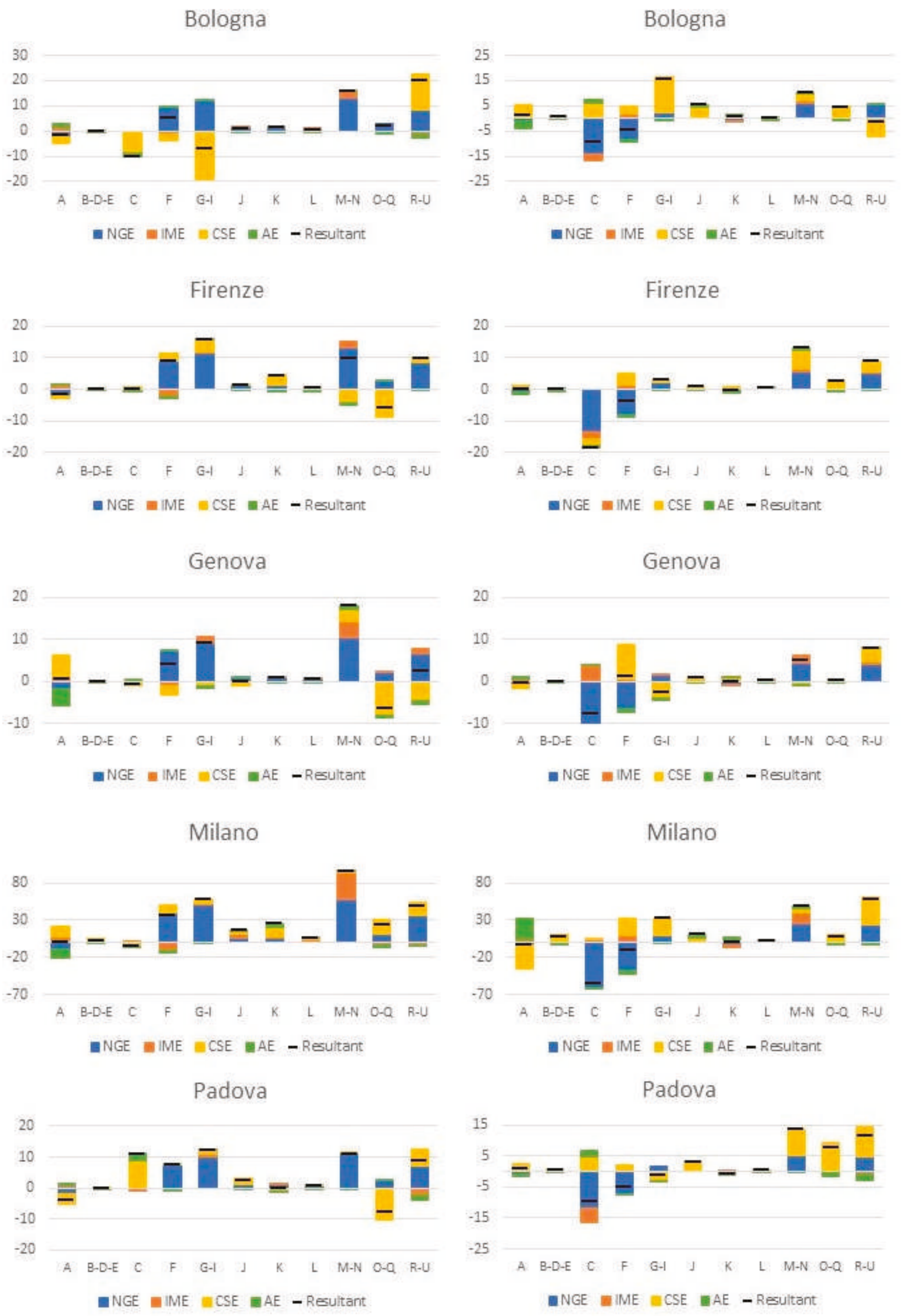
3.2. Strong Resilient Italian Metro-Regions

The dark blue sector of Figure 5 identifies the group of the most resilient territories. It includes the two largest metro-regions of Italy, which are also Metropolitan cities (Milano and Roma), three smaller Metropolitan cities (Bologna, Firenze, and Genova) and three medium-sized metro-regions (Padova, Parma, and Verona). Due to their employment stability, they can be considered the strongest and driving regions of the national economy. Roma, Milano and the northern metro-regions stand out with positive performances in all the variables considered in the analysis (pre and post-crisis relative employment performance, resistance and occupational capacity). Conversely, the smaller Metropolitan cities of Genova, Firenze and Bologna show negative values in the pre-crisis dynamic, and they also register a negative relative occupational capacity (quantified, respectively, in −22.5%, −17.8% and −5.2%). This latter condition, in particular, derives from the fact that, at the time the crisis started, these metro-regions had already suffered from a consistent loss of employment that was just partly recovered after 2008.

Before the crisis, the employment growth rates of these metro-regions were beneath the national average; and, in the post-crisis period, they registered a smaller relative occupational capacity. Focussing on the results of the shift-share analysis (see Figure 6), the dramatic fall emerges, occurring after 2008, of the propelling role of the national level. It is evident above all in Milano and Roma, where the negative occupational dynamic of the nation (NGE effect) in the post-crisis period caused a loss of, respectively, 352,000 and 347,000 employees. However, the regions of this group succeeded in rebalancing the losses thanks to the overall competitiveness of the regional system (positive CSE effects are present in Milano, Padova, Verona, and Parma) and the favourable sectoral organisation of the local economy (testified, for instance, by the positive IME effect of Roma).

As Figure 6 shows, sectors with common dynamics in the post-crisis period are:

- Construction (f): in this sector the occurrence, after 2008, of widely negative national effects (NGE) has determined a shift from expansion to contraction, and losses that vary from −5000 to −10,000 employees. The only exception is Genova, where a substantial competitive effect (CSE) has determined an increase of approximately 1300 employees;
- Retail and Logistic (g–i): in all the regions, but Genova and Padova, this sector registers at the end of the post-crisis period an increase in employment, fuelled by the competitive effect (CSE), i.e., by the regions' capacity (strong and evident above all in Bologna) of supporting the occupation in the Retail and Logistic activities in a situation in which the sector suffered significantly from the crisis;
- Technical and Scientific Services (m–n): with the only exception of Verona, these are the sectors that grew most in the pre-crisis period. In addition, the persistence of a positive, although reduced, national effect (NGE) allowed them to maintain a trend of employment growth;
- Public Administration Services (o–q): independently from what happened before 2008, in the 2008–2016 period, in this sector, all the regions showed positive competitive effects that helped them to maintain (or increase) the employment levels. Remarkably, the most positive increases occurred in Milano, Roma (approximately +7800 employees both) and Padova (+7500 employees).



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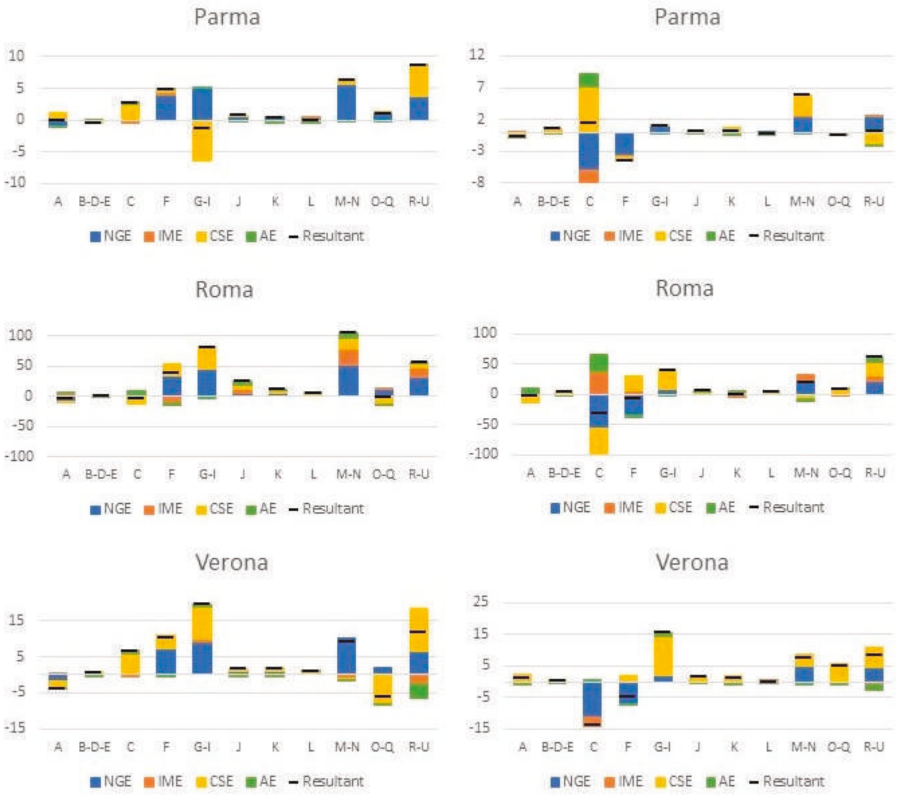


Figure 6. Shift-share effects of the sectoral employment of the strong resilient Italian metro-regions: Bologna, Firenze, Genova, Milano, Padova, Parma, Roma, and Verona. Periods: 2000–2008 (**left**), 2008–2016 (**right**). The *x*-axis represents the codes of the economic sectors, as specified in Appendix A.

The sectors of Agriculture (a), Non-Manufacturing Industry (b-d-e), Information and Communication (j); Finance and Insurance (k), and Real Estate (l) show a trend that is not specific to this group but is similar in all the Italian metro-regions, both resilient and vulnerable. In these sectors, the crisis had the result of "freezing" the previous occupational dynamic (if any and of any sign), determining in the 2008–2016 period limited effects, mainly of the type competitive (CSE) and allocative (AE), which have an opposite sign and compensate each other. If we exclude the increases in ICT employment in Milano (+11,800) and Roma (+6100), the largest increase was in Bologna of around +4300 employees in the same sector. In the remaining sectors, it is difficult to find a typical behaviour. The Manufacturing sector (c) has a widely negative national effect (NGE) that adds up with different combinations of other negative effects: in the case of Roma, a significant contribution comes from the competitive effect (CSE); in the case of Firenze, from the combination of the allocative (AE) and the competitive effect (CSE); in the case of Verona, Padova, Parma, Bologna, and Genova from the industrial mix effect (IME). In all these cases the final result is the same: a loss in Manufacturing employment, which ranges from −56,700 employees in Milano to −7800 in Genova. Finally, the sector of Cultural and other Services (r–u), often driven by the competitive effect (CSE), plays a vital role in the final employment rate, in cases of both positive and negative signs.

3.3. Weak Resilient Italian Metro-Regions

In the graph of Figure 5, the group of the weak resilient regions corresponds to the light blue sector. This group includes the Metropolitan cities of Venezia and Torino and the northern, medium-sized metro-region of Bergamo. As to the occupational capacity, the information represented by the spheres shows it is positive in Bergamo (+19.9%), quite positive in Venezia (+8.2%), highly negative in Torino (−42.3%). This is due to the different occupational dynamic these metro-regions had when the crisis started.

Figure 7 depicts the post-crisis dynamics, showing common effects mainly in the following sectors:

- Construction (f): in this sector the crisis had the effect of turning the previous positive values of the national, industrial and competitive effects into negative values, of almost the same intensity, determining a loss of employment, not compensated by the fact that the regional labour market could perform better than the national one. In the case of Torino and Bergamo, in particular, this advantage with respect to the nation (i.e., a positive value of the CSE) appears only after 2008. In the case of Venezia, it is already present in the pre-crisis period.
- Technical and Scientific Services (m–n): in this sector, the crisis had determined a resize of employment, imputable above all to the national and competitive effects, that did not, however, change the positive sign of the occupational dynamics. In all the three regions, the period 2008–2016 ends with an increase in employees that amounts to +18,800 in the case of Torino, +3300 in Bergamo, and +4400 in Venezia.

Figure 7. Shift-share effects of the sectoral employment of the weak resilient Italian metro-regions: Bergamo, Torino and Venezia. Periods: 2000–2008 (**left**), 2008–2016 (**right**). The *x*-axis represents the codes of the economic sectors, as specified in Appendix A.

In the Retail and Logistic sector (g–i), the situation of the three regions varies greatly both in the final balance of the pre-crisis and post-crisis periods, and in the consistency of the different effects. In Venezia, the fading away of the positive contribution given by the national effect is compensated by a strong increase in the competitive effect, which raises the employment in the sector of around 13,200 units. In Bergamo, this balance amounts to +2100, while in Torino it reaches the negative value of −500. In addition, in the sector of the Public Administration services (o–q) and the sector of the Cultural and other Services (r–u), a common trend does not seem to be identifiable. While in the remaining sectors, we notice the same "levelling" dynamic observed for the strong resilient metro-regions, that sets to zero the variation of employment in the 2008–2016 period. The most extensive variation for all these sectors is the one of Venezia: −2100 employees in Finance and Insurance (k), pulled down by a negative competitive effect (CSE).

3.4. Not Resilient, Reactive Italian Metro-Regions

This group, depicted in the purple sector of Figure 5, includes just two metro-regions: Prato in the centre of Italy, and Bari in the South. With such a limited sample, it follows that the identification of a common trend has to be taken with caution. As to the occupational capacity, these two regions are both characterized by a very negative situation (quantified, respectively, in −70.1% and −115.7%), which emerges as structural, as a negative occupational balance was already present in the years before 2008.

These regions emerge from the rest of the sample for the presence of an ambiguous condition of vulnerability. This condition is characterised by a low occupational capacity (testified by the size and negative value of the spheres in the graph of Figure 5) and an occupational performance always weaker than the national one, but with a certain reaction to the crisis.

Again, in this group, the sectors of Agriculture (a), Non-Manufacturing Industry (b-d-e), Information and Communication (j); Finance and Insurance (k), and Real Estate (l) tend to give a residual contribution to employment (see Figure 8), while in all the remaining sectors, it is not possible to distinguish a common dynamic. We interpret this result as the clue (still to be tested) that, differently from resilience, the reactiveness relies above all on the specific conditions that characterise the region before and after the crisis.

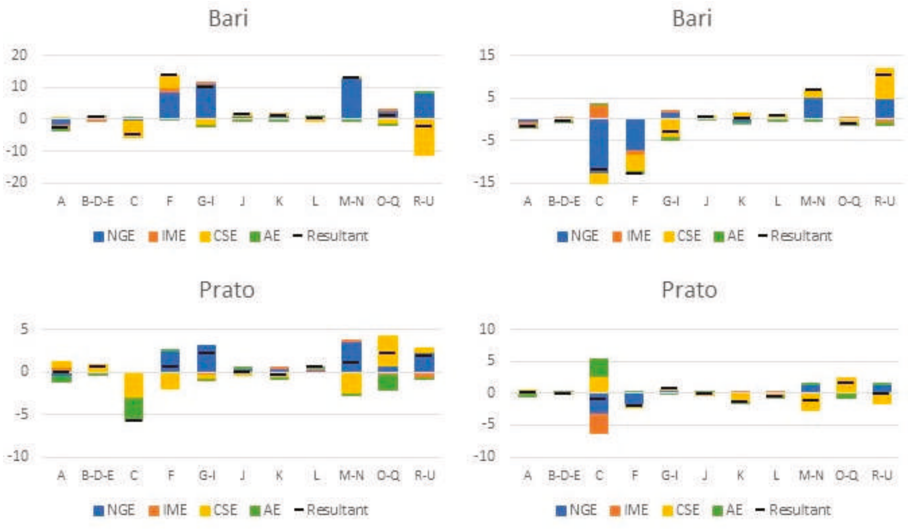
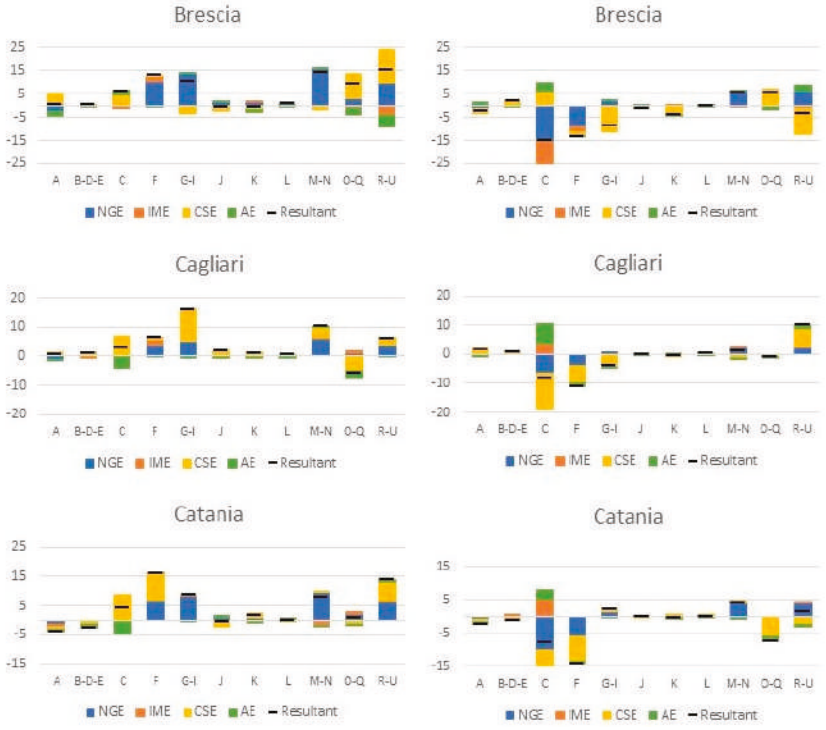


Figure 8. Shift-share effects of the sectoral employment of the *not resilient*, *reactive* Italian metro-regions: Bari and Prato. Periods: 2000–2008 (**left**), 2008–2016 (**right**). The x-axis represents the codes of the economic sectors, as specified in Appendix A.

3.5. Not Resilient, Vulnerable Italian Metro-Regions

In Italy, the group of the vulnerable metro-regions, represented by the grey sector of Figure 5, is the most crowded of all but paradoxically a bit less heterogeneous. From a geographical point of view, with the only exception of the metro-regions of Brescia and Reggio Emilia, all the regions falling in this group are metro-regions of the south of Italy: Cagliari, Catania, Messina, Napoli, Palermo and Taranto (see Section 4). Secondly, what distinguishes mostly these regions from the resilient and reactive ones is an occupational dynamic that is weaker than the nation in all the considered variables with the only exception of the occupational capacity of Palermo, Cagliari, and Reggio Emilia, which is positive and higher than the average. Conversely, Napoli and Messina are the most vulnerable of the group. While in the remaining cases, the loss of employees is mainly limited, also compared to the national average. As to the variable of the occupational capacity, situations are highly diversified, with values that range from the highly positive value of Palermo (+91.8%) to the highly negative one of Napoli (−100.1%).

Some further considerations on the sectoral response to the crisis derive from the graphs shown in Figure 9. As noted for other types of resilience, also the regions of this group are characterised by residual post-crisis effects in Agriculture (a), Non-Manufacturing Industry (b-d-e), Information and Communication (j), Finance and Insurance (k), and Real Estate (l). The Agriculture sector in Napoli is the only exception, registering a final balance of employees of around −8.200. In the other sectors, the crisis resulted in a “turmoil effect”, producing a generalised amplification of the magnitude of all the effects. The sectors Manufacture (c), Construction (f) and Retail and Logistic (g–i) usually end the 2008–2016 period without a loss of employment or, at their best, with a residual increase. Only Taranto registers an increase in a certain relevance, that amounts at around +3800 employees in the sector of Retail and Logistic.



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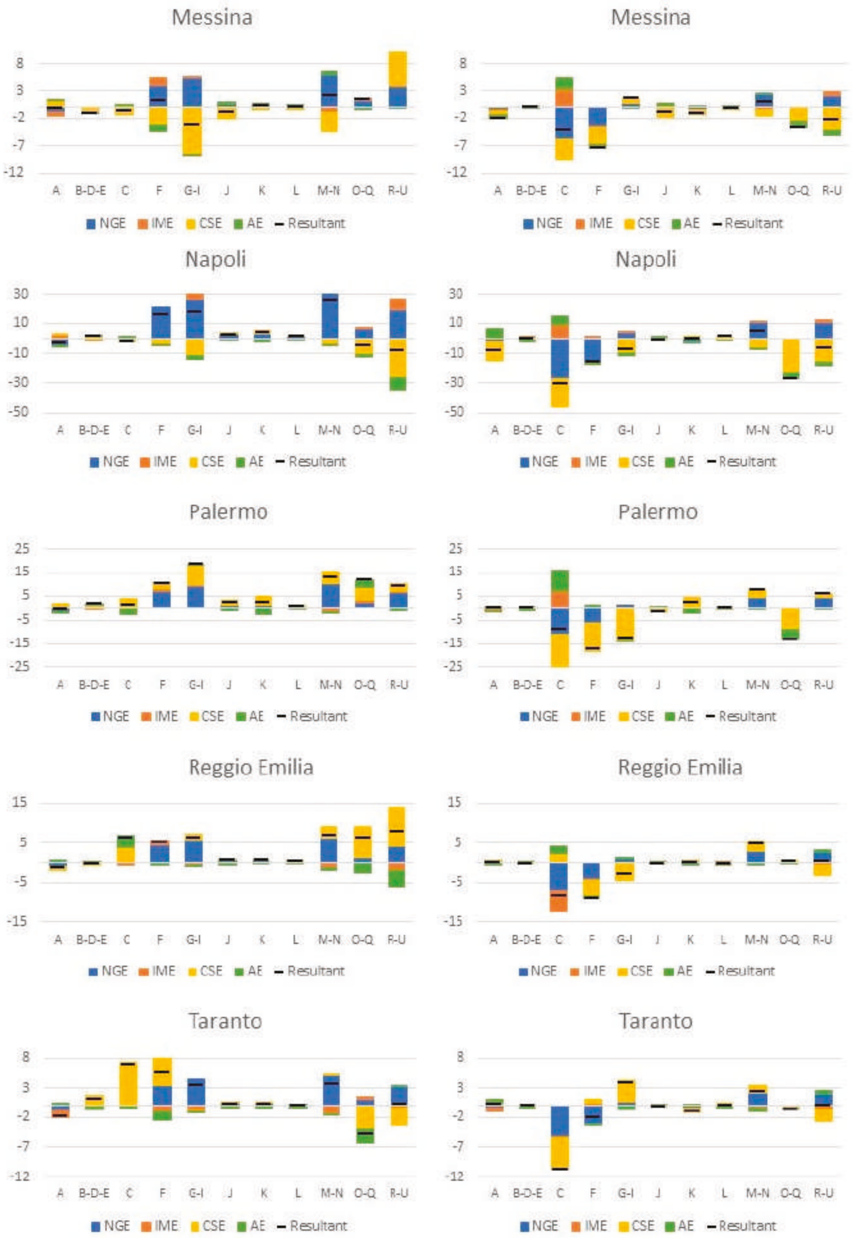

Figure 9. Shift-share effects of the sectoral employment of the *not resilient*, *vulnerable* Italian metro-regions: Palermo, Cagliari, Reggio-Emilia, Brescia, Catania, Taranto, Napoli, Messina. Periods: 2000–2008 (**left**), 2008–2016 (**right**). The *x*-axis represents the codes of the economic sectors, as specified in Appendix A.

4. Discussion

The paper proposes an analysis exploring a different way to construct regional taxonomies of resilience. In doing that, it refers to the consistent bulk of literature that deals with economic resilience, and assumes the employment variable, as it provides useful hints from both an interpretative and methodological perspective.

Indisputably, employment is not the only variable representative of regional resilience. We are aware it is just a proxy of a specific type of resilience, which is economic resilience. Other types of resilience, also inclusive of the social, institutional and environmental dimensions of growth, the influence of territorial spillovers [32] and the occurrence of international effects [57], would have requested not just a variable but a multidimensional set of variables [34,36,40]. Resting on the economic literature, we are also aware that some more variables could have been explored, such as the value-added or the gross domestic product [38,58]. However, we intended this paper as a preliminary study, open to be tested with other data and other types of resilience. In such a perspective, the employment variable has the advantage of representing both economic and social issues. It is, in fact, a measure of the human capital of a region and its level of specialisation/diversification. Furthermore, it allows for a regional and sectoral disentanglement of a dynamic of growth, which is distinctive of the shift-share methodology and allows, in a non-deterministic way, one to describe how the different sectors contribute to distinguishing the regional path from the national one.

The analytical instrumentation adopted in this study allows one to highlight the economic resilience of the Italian metro-regions to the 2008 crisis. Moreover, it allows one to formulate some hypotheses on the influence of the economic sectors on the reactiveness of metro-regions. In the geographical and regional literature, this is a critical issue. Economic specialisation is considered a crucial factor in the explanation of economic growth and innovation. Employment in high-tech industries and services goes on being considered a vital factor for the regional economy as businesses in these sectors keep on playing a particularly important role in pushing economic attractiveness and introducing new products and services that impact the entire economy.

From this point of view, however, the results of the shift-share we developed are not conclusive. The combination in time and space of the shift-share effects shows that the main common emergent trait of the resilient regions is the persistence, before and after the crisis, of a positive competitive capacity (CSE). At the level of the Italian economy, the negative effects of the crisis are evident above all in the national effects (NGE) of the Manufacturing and Construction sectors. The Construction sector is also the branch of the economy that contributes most—together with the sector of Technical and Scientific Services—to differentiate the resilient regions, both strong and weak, from the not resilient ones.

The second point of discussion with implications on the geographical and regional debate regards the representation of the economic performances of the Italian territories. The taxonomic analysis of regional resilience we developed with reference of Italian metro-regions, in fact, draws a geographic representation of the leading economies at the national scale (represented in the map of Figure 10) that is only partially consistent with the most popular representations of the economic growth imbalances within the country.

As reported in Table 2, if we consider the most famous “visions” of the national economy produced since the 60 s (for a review, see the interesting work of Bartolini [59]), we find that only the North–South divide shows a good correspondence with the results of our analysis. Indeed, with the only exception of Brescia and Reggio Emilia, all the vulnerable metro-regions are southern regions, and all the resilient ones are northern or central regions. Roma is the most southern region in the group of the strong resilient.

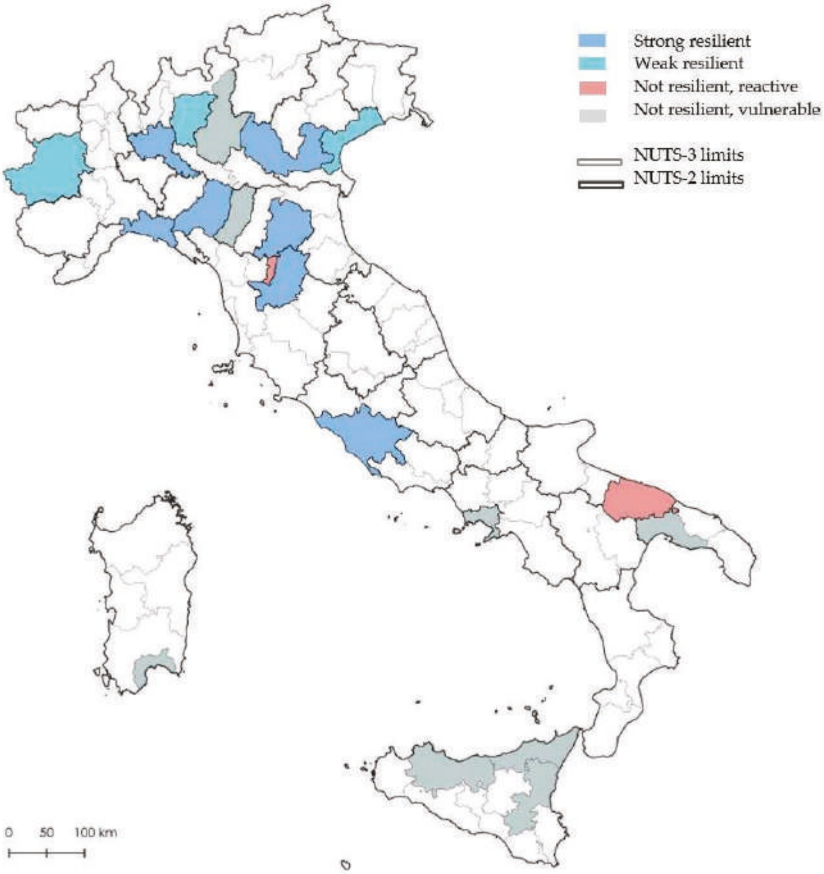

Figure 10. The economic resilience to the 2008 crisis of Italian metro-regions.

Table 2. The consistency of the proposed taxonomy of resilience with some main representations of the Italian economic divides.

Representations	Consistency	Analogies	Divergences
North–South divide [60]	High	Milano, Genova, Verona, Padova Parma, Bologna, Firenze, Roma, Venezia, Torino, Bergamo are core/resilient.	Brescia and Reggio Emilia are vulnerable. Bari is reactive, although not resilient.
Third Italy/North–East–Centre Marshall economies [61,62]	Low	Verona, Padova, Bergamo are core/resilient.	Brescia and Reggio Emilia are vulnerable. Prato is reactive, although not resilient.
Metropolitan cities as national champions [63]	Low	Milano, Torino, Genova, Bologna, Firenze, Roma, Venezia, Torino are core/resilient.	Napoli, Messina, Catania, Cagliari, Palermo are vulnerable. Bari is reactive, although not resilient.
Large urban economies (core cities >500,000 inhabitants) [64]	Moderate	Roma, Milano, Torino, Genova are core/resilient.	Napoli and Palermo are vulnerable.

Source: authors' elaboration.

The correspondence is very poor, instead, concerning both the "rhetoric" of the national champions assumed by the Italian reform of the local entities (Delrio Reform) and the conceptualisation of regional growth as a function of the urban rank/competitiveness. Eight of fifteen Italian Metropolitan cities—which the Delrio Reform entrusted to push the overall national economy forward [63]—present features of resilience. The residual ones except for Reggio Calabria, not included in the analysis as not inserted in the list of the metro-regions by Eurostat) are vulnerable. Even less are the metro-regions that are consistent with the so-called "Third Italy" or "NEC" (North–East–Centre) territories, characterised by a prolonged presence of Marshallian economies.

Finally, the Gramscian vision of the role of large urban economies results partly coherent with our results. If we consider the population of the core cities of each metro region, we see that four of the six largest cities in Italy (>500 thousand inhabitants) are part of a resilient region. However, the evaluation of this last representation is biased by the criteria used to select the cases analysed, as population size is one of the criteria used by Eurostat to identify the European metro-regions.

Table 2 proposes a synthetic, not-exhaustive description of the consistency of the classification of the Italian metro-regions with some well-established representations of the economic divides within the country. As the table shows, there are divergences concerning all the representations. In addition, among the cases listed in the column of the analogies, slight differences derive from the fact that we distinguished the strong resilient from the weak resilient ones. It is the case, for instance, of Torino and Venezia, which emerge with a feeble resilience compared to other metro-regions similar for population or economic size (Milano and Bologna for Torino, Padova for Venezia; see Table A2 in Appendix C). How to explain these discrepancies and differences? A first option is that the discrepancies derive from the methodology adopted and the choice to measure resilience only via the employment growth rate and the 11-sector employee distribution. However, our results are also consistent with the evidence resulting from place-specific studies and analysis.

Going back to Torino and Venezia, in the first case, a relevant number of studies have identified a process of golden decline determined by the post-Fordist restructuration of the local and the global economy [65,66]. In the case of Venice, the transition towards post-industrial forms of economic development has been poorly managed by the local and national politics [67] and a lack of a comprehensive strategic vision has been produced, namely, regarding the old industrial areas still present in the metro-region [68]. Brescia and Reggio Emilia suffered both from the global economic crisis and other unfavourable events (such as the 2012 earthquake in Reggio Emilia) in a way that mined the competitiveness of the local labour market. A relevant bulk of literature [30,63,65,66] also testifies the failure of the majority of the Metropolitan cities created by the Delrio Law in being levers of economic growth (including those in row 3 of Table 2). In such a context, Bari (quoted in rows 1 and 3 in Table 2 as reactive), however, emerges as a large Metropolitan city of the south of the country that had the benefit in recent years of two important pushing conditions: the availability of public funding from the EU structural funds and some important national programs (such as the Agenda Digitale and Smart Cities programs) and the presence of effective governance processes [69].

A second option is thus that some of the most renowned geographies of the Italian divides—often elaborated before the crisis started—have at least partly changed.

Besides confirming the importance of an evolutionary, path-dependent approach to the analysis of economic resilience, this result is quite intriguing and paves the way for further research. In the reflection on economic development, there are at least two other important representations that it may be worth testing with an analysis of the type we proposed: the small places' dynamism and the revenge of the "forgotten" places. Both these representations recognise economic centrality to the marginal, the rural and the inner areas, recognising them trajectories of growth alternative with respect to a neoliberal technology-led development model. The former, particularly, emphasises the capacity of small villages to allow healthier lifestyles and exploit the opportunities of economic growth of an ageing (silver) society [58,70]. The latter supports the idea of an uneven centrality of marginal cities and regions, often ignored by the national policy as "places that don't matter" [71].

The focus on metro-regions does not allow for the consideration of small- and medium-sized economic systems. The smallest metro-region in Italy corresponds to the province of Prato, which hosts 255 thousand inhabitants, while the national average is 550 thousand inhabitants per province. However, it might be highly instrumental in testing the resilience of all the subnational regions forming the national economy using, for instance, the research unit of the local labour systems. In such a perspective, the National Statistical Agency of Italy (Istat) has recently released a report entitled "*Rapporto sul Territorio*" that provides some interesting clues to read the changing national economy.

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Appendix A

Table A1. Correspondence between the economic sectors used in the shift-share analysis and the Nomenclature of Economic Activities NACE rev.2 codes.

Sectors	NACE Rev. 2
Agriculture	A: Agriculture, forestry and fishing
Manufacturing	C: Manufacturing
Non-Manufacturing Industry	B–D–E: Mining and quarrying; Electricity, gas, steam and air conditioning supply; Water supply; sewerage, waste management and remediation activities
Construction	F: Construction
Retail and Logistic	G–I: Wholesale and retail trade; repair of motor vehicles and motorcycles; Transporting and storage; Accommodation and food service activities
Information and Communication	J: Information and communication activities
Finance and Insurance	K: Financial and insurance activities
Real Estate	L: Real estate activities
Technical and Scientific Services	M–N: Professional, scientific and technical activities; Administrative and support service activities
Public Administration Services	O–Q: Public administration and defence, compulsory social security; Education; Human health and social work activities
Cultural and other Services	R–S–T–U: Arts, entertainment and recreation; Other services activities; Activities of households as employers; Activities of extraterritorial organisations and bodies

Appendix B

The idea of the occupational capacity originates from the cumulative formulation of the shift-share adopted in this study. Using the conceptual framework of Equation (5), we propose the introduction of the absolute occupational capacity of region r and sector i, $AOC_{ir}{}^{t_0-t_{0+h}}$, defined over the interval between year t_0 and year t_{0+h} and calculated as the summation of all the cumulative sum introduced in Equation (5) for every year of the time period, as expressed by:

$$AOC_{ir}{}^{t_0-t_{0+h}} = \Sigma_n CS_{ir}{}^{t_0-t_{0+n}} = CS_{ir}{}^{t_0-t_{0+1}} + CS_{ir}{}^{t_0-t_{0+2}} + \ldots + CS_{ir}{}^{t_0-t_{0+h}} \quad \text{(A1)}$$

where n varies between 1 and h.

To better clarify the metrics introduced in this paper, we consider the exemplificative case study of the metro-region of Roma. Figure A1 (left) shows, for every year of the interval 2000–2016, the histograms representing the four shift-share effects calculated with expressions (3) and (4). These equations contain information on the employment variation of each single year with respect to the previous one, but do not say anything about the global final results. The cumulative sum, defined in Equation (5) and reported in Figure A1 (right), provides the desired information, because it calculates, for each year, the result of the partial summation.

Figure A1. The exemplificative case study of the metro-region of Roma. Shift-share effects calculated with expressions (3) and (4) (**left**), and their cumulative sum, defined in Equation (5) (**right**). Black lines indicate the resultants.

The absolute occupational capacity, defined by the summation of Equation (A1), represents, from a mathematical point of view, the discrete version of the integral of the cumulative sum (the curve reported in Figure A1 right).

To focus on the differences between regions and the nation, we introduce the definition of the *relative occupational capacity*, $ROC_{ir}{}^{t_0 - t_{0+h}}$, calculated as the difference between the absolute occupational capacity of the region and the absolute occupational capacity of the nation:

$$ROC_{ir}{}^{t_0 - t_{0+h}} = AOC_{ir}{}^{t_0 - t_{0+h}} - AOC_{iN}{}^{t_0 - t_{0+h}} \quad \text{(A2)}$$

where N indicates the national value.

Appendix C

Table A2. Population and employment of Italian metro-regions in 2016.

Metro-Region [1]	Population	Employment
Bari	1,263,820	471,100
Bergamo	1,108,298	483,400
Bologna	1,005,831	518,100
Brescia	1,264,105	555,900
Cagliari	561,289	230,300
Catania	1,115,535	352,300
Firenze	1,013,348	508,600
Genova	854,099	393,200
Messina	640,675	200,400
Milano (Provinces of Milano, Lodi, Monza Brianza)	4,303,998	2,347,600
Napoli	3,113,898	981,400
Padova	936,887	445,000
Palermo	1,271,406	375,500
Parma	447,779	223,200

Table A2. *Cont.*

Metro-Region [1]	Population	Employment
Prato	253,123	121,800
Reggio nell'Emilia	532,872	242,400
Roma	4,340,474	2,127,300
Taranto	586,061	188,700
Torino	2,282,197	988,200
Venezia	855,696	371,600
Verona	922,383	426,800

[1] All the Italian metro-regions, except Milano, correspond to the NUTS II level and the Province/Metropolitan city level. In the case of Milano, the metro-region results from the sum of three NUTS II: Milano (which is also a Metropolitan city), Lodi and Monza Brianza (Provinces).

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Dynamic Models for Exploring the Resilience in Territorial Scenarios

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Abstract: The present paper focuses on the role covered by dynamic models as support for the decision-making process in the evaluation of policies and actions for increasing the resilience of cities and territories. In recent decades, urban resilience has been recognized as a dynamic and multidimensional phenomenon that characterizes urban and metropolitan area dynamics. Therefore, it may be considered a fundamental aspect of urban and territorial planning. The employment of quantitative methods, such as dynamic models, is useful for the prediction of the dynamic behavior of territories and of their resilience. The present work discusses the system dynamics model and the Lotka–Volterra cooperative systems and shows how these models can aid technicians in resilience assessment and also decision makers in the definition of policies and actions, especially if integrated in wide evaluation frameworks for urban resilience achievements. This paper aims to provide an epistemological perspective of the application of dynamic models in resilience assessment, underlying the possible contribution to this issue through the analysis of a real case study and methodological framework. The main objective of this work is to lay the basis for future compared applications of these two models to the same case study.

Keywords: urban resilience; dynamic models; decision making; scenario planning

1. Introduction

Cities and territories across the world are increasingly exposed to a number of risks, hazards and stresses [1,2]. These affect all urban system dimensions, from the environmental to the social and economic [3,4]. Therefore, the concept of resilience is increasingly being used in urban and territorial policy in order to prepare urban systems for hazards and uncertainties [2,5,6]. Urban resilience is defined as a dynamic and multidimensional phenomenon that characterizes metropolitan areas as complex systems at all scale dimensions [7–9]. Urban resilience is related to several disciplines and domains, such as risk reduction, climate change and adaptation strategy. More recently, urban resilience has also been involved in the definition of policies and actions for achieving urban and territorial purposes [2,7,9]. The guidelines for increasing urban resilience are effective planning procedures—the identification and prioritization of which require the involvement of experts with specific competences and from different disciplines in the decision-making process [10]. This paper explores the role of dynamic models in support of the definition of policies and actions to enhance urban resilience. These models belong to the family of mathematical modelling, which is able to simulate the behavior of complex systems over time by using a set of Ordinary Differential Equations (ODEs). In this paper, dynamic models are investigated according to methodological background and operative characteristics. The main aim is to consider their general characteristics and peculiarities in order to underline dynamic model (DM) features that are closely related to the decision-making process in territorial and urban planning [11]. DMs are recognized as suitable tools to evaluate policies and actions aimed at increasing urban resilience [12–14]. This property is related to the fact that these models are built and grounded on dimensions related to both urban systems and urban resilience. In fact, during the construction of the model, it is necessary to select and identify which aspects of a territorial system have to be included with reference to the evaluation goal, from the environmental to the economic dimension [11,12,15]. In this sense, DMs are able to reveal both the dynamic behavior of urban and territorial systems and the impacts of policies on the key variables identified.

Specifically, the main aim of this work is to study the principal characteristics of the system dynamics model (SDM) and Lotka–Volterra models (LV) in order to apply both to the same case study. The final purpose of this investigation is to understand the importance of the modelling approach in the field of resilience evaluation.

The paper is structured as follows: Section 2 describes the current state of the art of resilience and urban resilience; Section 3 explains the role of dynamic models—the system dynamic models (SDM) and Lotka–Volterra models (LV)—in the decision-making process and summarizes their methodological background, state of art and some illustrative examples; Section 4 explains how the SDM models and LV models could contribute to urban planning; a comparative matrix is developed to investigate the utility of the considered models in predicting support in the design of future transformation scenarios; and Section 5 includes some final remarks and future perspectives.

2. State of Art of Resilience and Urban Resilience

The concept of resilience is used in a wide range of disciplines and domains such as psychology [16,17], ecology [18], engineering [19,20], socio-ecological systems [21–23], climate change and adaptation [24–26], urban planning [27,28] and disaster risk management [9,29–32]. Furthermore, in the last two decades, resilience has become an important goal for cities that are often theorized as highly complex with an adaptive system [32–34].

The term “resilience” came from the Latin word resilio, which literally means “to bounce back” [35]. However, its origins, meanings and interpretations are quite ambiguous [36,37].

Table 1 summarizes some of the most representative definitions of resilience in different disciplines. It reveals that engineering, ecological and socio-ecological resilience are the most used definitions in literature [38]. Furthermore, this table makes clear the division between the dynamic and the static interpretation of resilience [32].

The static interpretation refers to the engineering definition [9], whereas the dynamic interpretation is related to the socio-ecological perspective [18]. Engineering resilience should be understood as the measure of the speed with which the system can return to its previous equilibrium. Therefore, the engineering perspective does not consider the transformation [32]. On the other hand, the socio-ecological perspective is grounded on the assumption that a return to the previous equilibrium may be not possible in complex ecosystems [32,39]. Socio-ecological resilience refers to the capacity of the system to transform itself, thus returning to a previous equilibrium.

This recognition is fundamental to understand which perspective may be adopted to analyze an urban system, in order to concern about urban resilience with the correct background.

At the beginning, it was particularly referred to climate change [40,41]. Subsequently, in the latest studies [7,9,42] it has also been related to stresses and hazards which effect the different dimensions of an urban system [33]. From a careful literature review, what emerges clearly about urban resilience are these highlights: (1) The most important study of resilience applied on urban systems is Holling’s studies which referred to socio-ecologic resilience [43]; (2) Urban resilience is defined as a complex and multi-dimensional phenomenon [9]; (3) Urban resilience is not a static condition, but it is a dynamic process in spatial and temporal scales [8]; (4) There is not a unique definition [32]; and (5) Urban resilience has recognized an increase in literature, in academic studies, political studies, social debate and urban planning [9,30,36,44–46].

Table 1. Representative resilience definition by different fields (Elaboration from Meerow, 2016 and Bharma et al., 2011).

Author	Field	Definition of Resilience	Static or Dynamic
Holling, 1973	Ecology	"The ability of these systems to absorb changes of states variables, driving variables, and parameters, and still persist" (p. 17).	Dynamic
Pimm, 1984	Ecology	"How fast the variables return towards their equilibrium following a perturbation" (p. 322).	Static
Carpenter et al., 2001	Social-ecological systems	"The magnitude of disturbance that can be tolerated before a socioecological system (SES) moves to a different region of state space controlled by a different set of processes" (p. 765).	Dynamic
Adger, 2000	Geography	"The ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (p. 347).	Dynamic
Rose, 2007	Economics	"The speed at which an entity or system recovers from a severe shock to achieve a desired state" (p. 384).	Dynamic
Fiksel, 2006	Systems engineering	"The capacity of a system to tolerate disturbances while retaining its structure and function" (p. 16).	Dynamic
Zhu and Ruth, 2013	Industrial ecology	"The ability [for industrial ecosystems] to maintain their defining feature of eco-efficient material and energy flows under disruptions" (p. 74).	Dynamic
Zeng and colleagues, 2013	Networks	"The critical threshold at which a phase transition occurs from normal state to collapse" (p. 12).	Static
Ouyang, 2014	Engineering	"The joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation" (p. 53).	Static
Adger, 2000	Social resilience	"Ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (p. 347).	Static

From these aspects, this paper aims to focus on the definition of urban resilience to highlight the communalities and differences in academic and policy debate. The objective of this analysis is to highlight the malleability of the urban resilience concept and to stress on its implications in policy definition [47]. Table 2 lists a series of definitions on urban resilience by considering academic and political references with the purpose to better understand what the needs and the tools are to be employed as support of the decision-making process for building resilient cities.

Table 2. Some peculiar definitions of Urban Resilience (Authors' elaboration, 2019).

Authors and Year	Definition	Field
Meerow et al., 2016	"Urban resilience refers to the ability of an urban system—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" (p. 39).	Academic
100 Resilient City Campaign, 2013	"Urban resilience is the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience" (p. 10).	Political
UN-Habitat	"Urban resilience is the measurable ability of any urban system, with its inhabitants, to maintain continuity through all shocks and stresses, while positively adapting and transforming toward sustainability" (p. 5).	Political
Urbact, 2004	"Urban resilience is the capacity of urban systems, communities, individuals, organisations and businesses to recover, maintain their function and thrive in the aftermath of a shock or a stress, regardless its impact, frequency or magnitude" (p. 6).	Political
Desouza and Flanery, 2013	"Urban resilience is the ability to absorb, adapt and respond to changes in urban systems" (p. 89).	Academic
Hamilton, 2009	"Urban resilience is the ability to recover and continue to provide their main functions of living, commerce, industry, government and social gathering in the face of calamities and other hazards" (p. 109).	Academic
Lu and Stead, 2013	"Urban resilience is the ability of a city to absorb disturbance while maintaining its functions and structures" (p. 200).	Academic
Thornbush et al., 2013	"Urban resilience is a general quality of the city's social, economic, and natural systems to be sufficiently future-proof" (p. 2).	Academic
Leichenko, 2011	"Urban resilience is the ability to withstand a wide array of shocks and stresses" (p. 164).	Academic

Table 2. *Cont*.

Authors and Year	Definition	Field
Romeo—Lankao and Gnatz, 2013	"Urban resilience is a capacity of urban populations and systems to endure a wide array of hazards and stresses" (p. 358).	Academic
OECD, 2016	"Resilient cities are cities that have the ability to absorb, recover and prepare for future shocks (economic, environmental, social and institutional). Resilient cities promote sustainable development, well-being and inclusive growth" (p. 3).	Political
Resilience Alliance, 2002	"A resilient city is one that has developed capacities to help absorb future shocks and stresses to its social, economic and technical systems and infrastructures, so as to still be able to maintain essentially the same functions, structures, systems and identity" (p. 4).	Political
ICLEI, 2015	"A resilient city is prepared to absorb and recover from any shocks or stress while maintaining its essential functions, structures and identity as well as adapting and thriving in the face of continual change. Building resilience requires identifying and assessing hazard risks, reducing vulnerability and exposure, and lastly, increasing resistance, adaptive capacity and emergency preparedness!" (p. 1).	Political
C40, 2017	"Cities are the forefront of experiencing a host of climate impacts, including coastal and inland flooding, heat waves, droughts, and wildfire. As a result, there is widespread need for municipal agencies to understand and mitigate climate risks to urban infrastructure and services and the communities they serve" (p. 1).	Political
Urban Resilience HUB, 2015	"The measurable ability of any urban system, with its inhabitants, to maintain continuity through all shocks and stresses, while positively adapting and transforming toward sustainability" (p. 6).	Political
UNISDR, 2015	"The ability of a system, community or society exposed to hazards, to resist, absorb, accommodate, adapt to, transform and recover from its effects in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management" (p. 3).	Political

These different definitions are listed to underline their communalities and differences in their meaning. They are different from the formal point of view. However, all these definitions concern with the multidimensional and transformative approach of urban resilience [7]. They also focus the attention on the dynamic behavior of resilience processes both in spatial and time scales [6].

This means that building urban resilience requires looking at urban and territorial systems holistically. It is necessary to understand cities in all dimensions and identify interdependencies and risks they may face.

For this application, the definition of Meerow et al. [32] has been considered for its holistical view of urban systems and its attention to both spatial and temporal scales.

Nowadays, the main problems which regard the design of policies and strategies to build urban resilience lies in the difficulty of evaluating this process over time and in spatial dimensions.

This paper explores the DMs in order to verify their efficiency in application in scenario planning, in order to find suitable tools which may support decision makers to define and prioritize strategies and policies to enhance urban resilience.

3. Dynamic Models in the Decision-Making Process

The definition of effective policies needs to be informed by a holistic understanding of the system processes. Their complex interactions and the ways they respond to various changes and inputs have to be evaluated. In this sense, models are, in general, seen as useful tools to aid actors and stakeholders to analyze alternative possible solutions and assess their outcomes. In fact, models generally integrate knowledge developed across a broad range of fields. They are generally used for different purposes. In this section, we focus on their application in management and treatment of uncertainty. Dynamic models cover a number of different methods and approaches able to simulate the behavior of future scenarios. Among the different methods belonging to the family of mathematical modelling, the present paper considers the system dynamics model (SDM) and the Lotka–Volterra model (LV). In this section, the methodological background and the state of art are investigated for both the SDM and LV models with the aim to highlight their fundamental role in the prediction of possible future scenarios for exploring urban resilience. Moreover, an illustration of some relevant applications is proposed in order to explain the methodological steps for the applications and the type of results that can be obtained.

3.1. Urban Simulation Models

In this paragraph, an overview of the urban simulation methods is given. The selected urban simulation methods are here discussed as reliable support in the decision-making process, especially in the case of designing urban and territorial transformations that may solicitate perturbations on the system on its resilience. Starting from a literature review [48], different simulation models have been selected to be analyzed. Table 3 lists the considered models and describes them, considering field and purpose of applications, types of data, treatment of space, time and uncertainty.

Table 3. Overview of urban simulation models (Authors' elaboration from Kelly et al., 2013).

Model	Field of Application	Types of Data	Treatment of Space	Treatment of Time	Uncertainty
Bayesian networks	Decision-making and management, Social learning, System understanding, Prediction	Qualitative and quantitative	Non-spatial	Non-temporal	Structural learning from data and knowledge is possible
Coupled component models	Prediction, Forecasting, System understanding, Decision-making and management	Mainly quantitative but qualitative are possible	Comprehensive set of options	Routine	Comprehensive discrimination tests between alternatives
Agent-based models	Social learning, System understanding	Mainly quantitative	Limited	Limited	Comprehensive discrimination tests between alternatives
Knowledge-based models	Decision-making and management, Prediction, Forecasting	Qualitative and quantitative	Non-spatial	Usually non-temporal	Comprehensive discrimination tests between alternatives

This overview of different models has been useful to support the choice of the model to experiment and use in investigating the urban resilience.

3.2. System Dynamics Model

3.2.1. Methodological Background and State of Art

System dynamics model (SDM) is an operative approach for helping reveal temporal behavior of complex systems considering their non-linearity, time-delay and multi-loop structure [49,50]. SDM is based on the System Dynamics approach which was introduced by Forrester [51,52] for investigating the feedback information of industrial systems and improving the organizational form [53]. SDM is an effective tool for modelling intersectional dynamics, such as the prey–predator models [54,55]. The relationships and interactions between variables in the system are analyzed by this tool (SDM) in order to simulate its dynamic evolutions in terms of processes, information and organizational boundaries [50].

In SDM, complex and dynamic systems are described both in qualitative/conceptual and quantitative representations. The qualitative modelling is performed by the causal loop diagram (Figure 1). This tool is used to graphically represent the feedback loops structure of the system. Causal loop diagram (Figure 1) describes the basic mechanism of the system, in order to represent the causes of its dynamics behavior over time [50,56]. The relationships between the variables can be either positive or negative, as shown in Figure 1. A positive relationship signifies that variables change equally. By contrast, a negative relationship means that the variables change inversely.

Quantitative modelling is represented by stock and flow diagram (Figure 2). Stock is the first basic building block in SDM and it represents the variable which describes the condition of the system at any particular time [12,50,57–59]. Flow is the second block in SDM and it tells how stocks change over time.

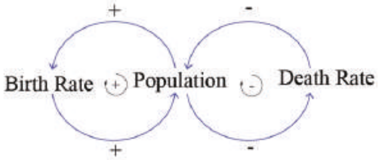

Figure 1. Causal loop diagram (Tan et al., 2018).

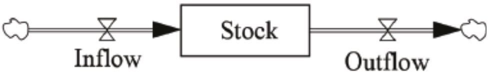

Figure 2. Stock and flow diagram (Source: Authors elaboration).

From a mathematical point of view, stock and flow diagrams are represented by first-order finite difference equations. These allow to simulate the dynamic behavior of the system. The differential equations which characterize stock and flow can be expressed as:

$$tock(t) = stock(t0) + \int_{t0}^{t} (inflow(t) - outflow(t))dt \quad (1)$$

and this integration equation in the differential equation form is:

$$\frac{d(Stock)}{dt} = inflow(t) - outflow(t).$$

The most frequent type of possible system behavior can be summarized as follows [60]:

- Exponential growth or decline, which is characterized by only positive or only negative feedbacks;
- Goal-seeking behavior, which is created by first-order negative feedback;
- S-shaped growth. This behavior, over time, is created by a combination of positive and negative feedback loops. In this case, both loops struggle for dominance until the struggle ends with a long-term equilibrium;
- Oscillations. This is one of the most common types of dynamic behaviors in the world and it can have different forms, such as (1) sustained oscillations; (2) damped oscillations; (3) exploded oscillations; (4) chaos. The structure that creates oscillations is a combination of negative feedback loops and delay.

Currently, SDMs are used to support policy design and management for sustainable development in those fields characterized by a high level of uncertainty, such as transport management [58,61,62], land use [63], waste management [59] and also sustainable urban development [13,57,64,65]. In the last few decades, an increase of SDM application has been observed in literature [66], especially in the urban development field. Table 4 lists some of the prevalent SDM applications with particular attention to urban system and urban development.

Table 4 shows that SDM is an effective tool for supporting the evaluation of different development scenarios' performance, considering their possible effects over time. For this reason, it is considered as a useful tool to support decision makers in setting policies.

Table 4. Example of recent applications of System Dynamics Model in urban planning (Authors' elaboration, 2019).

Authors and Year	Territorial Scale	Method	Outcome
Wu et al., 2018	Metropolitan (Beijing, China)	System Dynamics Model System of urban sustainability indicators GIS (Geographic Information System)	Simulating different urban development scenarios to assess their possible effects both temporally and spatially. The objective is to choose the preferable development strategy.
Pagano et al., 2017	Municipal (L'Aquila, Italy)	System Dynamics Model System of performance criteria	Assessing the evolution of the resilience of a drinking water supply in case of natural disaster.
Tan et al., 2018	Metropolitan (Beijing, China)	System Dynamics Model System of indicators	Evaluating three different urban development scenarios considering their possible impacts over time on social, economic and environmental sectors.
Guan et al., 2011	Metropolitan (Chongqing, China)	System Dynamics Model GIS Analytic hierarchy Process (AHP) System of indicators and indices	Development of an integrated evaluation model to assess four different urban scenarios considering the dynamic evolution of considered indicators in both temporal and spatial dimensions.
Park et al., 2013	Metropolitan (Seoul, Korea)	System Dynamics Model	Quantitative analysis of self-sufficient urban development policies for assessing their impacts over time.

3.2.2. Illustrative Example

In this section, the application of SDM developed by Tan et al. [13] to the case study of Beijing (China) is considered for the illustration of the fundamental steps of the procedure and the typology of results that the method is able to deliver. In [13], the SDM are applied to simulate the urban sustainability performance of the city, considering three different development scenarios. The SDM has been developed following these steps: (1) identifying the key variables by a review of urban sustainability indicators; (2) building the stock and flow diagram to identify the relationships between the variables; and (3) simulating different scenarios. Figure 3 shows the stock and flow diagram of the social sector. In particular, the stocks of the diagram are (1) Total population, (2) Urbanization rate, and (3) GDP, whereas all the other variables represent the flows. The diagram also shows the relationships that exist among the considered variables. As an example, we can consider the relationship that exists between "local government annual fiscal revenue" and "financial educational investment". That means the investment in educational fields strictly depends on the availability of government financial resources. It appears clear that the SDM model tries to describe the real-world functioning through its stock and flow diagram, based on real behavior.

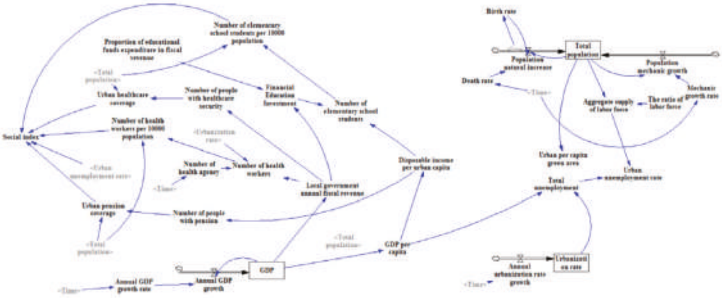

Figure 3. Stock and Flow diagram of social dimension (Source: Tan et al., 2018).

Figure 4 illustrates the results of SDM scenarios simulation, gathered by the stock and flow diagram in Figure 3.

These outcomes reveal the evolution of the indicators over time, referred to three different development scenarios (Figure 4). Simulation has been obtained by mathematical equations. For instance, Equation (2) illustrates the equation of annual household waste emission:

$$HWS = DSWE\ per\ capita * Total\ population\ (Unit\text{:}\ ten\ thousand\ tons) \tag{2}$$

where:

(1) "*HWS*" is the annual household's waste emission;
(2) "*DSWE*" is the domestic solid waste emission.

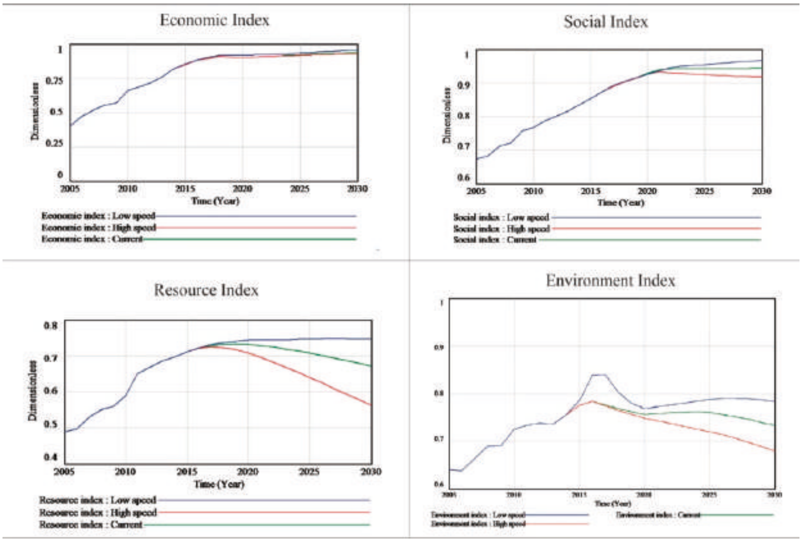

Figure 4. SDM simulation results of economic, social, resource and environmental index (Source: Tan et al., 2018).

Specifically, in Figure 5, the SDM simulation results are referred to (1) "Current scenario" which represents no change in urban development actions; (2) "High speed scenario" that is characterized by a faster urbanization process and a higher economic growth rate; and (3) "Slow scenario" in which the urbanization process is limited.

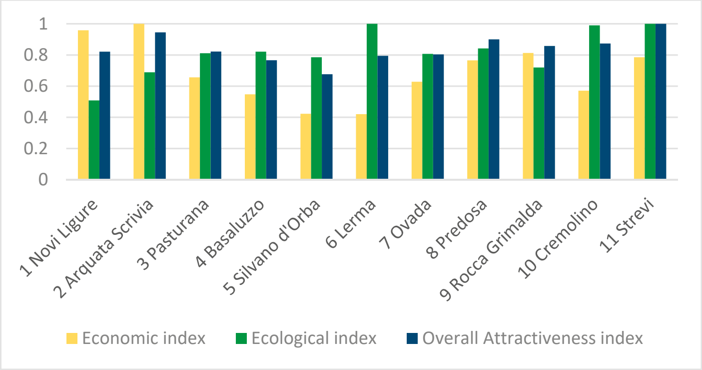

Figure 5. The histogram illustrates the ecological indices, the economic indices and the Overall Attractiveness index that were calculated for the considered 11 Clusters (Elaboration from Assumma et al., 2018).

3.3. Lotka–Volterra Cooperative Systems

3.3.1. Methodological Background and State of Art

Lotka–Volterra models (LV) are generally employed in the field of landscape ecology for exploring the prey–predator interactions [67,68]. These models have been integrated only recently in wide integrated evaluation frameworks to better interpret non-linear dynamics of territories, and so, their capability to adapt themselves to natural and/or anthropic disturbances and disasters, thus going beyond the analyses of ecological systems [55].

In fact, the aim of Lotka–Volterra models within territorial and urban planning consist in being a support for the investigation of a given environmental system N and the prediction of possible future transformations.

As shown in Equation (3), these models assume the form of a pair of non-linear Ordinary Differential Equations (ODEs) [69]:

$$\begin{aligned} p_1' &= a_1 p_1 + b_1 p_1^2 + a_{12} p_1 p_2 + I_1 \\ p_2' &= a_2 p_2 + b_2 p_2^2 + a_{21} p_1 p_2 + I_2 \end{aligned} \tag{3}$$

where

a_1 and a_2 are Malthusian coefficients that consider the dynamic evolutions of the populations p_1 and p_2 in terms of natality and mortality rates;

b_1 and b_2 are Verhulst coefficients that considers scarce territorial resources, with $b_1, b_2 < 0$. These coefficients are proportional to carrying capacity (c_1, c_2) with $b_1 = \frac{e}{c_1}$ and $b_2 = \frac{e}{c_2}$;

a_{12} and a_{21} are the terms that characterize the interaction between the two populations. In this way, we may consider three cases that correspond to three types of Lotka–Volterra models [69]:

- if $a_{12}, a_{21} > 0$, p_1 benefits from the presence of the second state variable p_2, then Lotka–Volterra models are defined as "cooperative";
- if $a_{12}, a_{21} < 0$, the first state variable competes with the second state variable, then Lotka–Volterra models are "competitive";
- if $a_{12} < 0$ (prey), $a_{21} > 0$ (predator), it means that the two variables are opposite, then Lotka–Volterra models are "prey/predator".

Lastly, I_1 and I_2 represent the rates of in-migration and out-migration.

Among the types of Lotka–Volterra models, this paper is focused on Lotka–Volterra cooperative type models. An example of a Lotka–Volterra cooperative type model for the state variables V and E is:

$$\begin{aligned} V' &= b(1 - V)V - cV \\ E' &= d(1 - E)E - f(1 - V)E \end{aligned} \tag{4}$$

where

$$\begin{array}{llll} a_1 = b - c & b_1 = -b & a_{12} = 0 & I_1 = 0 \\ a_2 = d - f & b_1 = -d & a_{21} = f & I_2 = 0 \end{array}$$

In Table 5, a number of literature contributions are listed, in that the outcome of Lotka–Volterra systems may be interpreted as a resilience factor. More in details, Finotto and Monaco [70] and Gobattoni et al. [71,72] are generally used for developing stability analyses on ecological sectors, thus predicting future possible equilibrium states; Monaco and Servente [69] are used to simulate the population's mobility and Monaco [73] integrates a synthetic index calculated through a system of indicators for investigating the population's mobility with respect to Gross Leasable Areas (GLAs); Assumma et al. [74,75] predicts the population's flow over time in rural landscapes with respect to the economic attractiveness; Assumma et al. [76] simulates the dynamics related to economic attractiveness and ecological quality as resilience factor.

Table 5. Application of Lotka–Volterra models applied to territorial and urban planning (Authors' elaboration, 2019).

Lotka–Volterra Models Applied to Territorial and Urban Planning			
Authors and Year	**Territorial Scale**	**Method**	**Outcome**
Finotto and Monaco, 2010	Municipal	Stability analysis for predicting the production and the time variation of bioenergy; Analysis of territorial characteristics using the ecological graph	Identification of interventions to guarantee the ecological functions of the environmental system with attention on the reduction of the urban sprawl.
Gobattoni et al., 2012, 2014, 2016)	Provincial	PANDORA model	Stability analysis on ecological equilibria as future ecological scenarios.
Assumma, Bottero and Monaco, 2016, 2019)	Sub-regional	Lotka–Volterra models; System of indicators and indices	Simulation of the population's mobility with respect to the economic attractiveness.
Assumma, Bottero, Monaco and Soares, 2018	Supra-Municipal	Lotka–Volterra models; System of indicators and indices	Simulation of the population's dynamics related to economic attractiveness and ecological states as resilience factor.
Monaco, 2015 Monaco and Servente, 2006	Provincial	Lotka–Volterra models; System of indicators and indices	Customer flow is intended as the attractiveness expressed by a system of Gross Leasable Areas (GLAs) by considering their degree of accessibility.
Capello and Faggian, 2002	Municipal	Lotka–Volterra models of prey–predator type	Urban population, urban rent and production profits are combined for understanding urban dynamics of Italian cities.

Therefore, Lotka–Volterra models have been employed at different spatial scales with different purposes, thus obtaining useful insights, such as in the field of landscape ecology and landscape economics [77]. In this section, a recent application on a supra-municipal context in Piedmont region (Italy) is proposed [76].

3.3.2. Illustrative Example

In Assumma et al. [76], an extension of a Lotka–Volterra model by Monaco and Rabino [78] was developed (Equation (5)) with the aim at simulating population dynamics as a resilient factor related to ecological and economic states for the territory of the Monferrato Ovadese in Southern Piedmont (Italy). The case study under investigation was intended as a multi-pole territorial system, where the poles refer to 37 municipalities that were grouped into 11 territorial clusters.

$$P'_i = A_i P_i(t)(1 - P_i(t)/S_i) + \sum_{j \neq i}^{n} A_i/A_j \left[1 - \left(d_{ij}/d_M\right)\right] P_J(t) \tag{5}$$

where P'_i is the state variable of the population i; A represents a synthetic index of ecological quality and economic attractiveness calculated for the poles i and j; d_{ij} consists in the distance recorded between the poles i and j, whereas d_M measures the recorded highest distance between the poles; and S_i is the carrying capacity, that is intended as the threshold number of people in a given pole.

It has to be noticed that the parameter A_{i} was calculated by considering a system of landscape economic indicators and a system of ecological indicators, according to a Multicriteria approach (for more, please see [74,79,80]). The considered systems of indicators and their indices aim to calculate a super-index that measures the overall attractiveness of the territory by considering the ecological quality and the economic attractiveness. The index of overall attractiveness was integrated into the Lotka–Volterra model in order to simulate the trends of populations with respect to both ecological and economic states. The results obtained by an evaluation procedure based on a Multicriteria approach are illustrated in Figure 5, whereas the results of the Lotka–Volterra model simulations are shown in Figure 6.

The results of the model are useful for predicting possible future evolutions about the mobility of resident populations. As shown in Figure 6, the first group of populations (P1–P4) behave similarly in the transitory time, with an exception for population (P1) because of a consistent degrowth. The second group of populations (P5–P8) behave differently; in fact, the population of the cluster of Novi Ligure (P5) is interested by a slight degrowth, the population of the cluster Lerma (P6) grows significantly and finally, populations of the clusters of Ovada and Predosa (P8 and P9) show similar growing behaviors. In this sense, the poles were intended as receptors of the considered territory that absorb and evolve toward a new state, as already said, with respect to ecological and economic aspects. The predicted scenarios on population dynamics were interpreted as the effects of the non-linear interactions between the ecological and economic components with the multi-pole territorial system. In fact, when the multi-pole territorial system shows a good equilibrium between ecological and economic aspects, the population grows significantly, as in the case of the population of the cluster of Predosa (P8); whereas when one of the considered components records negative values, the population decreases, as in the case of the population of the cluster of Novi Ligure (P1).

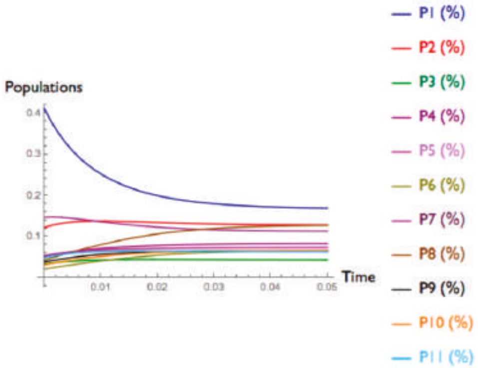

Figure 6. Future scenarios simulation of Lotka–Volterra model on population dynamics through Mathematica Software. (Assumma et al., 2018).

4. How Can These Models Contribute for Building Resilient Systems?

SDMs constitutes a family of tools that uses the ODEs to predict the performance of a given criterion over time and more in general cycles that depends on a number of factors, whereas the Lotka–Volterra are models that face more complex problems.

The link between the SDMs and LV models is pointed out by Crookes and Blignaut [55], who stated that prey–predator models are suitable to be used in system dynamics models [54], also finding some applications in the field of economics [81,82], ecology (see e.g., [83,84]), and in multidimensional sectors in a supply chain [85]. The most important commonality of these two methods, especially regarding to the assessment of urban resilience referred to in urban and transformation strategies, is that both the models can consider the interactions between the different elements and sectors in urban contexts. This characteristic represents the real peculiarity of these systems for evaluating urban resilience, in fact, there are no consolidated assessment methods in literature on urban resilience [86].

In this sense, a clarification about specific characteristics of SDM and LV has to be done, before the analysis of their possible contribution in decision-making for resilience enhancing. Indeed, beyond the similarity which concerns the mathematic bases, these models are quite different.

As shown in Table 6, a comparison matrix has been structured with the aim to investigate both commonalities and differences between the SDM and LV models in orienting decision problems related to urban planning, with specific attention to the resilience enhancement.

Table 6. Lotka–Volterra models and System Dynamic Models: summarizing comparison matrix (Authors' elaboration, 2019).

		Lotka–Volterra Models	System Dynamic Models
Nature	Essence and characters *	🙂	🙂
Input	Use of qualitative and quantitative data	☹	☹
	Participatory process	☹	🙂
	Use of different spatial scales	🙂	😐
Output	Scenario simulation	🙂	🙂
	Time scale	☹	🙂
	Spatial scale	🙂	🙂
	Graphical representation	😐	🙂
	Sensitivity analysis	😐	🙂
Software	Availability	🙂	🙂
	Use of Ordinary Differential Equations	🙂	🙂
Integration	Integration with different techniques and methodologies	🙂	🙂
Mapping	GIS visualization	☹	☹
	Interactivity	😐	😐
Scenario planning	Definition of objectives and strategies	🙂	🙂
	Prediction of future scenarios	🙂	🙂
Scale	Multiscale	🙂	🙂

* Lotka–Volterra model is used to show the functioning of the system, whereas the System Dynamic Model is a tool used to study and analyze the model or the system.

In particular, a number of criteria have been considered for this analysis. The criteria are selected according to relevant literature review [48,54,55] and to authors' researches:

- Nature highlights the different essence and characteristics of both dynamic models. On one hand, the Lotka–Volterra are models that aim to explore the dynamic functions of a given environmental system N, whereas the SDM models may be considered as a tool used to study and analyze the model or the system.
- Input is intended as the modalities to insert and deal with data at different spatial scales, as well as the possibility to integrate the participatory process. Generally, the considered dynamic models

allow the insert of only quantitative data and the employment of different spatial scales (from local to regional and superior). As far as the participatory process is concerned in the SDM models, the decision makers may be integrated since the early phases of the process by using causal loops (Figure 1) that facilitate the interpretation of the system functioning and the integration of different stakeholders' perspectives [14,50]. In the LV models, the participatory process may be integrated only by other evaluation procedures, such as the Multicriteria Analysis (MCA), by using a system of indicators and indices [79,87].

- Output refers to the final result produced through the considered dynamic models, such as the scenario simulation, the use of the time scale, the spatial scale, the graphical representation and the sensitivity analysis with the aim to validate the scenarios produced. Particularly, both SDM and LV models simulate possible future scenarios and these represent, generally, the final output through a graphic plot in that the linear function is represented. Unlike the LV models, the SDM models show, since the initial phase, a graphical representation of the relations between the considered variables and they allow to make, after the scenario simulation, a sensitivity analysis. These two DMs use, in different ways the time scale: the SDM model use a real time scale that may be traduced in months, years or centuries, whereas the LV model uses an arbitrary time scale that may be subdivided in an initial phase when the function starts with the state of art conditions (t_0), transitory phase, when the linear function evolves in terms of growth or degrowth, and a final phase, when the linear function became stable. The arbitrary time scale may be traduced in a real time scale by considering the historical series of the analyzed parameters [74]. Sensitivity analysis is a valuable procedure for testing the model response with respect to the variation of parameter values, as well as to identify those parameters that have more impact than the others on the investigated phenomenon [88]. Sensitivity analysis can increase the reliability of the model and thus, reduce the uncertainty of parameters used in the models. A very common sensitivity test is the One-At-Time approach (OAT) [89] that is often used in Multicriteria Analysis as final tuning [75,90,91]. This, in fact, facilitates the scenarios' assessment when actors and stakeholders are involved in a participatory decision-making process [92,93].
- Software refers to the availability of software and the modalities to solve the Ordinary Differential Equations (ODEs). On one hand, the SDM models are characterized by the use of specific software, such as STELLA, Venism and Powerism, that formulate themselves the ODEs from which the scenarios' simulations are produced. On the other hand, LV models are generally employed through mathematical software, such as MatLab and Mathematica Software, and these need to write manually the ODEs to obtain the prediction of scenarios (Figure 6). In this sense, both the dynamic models use the ODEs as an output, but in different ways. From the point of view of the availability, both dynamic models may be written through specific packages in open programming languages, such "deSolve" for R, "Simupy" for Python, "Mat Cont for Matlab" and "Nova modeler" for ecological modelling.
- Integration refers to the capability of DMs to integrate different techniques and evaluation methodologies. For instance, the considered dynamic models are a suitable tool to being integrated with Multicriteria Analysis (MCA) [75], as well as with the Agent-Based Models (ABM) [94] and Hedonic Price Model (HPM) [95]. Specifically, MCA can be used at two different phases: (1) at the beginning, to support the problem articulation and the identification of the variables to be included in the model; (2) after the scenarios' simulation to support the evaluation of the different performances through final score calculation or ranking elaboration. Shafiei et al. [96] integrate SDM and Agent-Based Models to better understand the effects, not only on the system but also on the agent of the transition to sustainable mobility.
- Mapping is intended as the possibility to visualize the scenarios using GIS-based methods and the possibility to interact the dynamic model and the GIS interface through a programming language (e.g., QGIS and Python). Actually, the integration of DMs simulation results into GIS is developed by users in specific plug-ins (e.g., PANDORA 3.0 [97]) or by using specific coding

platforms (e.g., QGIS Python console) and to get a spatial visualization of the output. Despite the requirement of specific competences to manage DMs in GIS environment, the users may support decision makers in better interpreting certain dynamics related to urban resilience by visualizing spatially the output of the dynamic model in a final map and therefore, identifying specific policies and solutions.

- Scenario planning refers to the prediction of future scenarios and the definition for each scenario of objectives and strategies. Both SDM and LV models allow to predict the way variables evolve, starting from the state of art conditions (t_0) [50]. In this sense, both the SDM and the LV models are useful supports for the decision makers for identifying the most critical areas and adopting specific policies and interventions.
- Scale refers to the application of dynamic models at different scales. Moreover, the SDM considers a system as a whole, analyzing and focusing on its components and sub-components. In fact, SDMs are mostly applied to municipal or metropolitan scales. LV models are generally employed to provincial and sub-regional scales and to those territories with a rural vocation.

5. Conclusions and Future Perspectives

This paper explored the role of the family of dynamic models (DMs) and their characteristics as support in the decision-making process for evaluating complex phenomena, as in the case of the resilience of urban and territorial systems. Particularly, the study on the state of the art of resilience, urban resilience, dynamic models and urban simulation methods provided an epistemological contribution to the issue. The examples considered in this paper can be useful to further explore the opportunities of analysis application to investigate the key variables of issues in cities and territories. The comparison matrix highlighted commonalities, differences and potential synergies between the SDM and LV models. Both the SDM and LV models may be considered reliable supporting tools for policy planning, thanks to their ability to predict possible future behaviors of selected key variables, thus helping actors and stakeholders to identify and prioritize shared objectives and strategies for increasing urban resilience. In fact, these DMs are able to integrate the scientific knowledge available in literature within the evaluation procedure with specific expert knowledge elicited in the participatory modelling processes [98]. Some final remarks with respect to building more resilient systems [99] could be:

- These DMs are currently considered as some of the most promising models for understanding multi-dimensional problems related to urban and territorial systems.
- If experiments are impossible in the real world, simulations become the main way we can learn effectively about the dynamics of complex systems. Dynamic models are the most appropriate techniques to simulate complex and dynamic systems with the aim of developing policy and learning to effectively manage the system [50,100].
- These models are able to predict the effects of the actions over time on the state of the system. For this reason, both the DMs considered can be applied to evaluate the possible effects of urban and territorial policies in order to enhance urban resilience.
- The integration of dynamic models with urban simulation methods makes it possible to support data collection and elaboration, problem structuring, and facilitate the involvement of actors and stakeholders [12,88,101–103].

The authors have applied both SDM and LV models to a common case study, of a city with more than 50,000 inhabitants, with the purpose of evaluating urban resilience performance. The aim of the authors consists in effectively testing the multi-scale by aggregating or disaggregating the data as variables of the models [103]. A set of urban development scenarios will be predicted, considering the short-, medium- and long-term period [64] and a set of objectives and strategies for enhancing urban resilience will be prioritized. From the methodological point of view, this will be developed as an interactive procedure through dynamic models that may interact with GIS software from the early stages of the process. Finally, an integrated tool will be developed to evaluate possible effects of natural or anthropic disasters that could compromise the resilience performance of systems, also evaluating the economic losses caused by the perturbations of the system.

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Energy Consumption Models at Urban Scale to Measure Energy Resilience

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Abstract: Energy resilience can be reached with a secure, sustainable, competitive, and affordable system. In order to achieve energy resilience in the urban environment, urban-scale energy models play a key role in supporting the promotion and identification of effective energy-efficient and low-carbon policies pertaining to buildings. In this work, a dynamic urban-scale energy model, based on an energy balance, has been designed to take into account the local climate conditions and morphological urban-scale parameters. The aim is to present an engineering methodology, applied to clusters of buildings, using the available urban databases. This methodology has been calibrated and optimized through an iterative procedure on 102 residential buildings in a district of the city of Turin (Italy). The results of this work show how a place-based dynamic energy balance methodology can also be sufficiently accurate at an urban scale with an average seasonal relative error of 14%. In particular, to achieve this accuracy, the model has been optimized by correcting the typological and geometrical characteristics of the buildings and the typologies of ventilation and heating system; in addition, the indoor temperatures of the buildings—that were initially estimated as constant—have been correlated to the climatic variables. The proposed model can be applied to other cities utilizing the existing databases or, being an engineering model, can be used to assess the impact of climate change or other scenarios.

Keywords: urban energy resilience; buildings energy balance; urban hourly model; residential buildings; urban variables; place-based analysis

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1. Introduction

The goal of European energy policies is to achieve energy and climate targets through an improvement in energy efficiency and a greater use of renewable energy sources in order to make cities more resilient. In Italy, these indications have been transposed by the "Integrated National Plan for Energy and Climate 2030" with the following objectives: (i) a 40% decrease in greenhouse gas emissions (compare to 1990); (ii) an increase to 32% of the share of renewable sources; (iii) a 32.5% improvement in energy efficiency. In European countries, almost 50% of the final energy consumption is used for space heating and cooling, of which 80% is for buildings [1]. For this reason, the optimization of building efficiency is one of the goals to promote the low-carbon and resilient urban development of cities [2,3].

Urban-scale energy models allow reliable estimates of the energy consumption of buildings to be made, which can in turn be used as a base for planning a resilient city [4,5]. Since the energy consumption of buildings is related to the local climate conditions and the urban morphology, these models have to consider the urban context (especially in dense, built-up areas) [6]. Therefore, energy simulation models and tools should take into account not only the characteristics of buildings, but also other urban energy-related variables [7]. It is necessary to consider several factors at different scales, since the energy consumption of buildings depends on a dynamic interaction between the envelope elements, technical systems, building surroundings, outdoor climate, and human behavior [8]. The already existing energy models and tools are able to simulate building consumption at an urban scale by assembling different sub-models [9]. However, these energy models only consider a few of the variables that actually influence the energy consumption of buildings at the urban scale [10], such as the presence of greenery [11], the albedo [12], the canyon effect [13], or the local climate conditions [14]. Indeed, designing these models at an urban scale is a complex task, since the available data usually lack some building-scale details; there is the need to make the right trade-off between model precision and the management of large amounts of data at different scales [15].

1.1. How Energy Can Influence Resilience in Cities?

Energy can be a key point in determining the resilience of a city, as the continuous supply of energy must always be guaranteed to enable all human activities to be carried out. This issue will be more serious, considering that all cities are growing, along with their energy demand, and with fewer renewable energy resources available [16–18].

In the energy field, the ability of a city to respond to critical events improves if the energy supply is always guaranteed for all the population. Then, the energy resilience of a city increases with the reduction in consumption, the greater use of renewable sources (with low environmental impact), and with affordable energy costs. In Table 1, the main actions affecting urban resilience from the environmental, economic, social, and governance perspectives are summarized.

Table 1. Impacts of energy on resilience in cities [19].

Environment	Greenhouse gas emissions (GHG) emissions: - GHG emissions influence climate change; - Energy is the largest contributor to GHG emissions. Heat emissions: - Heat due to energy consumption in cities contributes to urban heat island (UHI) effect; - UHI affects human health, the ecosystem, and energy demand. Environmental pollution: - Low availability of local renewable energy sources; - Air pollutant emissions: SOx and NOx are emitted by burning fossil fuels; - Water and land impact of energy-use.
Economy	Energy price fluctuations: - Energy prices affect human activities (i.e., industry, transport, households, …); Maintenance and renovation of energy infrastructure: - Costs of maintenance and renovation of the existing energy infrastructure.
Society	Disruptions of energy supply by disasters and critical events: - Millions of people lose energy supply; - Suspension of services; - Regional and global effects through supply chains.
Governance	Energy governance is affected by various factors: - Stable policy and regulatory framework; - The availability of local and non-local energy resources; - Local energy management (e.g. self-sufficient energy systems); - State of air pollution, water and land impact.

In order to be resilient, urban energy system needs to be capable of "planning and preparing for", "absorbing", "recovering from", and "adapting" to any adverse events that may happen in the future. Integrating these four abilities into the system would enable it to continuously address "availability", "accessibility", "affordability", and "acceptability" as the four sustainability-related dimensions of energy [17]. Some strategies to improve energy resilience in cities can be summarized as follows [19]:

- Energy management in urban policy: to measure the state of resources and to set achievable targets with a low environmental impact.
- Robust energy system: robust infrastructures and self-sufficient entities/communities.
- Redundant and flexible energy management: the diversification and optimization of energy sources and users by encouraging investments from public and private stakeholders (foreseeing social and economic changes).
- Resourceful and inclusive energy management: promoting local renewable energy production, and enhancing energy efficiency interventions in all sectors and among all stakeholders.
- Integrated energy management: regional and national coordination between municipalities and cities in order to create a multiplier effect on the territory.

Finally, energy data at the city level, including data on energy consumption and renewable energy production, are fundamental for understanding resilience challenges related to energy and for developing urban policies. Unfortunately, these data are difficult to find, often incomplete, and rarely available in a standardized format.

1.2. Research Gap

There are a number of simulation energy tools and models, such as CityBES (City Building Energy Saver), CitySim, SimStadt, UCB (UrbanSim), UMI (Urban Modeling Interface), that are able to estimate building stock energy demand considering the climate and urban morphology [20,21]. The existing models and tools are able to accurately simulate the energy performance at the block of buildings or neighborhood scale, but not at the city level. For example, CitySim, which is a large-scale building energy simulation, gives accurate results on the heat flow load at the neighborhood scale [22]. Additionally, Zhu et al., (2019) developed a method for building energy estimation on the district level using CityBES, and eight public buildings have been investigated [23].

In general, these models need the support of other combined tools, do not interact with the existing databases (e.g., Municipal Technical Maps, Digital Surface Model, Digital Terrain Model, satellite images, orthophotos), and are also paid for.

The model presented here is an engineering model based on buildings' energy balance that is implemented with a free GIS software using existing databases and is able to carry out simulations at the urban-territorial scale introducing urban variables. On the other hand, it is a simplified model and is therefore less accurate then engineering models at the building scale. Finally, this model is not a single building energy model applied at the urban scale [24,25]; it does not evaluate how local climatic conditions change according to urban morphology [26,27], and it is not a statistical model [28].

1.3. Research Questions

This work starts from studies conducted in the past with bottom-up and top-down models of the energy performance of buildings [29] which use data with high detail at the building level and data with low detail at the municipal level, respectively [30]. Then, an engineering bottom-up monthly model has been created to evaluate the energy performance of the buildings connected and not connected to the DH network in Turin [31]. For the evaluation of thermal peak loads, the problem of having an hourly model emerged. According to the standards on the energy balance of buildings (i.e., ISO 52016-1:2017, ISO 52017-1:2017), a simplified model has been designed using the available data of the buildings at the urban scale. The engineering model presented can be classified as a "grey-box model" that combines simplified physical information (i.e., geometrical and typological characteristics, local climate conditions) with historical data (i.e., thermal consumptions) to simulate the building energy consumption from the building to city level [32]. In a previous work [6], a comparison between a first hypothesis of the grey-box model and a "black-box model"—which is fully based on historical data and statistical analysis—using a machine learning approach was made on two residential blocks of buildings in Turin. The results of this work indicated that the grey-box model could give good results, and for this reason the authors decided to optimize that model.

1.4. Research Objective

The aim of this work is to create a dynamic energy model to be applied at the urban scale, starting from the energy balance equations at a building scale (according to: ISO 13786:2018, ISO 52016-1:2017, ISO 52017-1:2017, and ISO 13790:2008). This model has been designed to link with the existing territorial databases and then can be used for different urban contexts. One of the novelties of this urban energy model is that it can be applied to groups of buildings considering the energy-related variables that describe the urban morphology. These variables were introduced in the incoming and outgoing energy flows of the energy balance equations.

Summing up, the aim of this work has been to investigate the following topics:

- Why should we use hourly models? The DH network is dimensioned according to the peak of hourly energy demand. Then, the evaluation of the morning peak of consumption is a key factor related to the capacity of the energy distribution network. Moreover, hourly models can be also used to evaluate the optimization of the energy supply/demand, especially boosting renewable technologies.
- Is this hourly model accurate? How precise would the results be if the model is applied at an urban-territorial scale and to a group of buildings? The novelty of this model is its application to homogeneous groups of buildings using urban morphology variables. The model has been simplified so that it can use the data available for all the buildings in a city; it must provide results quickly, but these results should be accurate.
- Starting from the consideration that the model will be used to calculate the hourly consumption of buildings in a city, it is better to consider the temperature inside the buildings to be constant (e.g., set-point range) or variable according to the weather conditions?

Then, the novelty of the model here presented is that it is a simplified engineering model applied at the urban scale; it uses existing territorial databases and a place-based assessment through a Geographic Information System (GIS) tool. In this work, the model was studied to consider the interactions between buildings introducing new urban variables. Furthermore, with this energy model it is possible to evaluate the future energy efficiency or renewable energy scenarios, representing the spatial distribution of the energy demand/supply to achieve energy and climate targets [33–35].

2. Materials and Methods

This paragraph describes the input data of buildings at the urban scale and then explains the equations that use this data and that regulate the energy balance of buildings and groups of buildings.

In this first part of the work, residential buildings with different energy consumptions were characterized according to the main variables that influence their energy consumptions. Then, the buildings were characterized into archetypes and grouped into clusters according to their typologies and consumptions.

The energy balance model was applied to the different clusters, identifying the most effective input data. Then, to further reduce the errors, the buildings' temperature profiles were corrected, taking into account climate conditions.

The accuracy of this hourly energy balance model was evaluated by comparing the forecast energy supplied with the measured consumptions for the 2013–2014 heating season. This work can be divided into three parts (Figure 1):

1. Input data collection and processing: identification of the input data that have been collected using existing databases and the energy consumption provided by the DH Company. The data have been processed and georeferenced with the support of a GIS tool.
2. The energy balance with an iterative procedure was designed, dividing residential buildings into four clusters (homogenous groups) according to the hourly consumption profiles and the construction periods. The profiles of the building temperature—simulated using the energy balance equations—were compared with the indoor comfort temperature (according to ISO 7730: 2005 and EN 16798-1:2019). To further optimize the model, the internal temperature of the buildings was corrected, taking into account the climate conditions (external air temperature and sol-air temperature).
3. The energy consumptions were simulated using optimized energy balance equations and have been compared with the measured energy consumptions in order to test the accuracy of the model and validate it.

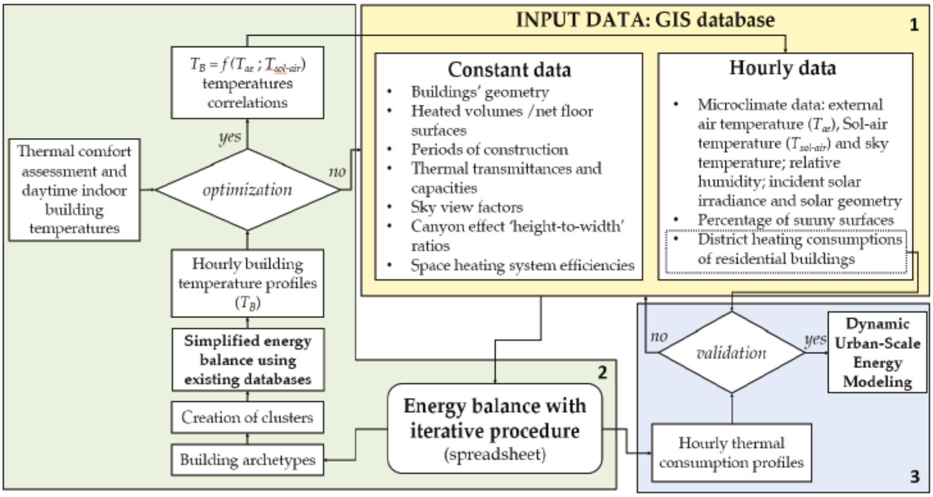


Figure 1. Flowchart of the methodology.

2.1. Input Data Collection and Processing

This section describes the input data, how they were treated and analyzed, and the tools that were used for their management and processing. A geo-referenced database was created using the data presented in the following sub-sections (see Tables 2 and A1 in the Appendix A).

The main steps in the management of data are indicated below:

- A sorting algorithm was used in the pre-processing phase to elaborate the DH energy consumption data. The raw data of the energy consumptions were interpolated with a constant time interval equal to 1 hour; building data with too many errors or missing data (more than 10%) were discarded.
- GIS software was used to locate each building, identifying its characteristics according to the availability of data at the urban scale. The input data were processed to evaluate the geometrical and typological characteristics of buildings and groups of buildings and all energy-related variables; at the block of buildings scale, also the sky view factor (*SVF)*, urban canyon height to distance ratio *(H/W)*, building orientation, and solar exposition were evaluated to characterize the buildings' surrounding context.

Table 2. Main input data of buildings and urban morphology characteristics.

	Input Data	Source	GIS Tool	Scale
Known data	Net and gross area, usable area, heated volume, dispersing surfaces (geometric characteristics)	Municipal Technical Map	Calculate geometry	Building
	Period of construction, type of user (typological characteristics)	Municipal Technical Map	Select by attributes	Building
	Type of roof	Municipal Technical Map, DSM, orthophotos	Aspect, Slope, Solar radiation	Building
	Solar exposition	Municipal Technical Map, Digital Surface Model (DSM)	Calculate Polygon Main Angle	Building/Urban
	Sky view factor	Municipal Technical Map, DSM	Relief Visualization Toolbox software	Urban
	Height-to-distance ratio	Building footprints	Generate near table	Urban
	Weather data	ARPA and Politecnico di Torino weather stations	Select by attributes	District
Hypothesized data	Percentage of transparent envelope	National Ministerial Decree of July 5th 1975 (in Italian)	Calculate geometry, Join by attributes	Building
	Thermal transmittance, resistance, system efficiency	ISO 52016-1:2017, ISO 52017-1:2017, UNI-TR 11552:2014, [36]	Join by attributes	Building
	Thermal capacity	ISO 13786:2018, UNI-TR 11552:2014 and UNI 11300-1:2014	Calculate geometry, Join by attributes	Building

2.1.1. Hourly Local Climate Data

Local climate data were used as energy-related variables for the hourly energy model to evaluate the energy consumption for the space heating of the buildings. The local climate data were processed with reference to the nearest weather stations (WS), the ENEA (Italian National Agency for New Technologies, Energy, and Sustainable Economic Development: http://www.solaritaly.enea.it/), and to the PVGIS portal (Photovoltaic Geographical Information System: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).

The hourly air and sky temperature, relative humidity, and incident solar radiation data from the nearest ARPA WS (Regional Environmental Protection Agency; in Italian: Agenzia Regionale per la Protezione Ambientale) were elaborated, and 34 typical monthly days with different air temperature and solar irradiation conditions were identified for the 2013–2014 heating season. The heating period for the case study (the city of Turin, Italy) is from October 15th to April 15th (183 days), and the analyzed weather data therefore refer to the same heating period.

The direct and diffuse components of solar irradiation were mainly obtained from the climatic data derived from weather station reports and from the PVGIS portal; the solar azimuth (a) and the solar height (h) were obtained from solar geometry correlations. According to [37,38], the relation between these parameters can be written as follows:

$$h = sin^{-1} \cdot (\sin\varphi \cdot \sin\beta + \cos\varphi \cdot \cos\beta \cdot \cos z), \tag{1}$$

$$a = sin^{-1} \cdot (\cos\beta \cdot \sin z / \cos h), \tag{2}$$

$$\beta = sin^{-1} \cdot \{0.398 \cdot \sin[0.9863 \cdot (d - 82)]\}, \tag{3}$$

where h is the solar height, φ is the latitude, β is the solar declination, $z = 15 \cdot (t - 12)$ is the hour angle, t is the solar hour, and d is the day.

The incident solar irradiance on walls ($I_{sol,wall}$) was assessed considering the hourly variation in the shadow percentage for each building (ξ) as a function of the solar height h and the canyon height to distance ratio *H/W* (Figure 2). When h is less than the urban canyon angle *arctan(H/W)*, the shadow quota of the building wall is equal to the *tan(h)/(H/W)*; instead, if *arctan(H/W)* is greater than/equal to 1, there is no shadow on the building wall:

$$\xi = \begin{cases} \frac{\tan(h)}{H/W} & if \quad h < arctan(H/W) \\ 1 & if \quad h \geq \arctan(H/W) \end{cases} \tag{4}$$

where ξ is the percentage of shadow on the vertical wall, h is the solar height, H is the urban canyon height, and W is the urban canyon width.

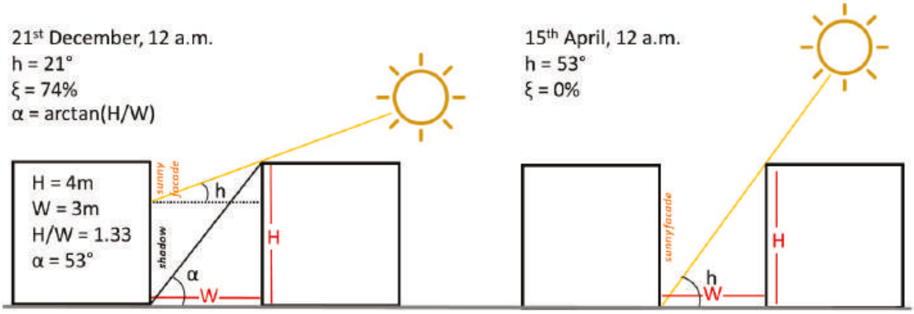


Figure 2. Shadow percentage assessment (an example for two days in April and December).

2.1.2. Hourly District Heating (DH) Consumption Data

Space heating consumption data at the building scale (in Wh) with different time intervals (from 20 min to 1 h) were provided by the Iren DH Company of Turin for the 2013–2014 heating season. The database, which has a large extension (5 GB), has been elaborated on, and in the pre-processing phase a sorting algorithm in python language has been used to extract and organize the data for each building with hourly time-steps according to the following actions:

- The raw data were interpolated with a constant time interval equal to 1 h, the missing data were computed from the available measurements, data with too many errors or missing data (with no information of 10%) were discarded (the useful sample of buildings decreased from 102 to 92 buildings).
- Space heating consumptions were geo-referenced at the building scale according to the coordinates/address of each energy meter using a GIS tool.

2.1.3. Constant Building Data

The thermo-physical and geometric parameters of the residential buildings were evaluated using information from the municipal technical maps, ISTAT (National Statistical Institute; in Italian: Istituto Nazionale di Statistica) census data for the year 2011, European Standards, and the literature. The Territorial DataBase (DBT) was implemented with other official information, such as the characteristics of the territory, using a Digital Surface Model, "DSM" (with a precision of 0.5 m); satellite images (Landsat 7 and 8); and orthophotos (with a precision of 0.1 m).

The typological characteristics of 102 buildings were calculated using the attributes of a 2D footprint derived from the municipal technical map with the GIS software:

- net and gross heated volume;
- net and gross floor surface;
- a transparent surface equal to 1/8 of the floor was assumed for the glazing (air-lighting ratio of D.M., 7 July 1975, and Turin building regulations);
- solar exposure and orientation, and shading elements, using the DSM and the solar geometry;
- the presence of uninhabited cellars and attics (very common in large Italian cities) has been hypothesized.

The thermal and construction characteristics of the residential buildings were assessed by identifying archetypes. The main input data were (ISO 52016-1:2017):

- the thermal transmittance (U) and resistance (R) of the building envelope elements;
- the total solar transmittance (g_G) of the transparent envelope;
- the solar radiation absorption coefficient (α_E) of the opaque envelope, which was determined considering the average color;
- the emissivity (ε_E *and* ε_G) of the envelope, which was assumed to be constant for opaque and transparent elements;
- a reduction frame factor (F_F) of the windows, which was hypothesized as being constant;
- thermal capacities (C) and system efficiencies (η);
- the type of system management (i.e., intermittent with night shutdown).

The data concerning the use of the buildings mainly refer to (i) the type of ventilation and (ii) the type of internal heat gains:

- As far as the type of ventilation is concerned, three scenarios were assessed in order to evaluate the quota of heat losses due to natural ventilation. Firstly, an air exchange per hour (*ach*) of 0.5 h^{-1} was assumed to be constant for all residential buildings during the day (24 h) resulting from infiltration. In the second scenario, *ach* was assumed to be variable during the daytime (with *ach* equal to 0.62 h^{-1}) from 7 a.m. to 9 p.m. and the nighttime (with *ach* equal to 0.30 h^{-1}) from 10 p.m. to 6 a.m. due to the use of shutters. In the last scenario, the thermal balance was implemented and the *ach* was assumed to be variable, considering a quota for infiltrations (3/4 h) and a quota for window opening (1/4 h) when the temperature inside the buildings exceeded the comfort temperature ($T_B > 22$ °C).

- According to ISO 52016-1:2017, the internal heat gains were assumed with daytime and nighttime profiles.

2.1.4. Constant Morphological Urban-Scale Parameters

Previous studies [39–44] confirm that certain variables, such as the climatic and local climatic conditions, the presence of vegetation, and/or the type of outdoor surfaces, can influence the thermal consumption of buildings. The morphological urban-scale parameters were evaluated using the municipal technical map (2015), ISTAT census data (2011), remote satellite images (i.e., Landsat 7 and 8), and a DSM with a precision of 0.5 meters. The urban characteristics that it was possible to consider were: the sky view factor (*SVF*), which measures the visible portion of the sky from a given location; the albedo, which is the percentage of solar incident irradiation reflected from a surface, and varies mainly according to the characteristics of the materials; the presence of vegetation, which is evaluated with the normalized difference vegetation index; the main orientation of the buildings; the urban canyon effect, which influences the outside air temperature and wind velocity, and which can be quantified considering the ratio between the urban canyon height "H" and its width "W"; the relative building height (H/H_{avg}), which describes the solar exposition in relation to the height of the surrounding buildings; the building coverage ratio (*BCR*) and the building density (*BD*), which describe the percentage of built area and the ratio of the building volumes to the sample area, respectively.

In this work, *SVF, H/W*, H/H_{avg}, and building orientation were used as input data in the thermal balance to take into account the characteristics of a specific urban context. *SVF* was used to describe the solar exposition and the thermal radiation lost to the sky from the built environment. *H/W*, H/H_{avg}, and building orientation were used to quantify the effect of direct solar irradiation on the building envelope at hourly time-steps.

2.2. Dynamic Urban-Scale Thermal Balance

Starting from the thermal balance at the building scale (according to ISO 52016-1:2017 and ISO 52017-1:2017), the thermal flux equations have been simplified using the available data at the urban scale. Then, the energy performance of buildings was based on the following assumptions:

- The buildings internal environments are considered with uniform thermal conditions to enable a thermal balance calculation (during the heating season, the heated space has a daily temperature of 20 ± 2 °C).
- To evaluate the heat flow between two environments, the heat transfer coefficients by transmission and ventilation are used.
- The energy need for humidification or dehumidification was neglected, as the heating systems of residential buildings are mainly central water systems with radiators and without mechanical ventilation systems; they can control only the temperature and not the relative humidity.
- The calculation time interval is one month or one hour.
- Compared to the monthly method, the main goal of the hourly calculation is to be able to take into account the influence of hourly and daily variation in weather and operation.

In this energy balance model, three thermodynamic systems (in Figure 3) were considered and the following assumptions were made: (i) the temperatures of the thermodynamic systems were uniform; (ii) the heat transmission through the building elements was one-dimensional and thermal bridges were neglected; (iii) the energy need for humidification or dehumidification was neglected; (iv) the energy balance equations can be applied also to groups of buildings with similar behavior.

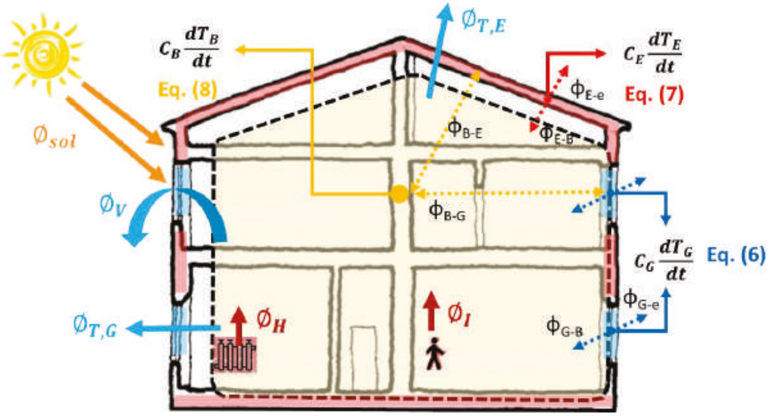


Figure 3. The three thermodynamic systems of the dynamic engineering model: B = internal structures of the building, furniture, and air; E = opaque envelope; G = transparent envelope (glass).

The three thermodynamic systems (TS) considered are:

E) The opaque envelope, which is composed of all opaque surfaces separating the heated internal volume of the building from the external environment or other unheated spaces;
G) The glazing, which consists of all transparent surfaces separating the heated internal volume of the building from the external environment or other unheated spaces;
B) The building, which is the inside part of a building with internal structures, furniture, and air.

The energy balance equations on the three systems make it possible to assess the temperatures of the three systems per hour using an iterative method. The maximum number of iterations and the acceptable error were set at 1000 and 0.001, respectively.

Starting from the general energy balance equation (Equation (5)), the equations for the three thermodynamic systems G, E, and B are shown below (the following paragraphs will explain all the variables in more detail):

$$C_{TS}\frac{dT_{TS}}{dt} = \varnothing_{sol} + \varnothing_I + \varnothing_H - (\varnothing_T + \varnothing_V), \tag{5}$$

$$C_G\frac{dT_G}{dt} = \sum \alpha_{G,k}\cdot I_{sol,k}\cdot\xi_k\cdot F_k\cdot A_{G,k} - \sum \frac{A_{G,k}}{\frac{1}{2}\cdot R_{G,k} + R_{se}}\cdot(T_G - T_{ae}) - \sum \frac{A_{G,k}}{\frac{1}{2}\cdot R_{G,k} + R_{si}}\cdot(T_G - T_B) - \sum F_r\cdot R_{se}\cdot U_{G,k}\cdot A_{G,k}\cdot h_{r,G,k}\cdot\left(T_{ae} - T_{sky}\right), \tag{6}$$

$$C_E\frac{dT_E}{dt} = \sum \alpha_{W,k}\cdot I_{sol,k}\cdot\xi_k\cdot F_k\cdot A_{W,k} - \sum \frac{A_{E,k}}{\frac{1}{2}\cdot R_{E,k} + R_{se}}\cdot b\cdot(T_E - T_{ae}) - \sum \frac{A_{E,k}}{\frac{1}{2}\cdot R_{E,k} + R_{si}}\cdot(T_E - T_B) - \sum F_r\cdot R_{se}\cdot U_{W,k}\cdot A_{W,k}\cdot h_{r,W,k}\cdot\left(T_{ae} - T_{sky}\right), \tag{7}$$

$$C_B\frac{dT_B}{dt} = \sum \tau_{G,k}\cdot I_{sol,k}\cdot\xi_k\cdot F_k\cdot A_{G,k} + \varnothing_I + \varnothing_H - \sum \frac{A_{E,k}}{\frac{1}{2}\cdot R_{E,k} + R_{si}}\cdot(T_B - T_E) - \sum \frac{A_{G,k}}{\frac{1}{2}\cdot R_{G,k} + R_{si}}\cdot(T_B - T_G) - c_a\cdot\dot{m}_a\cdot(T_{ai} - T_{ae}), \tag{8}$$

where, for each TS, C is the heat capacity (JK^{-1}); T is the temperature of the TS, air or sky (K); t is the time (s); ϕ_{sol} is the heat flow rate from solar gains; ϕ_I is the heat flow rate from internal gains; ϕ_H is the heat flow rate from the heating system; ϕ_T is the heat flow rate dispersed by transmission; ϕ_V is the heat flow rate dispersed by ventilation; α is the solar absorption coeff. (-); τ is the total solar energy transmittance (-); I_{sol} is the solar irradiance (Wm^{-2}); ξ is the envelope sunny quota (-); F is the reduction factor (-); A is the envelope area (m^2); R is the thermal resistance (m^{2}KW^{-1}); U is the thermal transmittance (Wm^{-2}K^{-1}); F_r is the form factor buildings-sky (-); h_r is the radiative heat flux coeff. (Wm^{-2}K^{-1}); c_a is the air specific heat (Jkg^{-1}K^{-1}); and $\dot{m}_a$ is the air mass flow rate (kgm^{-3}).

The hourly temperatures of the glazing (T_G) were obtained with Equation (6) from a balance of the thermal flows between the glazing and the building (T_B) and the glazing and the outdoor environment (T_{ae}); similarly, the hourly temperatures of the envelope (T_E) were calculated using Equation (7), and the hourly temperatures of the buildings were calculated using Equation (8).

The definitions of the equations and the input data of the model have been realized in order to have a building temperature equal to the set-point range during the heating season: 20 ± 2 °C. Then, it was observed that the building temperature (T_B) varied according to the outdoor climatic conditions, and therefore correlations were found with T_{ae} and $T_{sol\text{-}air}$. $T_{sol\text{-}air}$ was introduced because it allows one to take into account not only the outside air temperature but also the solar irradiation absorbed by the opaque envelope:

$$T_{sol-air} = T_{ae} + \left(\alpha_E \cdot \frac{I_{sol}}{h_e}\right), \tag{9}$$

where T_{ae} is the outside air temperature (°C), α_E is the absorption coefficient (-), I_{sol} is the incident solar irradiance (Wm^{-2}), and h_e is the external thermal adductance ($\text{Wm}^{-2}\text{K}^{-1}$).

The following subsections explain the different components of the energy balance in detail. To avoid repetitions in explaining the methodology for the three thermodynamic systems (i.e., B, E, and G), Equation (6) was used to explain the heat flux components for a generic TS.

2.2.1. The Heat Flow Rate from Solar Gains

The heat flow rate from solar gains (Φ_{sol}) is obtained directly by transmission or indirectly by absorption considering the solar irradiation through the building element (*k*). In accordance with standards ISO 13790:2008, ISO 52016-1:2017, and ISO 52017-1:2017, the heat flow rate from solar gains is given by:

$$\begin{gathered} \varnothing_{sol} = \varnothing_{sol,\alpha} + \varnothing_{sol,\tau}, \\ \varnothing_{sol,\alpha} = \sum \alpha_k \cdot I_{sol} \cdot \xi \cdot F_k \cdot A_k,\ \varnothing_{sol,\tau} = \sum \tau_G \cdot I_{sol} \cdot \xi \cdot F_k \cdot A_k, \end{gathered} \tag{10}$$

where ϕ_{sol} is the heat flow rate from solar gains, α is the solar absorption coefficient (-), τ is the total solar energy transmittance (-), I_{sol} is the solar irradiance (Wm^{-2}), ξ is the envelope sunny quota (-), F is the reduction factor (-) and, A is the envelope area (m^2).

The heat flow rate from solar gains $\phi_{sol,\alpha}$ was used for the envelope and glazing TSs, and $\Phi_{sol,\tau}$ was used for the building TS. In this model, the following data were used:

- I_{sol} was calculated considering the orientation and the inclination of the surfaces of the building envelope.
- ξ was calculated with hourly time steps, since the height of the sun (*h*) and the urban canyon height-to-distance ratio (*H/W*) were known [6].
- α_k was assumed to e equal to 0.6 for an opaque envelope (α_E), considering an intermediate color (not dark or light), while, for a transparent envelope, α_G depended on the type of glass used in the different periods of construction (e.g., 0.06 for single glass in buildings built before 1976).
- τ_G depended on the type of glass used in the different periods of construction (e.g., 0.72 for single glass in buildings built before 1976).
- the obstruction factor F_k has been calculated through the view factor and the *SVF* (on a grid of points at the street level and on the roof of buildings with the Relief Visualization Toolbox).
- A_k was calculated as all geometrical characteristics, with the support of the GIS software, considering the area of the walls (A_W), the glazing area (A_G), and the opaque envelope area (A_E), taking into account the non-dispersive walls between adjacent buildings.

2.2.2. Heat Flow Rate from Internal Heat Sources

The heat flow rate of residential buildings, resulting from internal heat sources (ϕ_I), depends on the average floor area per dwelling (S_f):

$$\varnothing_I = q_{int} \cdot S_f \cdot n, \tag{11}$$

where q_{int} is the internal heat flow rate (W/m^2), S_f is the average floor area of a dwelling (m^2), and n is the number of dwellings in a building (-).

The heat flow rate ϕ_I was calculated using the hourly profiles of q_{int} for daytime and nighttime due to occupants and equipment for residential buildings, according to the standards UNI/TS 11300-1:2014 and ISO 13790:2008.

2.2.3. Heat Flow Released from the Heating System

In Turin, the most widely used heating system is a centralized water heating system consisting of radiators and a climate control unit; only recently have room controllers been installed. In this model, the heat flow rate released from the heating system (ϕ_H) guarantees the set-point range in the buildings; then, when the comfort temperature is reached (i.e., 20 ± 2 °C in the daytime), the heating system is switched off.

If the heat flow rate supplied to the heating system $\phi_{S,H}$ is known, it is possible to calculate ϕ_H by multiplying $\phi_{S,H}$ by the system efficiency η_H:

$$\varnothing_H = \varnothing_{S,H} \cdot \eta_H, \tag{12}$$

where ϕ_H is the heat flow released into the building by the heating system (W); $\phi_{S,H}$ is the heat flow supplied by the DH network (W); and η_H is the system efficiency (-), which depends on the period of construction of the buildings.

2.2.4. Heat Flow Rate Lost by Transmission

The heat flow rate lost by transmission through the building envelope can be calculated considering the heat flow lost by transmission due to temperature differences and the extra heat flow due to the infrared radiation lost to the sky. The heat flow rate due to temperature differences through walls, the roof, slabs, and windows was calculated considering the thermal transmittances (U) and the thermal resistances (R) of the building element k, according to the thermal properties of common building elements for the different periods of construction (UNI-TR 11552:2014). $\phi_{T,t}$ was calculated in accordance with ISO 13790:2008, and it is given by:

$$\varnothing_{T,t} = \sum \frac{A_k}{\frac{1}{2} \cdot R_k + R_{se}} \cdot b \cdot (T_{TS} - T_{ae}) - \sum \frac{A_k}{\frac{1}{2} \cdot R_k + R_{si}} \cdot (T_{TS} - T_B), \tag{13}$$

where $\phi_{T,t}$ is the heat flow rate lost by transmission (W), k is the envelope element (-), A_k is the area of the element k (m^2), R_k is the thermal resistance (m^{2}KW^{-1}) of the building element k, R_s is the surface thermal resistance (m^{2}KW^{-1}) (R_{se}=0.04 m^{2}KW^{-1}, R_{si}= 0.13 m^{2}KW^{-1} for a horizontal heat flow, 0.17 m^{2}KW^{-1} for a downward heat flow, and 0.10 m^{2}K^{-1}W for an upward heat flow), b is the correction factor for unconditioned adjacent spaces (b=1 for external surfaces, b=0.5 for cellars, and b=0.9 for unheated attics), and T is the temperature of the thermodynamic system [K].

The extra heat flow due to thermal radiation lost to the sky ($\phi_{T,r}$), for opaque and transparent building elements is given by:

$$\varnothing_{T,r} = F_r \cdot R_{se} \cdot U_k \cdot A_k \cdot h_{r,k} \cdot \left(T_{ae} - T_{sky}\right), \tag{14}$$

where F_r is the form factor between a building element and the sky (-), R_{se} is the external surface thermal resistance (m^{2}KW^{-1}), U_k is the thermal transmittance of the element k (Wm^{-2}K^{-1}), A_k is the projected area of the element k (m^2), $h_{r,k}$ is the radiative heat transfer coefficient (Wm^{-2}K^{-1}), and T is the temperature of the external air and sky (K).

The form factor F_r depends on the presence of obstructions ($F_{sh,ob}$) and was calculated as a function of the sky view factor (SVF) and the view factor that depends on the surface inclination (γ). The radiative heat transfer coefficient $h_{r,k}$ was calculated according to ISO 13790:2008, with the emissivity ε of the external surfaces assumed to be equal to 0.9 for opaque elements and 0.873 for glass without low-emission coatings.

2.2.5. Heat Flow Rate from Ventilation

The heat flow rate from ventilation (ϕ_V) depends on the heat capacity of the air per volume ($\rho_a \cdot c_a$), the number of air changes per hour (*ach*), and the temperature differences of the air:

$$\varnothing_V = c_a \cdot \dot{m}_a \cdot (T_{ai} - T_{ae}) = \rho_a \cdot c_a \cdot \frac{ach \cdot V}{3600} \cdot (T_{ai} - T_{ae}), \tag{15}$$

where ρ_a is the air density (kgm^{-3}), c_a is the air specific heat (Jkg^{-1}K^{-1}), $\rho_a \cdot c_a$ the heat capacity of air per volume (Jm^{-3}K^{-1}), $\dot{m}_a$ is the air mass flow rate (kgm^{-3}), *ach* are the number of air changes per hour (h^{-1}), V is the volume of air (m^3), and T_a is the air temperature inside and outside the building (K).

Firstly, a constant air change rate ach= 0.5 h^{-1} was assumed during the day (24 h), considering natural ventilation through infiltrations (widely used in Italy in residential buildings). In the second phase of this work, in order to improve the accuracy of the model, *ach* was assumed to be variable during the daytime and nighttime; ventilation heat losses are minimal during the night due to the presence of shutters. Finally, *ach* was calculated considering that when the building temperature exceeds the set-point range, users can open windows; therefore, the air change rate can be calculated considering a quota for infiltrations and a quota for window openings. Then, the number of *ach* for the window openings was calculated according to [45] (in Figure 4).

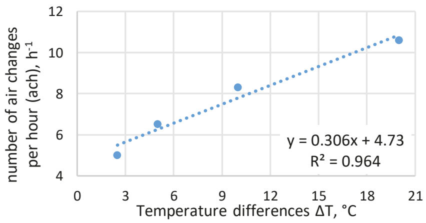


Figure 4. Correlation between $\Delta T = (T_{ai} - T_{ae})$ (°C) and the number of air exchanges per hour; measured data for typical Italian windows with a height = 1.5 m [45].

3. Model Application

The presented thermal balance model was applied to a district in the city of Turin (IT). Turin is located in the northwestern part of Italy, and it has a temperate continental climate (Italian zone E), with 2648 Heating Degree Days (HDD) at 20 °C (UNI 10349-3:2016). There are about 60,000 heated buildings in the city, nearly 45,000 of which are residential. These are mainly large and compact blocks of apartments, and 80% of them were built before 1976, before the first Italian law on building energy savings [6]. The energy consumption for space heating in Turin is rather important due to the high building density, the low level of energy efficiency of the buildings, and the cold climate; therefore, a DH network was built in 2000 to distribute energy effectively and reduce the high emissions of individual boilers; the DH network is currently connected to 60.3 Mm^3 of buildings with about 600,000 inhabitants in Turin [46].

In this work, the DH energy consumptions were used to design, optimize, and validate the dynamic urban-scale energy model. The definition of the model was carried out by choosing the input data and defining the balance equations in order to have comfortable temperatures in the buildings. Then, the model was optimized by finding correlations between the temperature of the building and the climatic conditions. The validation of the model was carried out using the model to calculate energy consumptions, setting the internal temperature of the building according to the external climatic conditions. The model was applied to a total of 92 residential buildings grouped in four clusters of various periods of construction in a central district of Turin.

3.1. Input Data

In this section, the main input data used for the model are described. All the data were geo-referenced, and a DBT for the city of Turin was created with the support of the GIS tool.

The energy consumptions of the buildings were provided by the Iren DH company and elaborated at hourly time steps. Starting from 102 residential buildings (whose thermal consumption was known for the 2013–2014 heating season), 92 were selected for the model application. The first selection was made considering only buildings with the heating system switched off during the night (typical of Italian buildings). Then, the other six buildings were excluded from this analysis due to anomalous/missing data. The local climate conditions were elaborated using hourly data (i.e., air temperature, relative humidity, solar irradiation) measured at the Politecnico di Torino WS.

The main thermo-physical and geometric parameters of the building elements are indicated in Tables 3 and 4. Table A1 in Appendix A reports the other main data used for the 92 analyzed residential buildings.

Data on the thermal transmittances (U) and relative thermal resistances (R) of the building elements for different periods of construction are reported in Table 3. The U data in the GIS database were calculated for each building according to its period of construction, distinguishing U values for vertical walls, glass, cellar slabs (with an adjustment factor b equal to 0.5), and ceiling slabs in unheated attics with un-insulated roofs (with an adjustment factor b of 0.9).

The heat capacities of the building elements are reported in Table 4 according to the period of construction. For the envelope elements, the thermal capacity reported considers the recurring stratigraphies for the different construction periods (UNI/TR 11552:2014). For the building, we started from the value of 165,000 J/m^2/K (per m^2 of envelope, from UNI/TS 11300-1:2014), which considers the inside part of the building plus 10 cm of the internal envelope; subtracting this last quota, the value of 30,496 J/m^2/K was obtained (per m^2 of net heated surface, considering that air and furniture have a heat capacity of 10,000 J/m^2/K, ISO 52016-1:2017).

Table 3. Thermal transmittances and resistances of the building elements and the TSs (E and G).

Building Element	**1919–1945**			**1946–1960**			**1961–1970**			**1971–1980**		
	U	$1/2 \cdot R_k + R_{se}$	$1/2 \cdot R_k + R_{si}$	U	$1/2 \cdot R_k + R_{se}$	$1/2 \cdot R_k + R_{si}$	U	$1/2 \cdot R_k + R_{se}$	$1/2 \cdot R_k + R_{si}$	U	$1/2 \cdot R_k + R_{se}$	$1/2 \cdot R_k + R_{si}$
Slab in cellar	0.79	0.63		0.62	0.81		0.65	0.77		0.61	0.83	
Slab in attic	1.76	0.28		1.35	0.37		1.49	0.34		1.35	0.37	
Wall	1.35	0.41	0.32	1.18	0.47	0.38	1.13	0.49	0.40	1.04	0.53	0.44
Envelope (E)	1.32	0.42	0.33	1.11	0.50	0.41	1.11	0.50	0.41	1.02	0.54	0.45
Glazing (G)	4.75	0.15	0.06	4.40	0.16	0.07	4.90	0.15	0.06	4.57	0.15	0.06

Values of thermal transmittances U are expressed in $Wm^{-2}K^{-1}$, and the thermal resistances R are in m^2KW^{-1}.

Table 4. Thermal capacities of the building elements and thermodynamic systems (E, G, B).

Building elements	<1945	1946–1960	1961–1970	>1971
Slab in cellar	317,867			
Slab in attic	434,400			
Wall	574,560	574,560	231,000	191,520
Envelope (E)	497,888	503,490	282,871	242,030
Glazing (G)	7314			
Building (B): air, furniture and internal partitions	30,496 *			

Values of the thermal capacities are expressed in $Jm^{-2}K^{-1}$ (per m^2 of envelope area). * The reference area [m^2] for the building (B) is its net heated surface and not the envelope area.

3.2. Building Clusters

In order to represent the average energy behavior of residential buildings, groups of buildings with similar characteristics were identified. This analysis can simplify the application of the model on an urban scale. Building archetypes were identified by analyzing the energy consumption profiles, the thermo-physical and geometric parameters, and the typology of the heating systems. The main energy-related variables identified for the building archetypes were the volume, the area of dispersing surfaces, the envelope technology, the percentage of windowed area, and the type and efficiency of the heating system [46]. The "surface-to-volume" (S/V) ratio was not considered because is quite constant, with an average value of 0.28 m^{-1} and a standard deviation of 0.04 (i.e., large apartment buildings). Then, after analyzing the trend in heating consumption, the buildings were grouped into four construction periods and with different envelope technologies, percentages of windowed area, and types and efficiencies of the heating system.

Table 5 indicates the characteristics of each cluster and the main input data that were used to analyze the energy balance model. The following discussion is on the four clusters, which have similar volumes (only cluster 4 has different values of net heated volume and floor due to low values of occupancy) and therefore allow a comparison of their results.

Table 5. Cluster characteristics.

Data	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Period of construction	1919–1945	1946–1960	1961–1970	1971–1980
No. of buildings	27	32	22	11
Gross heated volume [m^3]	131,219 (−9%) *	140,014 (−2%) *	159,195 (+11%) *	91,909 (−36%) *
Net heated floor [m^2]	37,983	40,634	41,816	25,066
DH consumption [$kWh/m^3/y$]	29.20	27.48	26.88	21.21
C_E [MJ/K]	23,884	25,996	10,896	5980
C_G [MJ/K]	46	50	48	28
C_B [MJ/K]	1262	1463	1403	799
No. of dwelling units	494	504	506	240
Heated surface/unit [m^2]	93.31	91.13	93.46	97.06
System efficiency [-]	0.783	0.783	0.794	0.816

* percentage with respect to the average volume of buildings in the three first clusters.

3.3. Typical Monthly Days

The hourly data on the external air, solar-air and sky temperatures, relative humidity, solar irradiation, and position of the sun from the Politecnico WS were elaborated, and 34 typical days were identified for the 2013–2014 heating season. These days were selected to identify all the possible climate conditions during a heating season, with daily T_{ae} = 1.70–7.97 °C and $I_{sol,d}$ = 169–5774 $Wh/m^2/d$.

Table 6 indicates the characteristics of the 34 typical days that were identified. Date 1 and date 2 were chosen with similar outdoor air temperatures but different solar irradiation conditions.

Table 6. Typical days of a heating season.

Date 1.	T_{ae} [°C]	$I_{sol,d}$ [Wh/m^2/d]	h_{sol} [h]	$T_{sol\text{-}air}$ [°C]	Date 2	T_{ae} [°C]	$I_{sol,d}$ [Wh/m^2/d]	h_{sol} [h]	$T_{sol\text{-}air}$ [°C]
30/01/2014	1.70	214	9.17	2.05	**29/01/2014**	1.81	397	9.17	2.49
09/12/2013	3.42	1232	8.67	5.24	**22/11/2013**	3.70	507	9.47	4.39
01/01/2014	4.33	1610	9.17	6.60	**27/11/2013**	4.44	1939	9.47	7.25
07/02/2014	5.17	324	8.67	5.71	**26/11/2013**	5.32	2077	9.47	8.37
22/02/2014	6.24	1003	10.27	8.04	**16/12/2013**	6.30	1644	8.67	8.64
07/01/2014	7.30	1233	9.17	8.99	**15/02/2014**	7.39	1860	10.27	10.36
15/11/2013	8.32	370	9.47	8.89	**10/01/2014**	8.69	993	9.17	10.09
25/02/2014	9.21	2706	8.67	15.01	**18/11/2013**	9.36	169	9.47	9.58
21/01/2014	9.86	1732	9.17	12.45	**22/02/2014**	10.00	3633	8.67	16.46
04/11/2013	11.19	1336	9.47	13.40	**05/03/2014**	11.20	4015	11.73	17.23
08/03/2014	12.48	4225	11.73	18.78	**13/11/2014**	12.63	2151	9.47	16.33
15/10/2013	12.99	1864	10.88	16.08	**01/11/2013**	13.22	2027	9.47	17.00
06/11/2013	14.68	2451	9.47	19.07	**19/10/2013**	14.16	1020	10.88	15.90
18/10/2013	15.02	2547	10.88	19.30	**18/03/2014**	15.31	4488	11.73	21.89
31/03/2014	16.22	5102	11.73	23.44	**30/10/2013**	16.22	1205	10.88	18.11
28/10/2013	17.08	1692	10.88	19.81	**09/04/2014**	17.32	5774	13.28	24.37
08/04/2014	17.97	2890	13.28	21.39	**14/04/2014**	17.68	5754	13.28	24.57

4. Results and Discussion

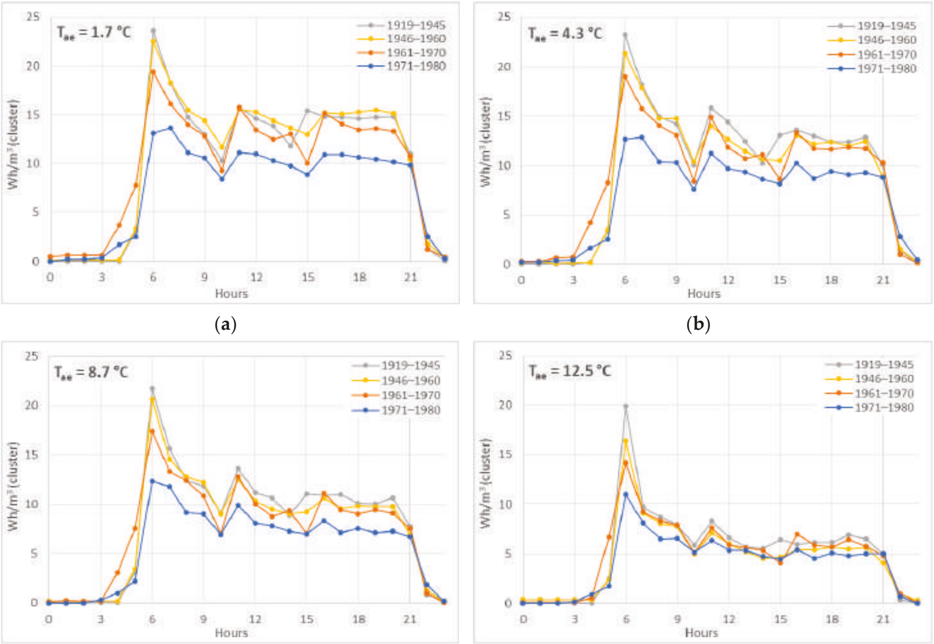
The main results pertaining to the analyses of the energy consumptions of buildings and clusters of buildings, the heat flow components of the energy balance, the trends of the temperatures of the three thermodynamic systems, and the application of the hourly energy balance model to clusters of buildings are reported in the following sections.

Building Cluster Identification

In a previous study [47], it had been shown that the hourly consumption profile for the space heating of buildings depends on the type of building, its level of energy efficiency, and the local climate conditions. For this case study on compact residential buildings, these characteristics can be represented by grouping the buildings by periods of construction. Four periods have been identified with different geometrical and material characteristics, types of envelope, and types of systems: 1919–1945, 1946–1960, 1961–1970, and 1971–1980 (new buildings in the urban environment are few and therefore it is more difficult to make this analysis).

The specific energy consumptions of the four clusters of buildings for four typical days are represented in Figure 5. It can be observed that the hourly energy consumption profiles of the clusters have a typical trend—the buildings have a night-time heating interruption, with a peak at 6 in the morning and a quite constant consumption up to 8 p.m. In general, the energy peak of the clusters decreases as the outdoor temperature (T_{ae}) increases. If the percentage of energy consumed daily is represented, the opposite would be observed: the percentage of energy consumed at 6 a.m. is higher if the outside temperature increases (as also reported in [47]). In addition, with the percentage of daily consumption, buildings that consume less have a higher peak at the same outdoor temperature: from 10% to 16% for the 1919–1945 period, from 9% to 15% for 1945–1960, from 8% to 12% for 1961–1970, and from 8% to 11% for 1971–1980. Moreover, consumption is constant at 6% from 9 a.m. to 8 p.m., regardless of the temperature and period of construction. The specific consumption per m^3 has been represented because the four clusters do not have the same heated volume (see Table 6).

Figures 6–9 show the trend of all the heat fluxes components and consequently the resulting trends of the temperatures of the three thermodynamic systems: building, opaque envelope, and glazing. The heat flux components in Equation (5) can be observed on the left; the heat flux through ventilation, ϕ_V (light blue), is quite constant. The temperatures of the three thermodynamic systems (B, E, and G) are represented, with the outside air temperature and the solar irradiance, on the right. These representations allowed us to control the input data and the weight of the energy balance components.



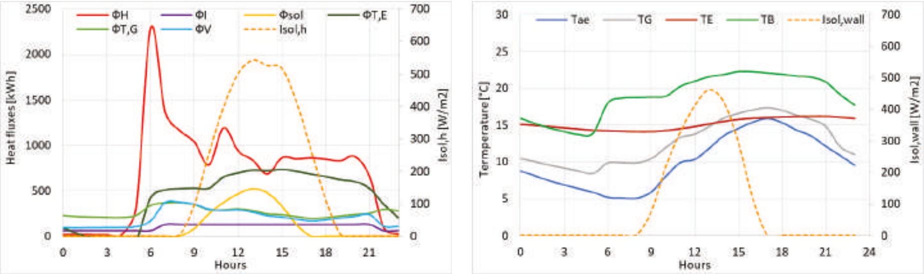
(**a**) (**b**)

(**c**) (**d**)

Figure 5. Space heating hourly consumptions (Wh/m^3) with different T_{ae}—(**a**) 1.7 °C, (**b**) 4.3 °C, (**c**) 8.7 °C, (**d**) 12.5 °C—for four clusters of buildings: cluster 1—1919–1945; cluster 2—1946–1960; cluster 3—1961–1970; cluster 4—1971–1980.

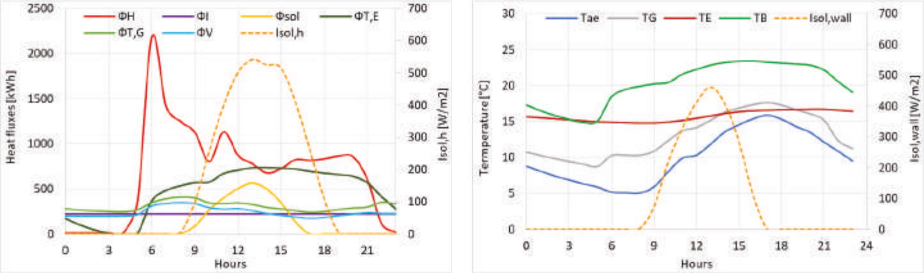
Figure 6 shows the results of the energy balance model with a number of constant air changes per hour of 0.5 h^{-1} over 24 hours for the typical day of February 22nd 2014, with a T_{ae}= 6.24 °C. It can be observed that the temperature of the building, $T_{B,}$ (in green), has a constant diurnal and nighttime trend; the set-point range (20 ± 2 °C) is reached during the day. Similar results have been obtained applying the energy balance model with variable ventilation between daytime (ach = 0.62 h^{-1}) and nighttime (0.3 h^{-1}) in Figure 7. Compared to the previous model (with constant ventilation), during the day the dispersions due to ventilation are slightly higher, and consequently the temperature B is lower. Figures 8 and 9 show results considering a variable number of air changes per hour and the opening of windows for typical days in February and October (the windows have been opened when the building temperature exceeds 22 °C). In Figure 8, the heat fluxes for February 22nd 2014 can be observed on the left with a clear difference in the heat flux from ventilation between the day and night and the high variation due to window openings. The temperature trend on the right is similar, but the temperature of the buildings does not exceed 22 °C.

The results of the energy balance model with a variable number of air changes per hour and the opening of windows have been presented also for a typical day in October, that is, October 24th 2013, with T_{ae} = 16.3 °C (Figure 9). In general, it is possible to see, on the left, the increase in the ϕ_V, due to the windows opening at 2 p.m. A similar trend can be seen for clusters 3 and 4, where the windows were opened more times, with a consequent stabilization of the building temperature.



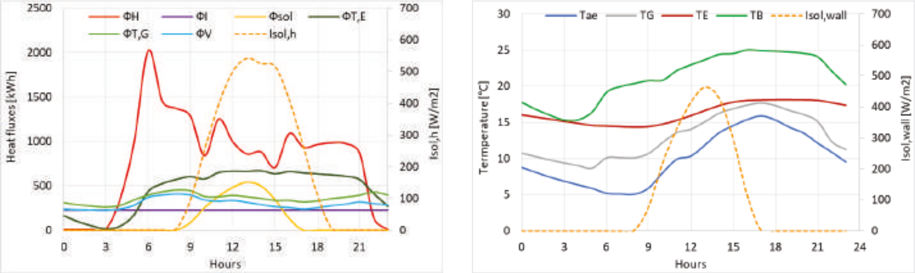
(**a**) Cluster 1 (1919—1945).

(**b**) Cluster 1 (1919—1945).



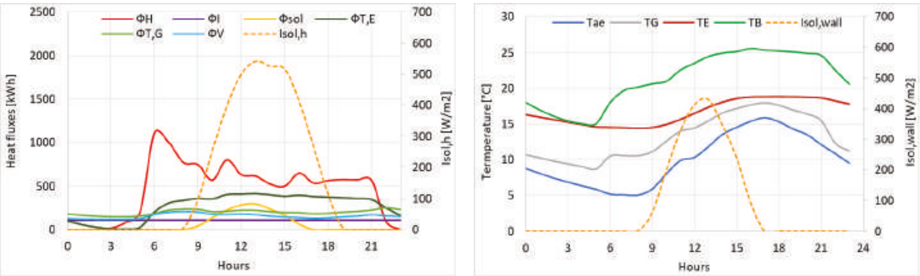
(**c**) Cluster 2 (1946—1960).

(**d**) Cluster 2 (1946—1960).



(**e**) Cluster 3 (1961—1970).

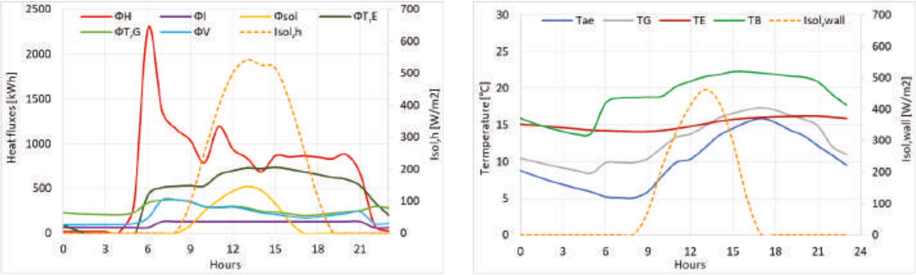
(**f**) Cluster 3 (1961—1970).



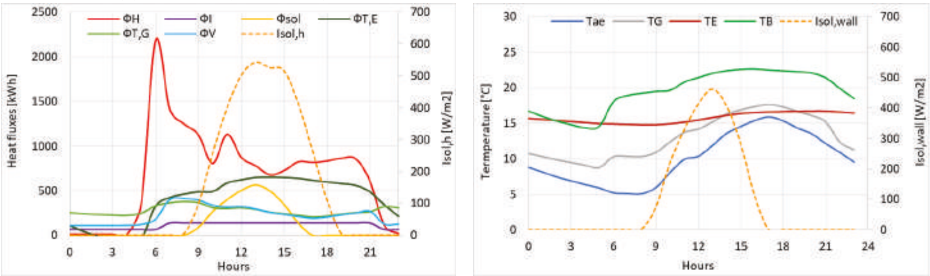
(**g**) Cluster 4 (1971—1980).

(**h**) Cluster 4 (1971—1980).

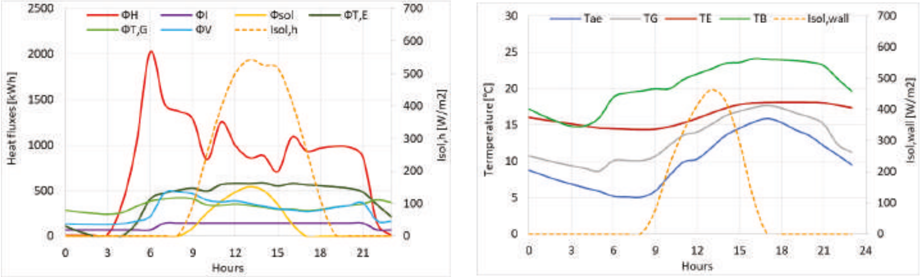
Figure 6. Heat flux components and building temperatures (with constant ach = 0.5 h^{-1}) for a typical day: February 22nd 2014, with a T_{ae}= 6.24 °C (clusters for the four construction periods).



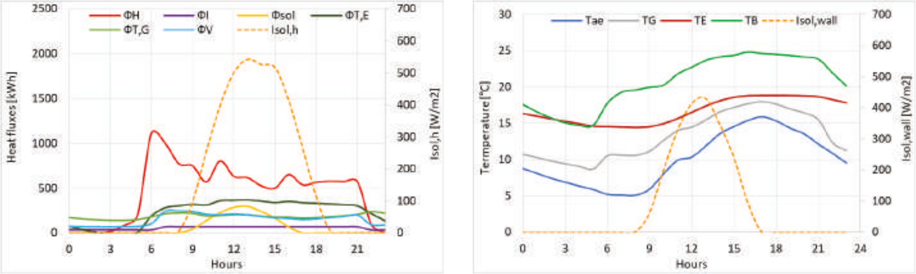
(**a**) Cluster 1 (1919—1945). (**b**) Cluster 1 (1919—1945).



(**c**) Cluster 2 (1946—1960). (**d**) Cluster 2 (1946—1960).

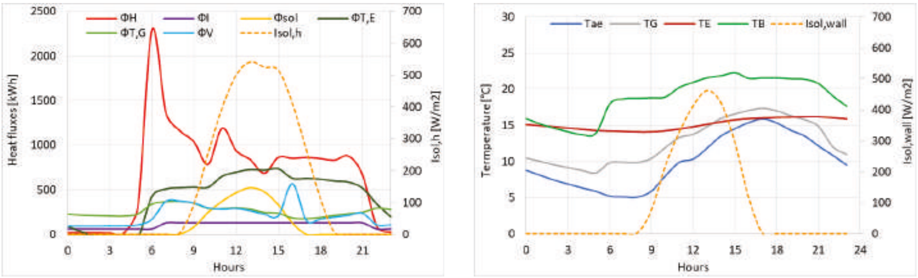


(**e**) Cluster 3 (1961—1970). (**f**) Cluster 3 (1961—1970).

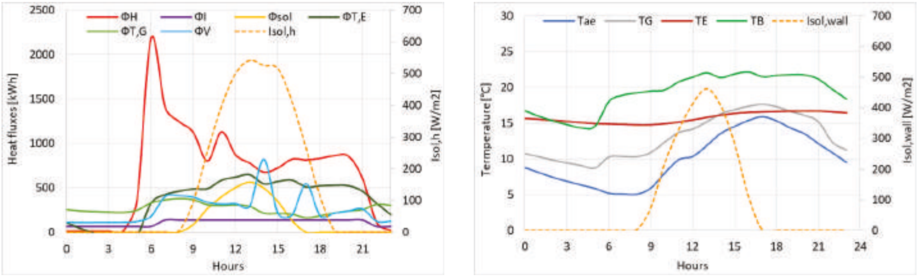


(**g**) Cluster 4 (1971—1980). (**h**) Cluster 4 (1971—1980).

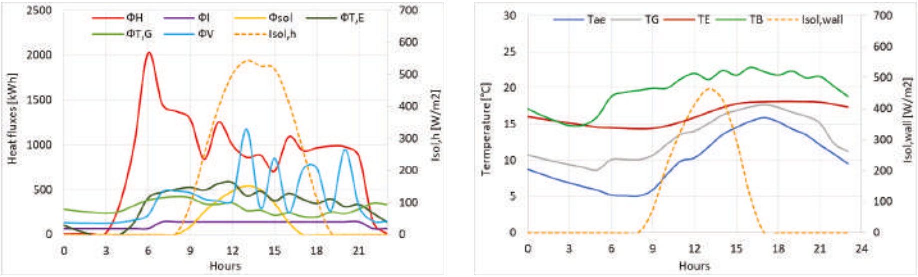
Figure 7. Heat flux components and building temperatures with a variable number of air changes per hour (in daytime *ach* = 0.62 h^{-1}, and in nighttime *ach* = 0.3 h^{-1}) for a typical day: February 22nd 2014, with a T_{ae}= 6.24 °C (clusters for the four construction periods).



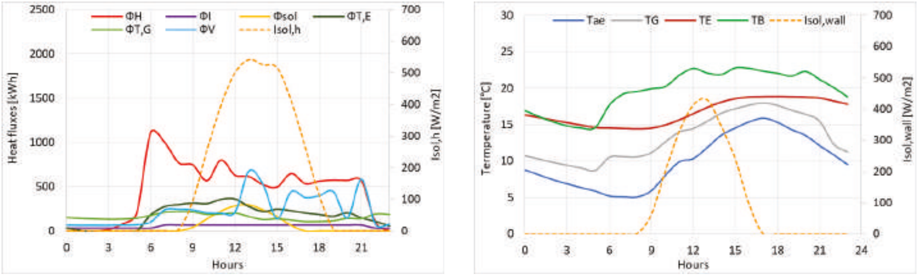
(**a**) Cluster 1 (1919—1945). (**b**) Cluster 1 (1919—1945).



(**c**) Cluster 2 (1946—1960). (**d**) Cluster 2 (1946—1960)

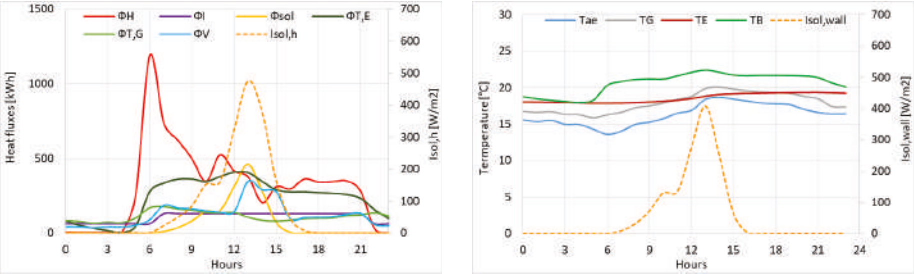


(**e**) Cluster 3 (1961—1970). (**f**) Cluster 3 (1961—1970).



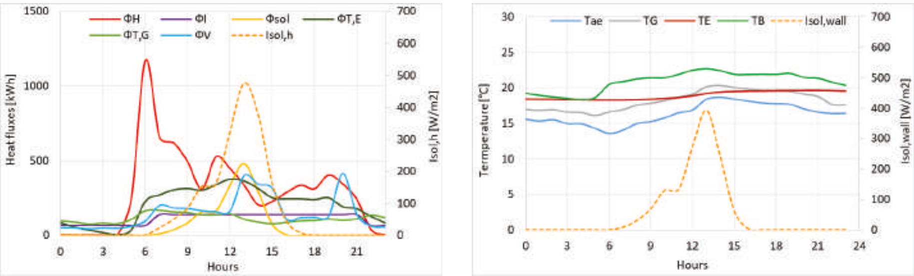
(**g**) Cluster 4 (1971—1980). (**h**) Cluster 4 (1971—1980).

Figure 8. Heat flux components and building temperatures (with a variable number of air changes per hour and windows opening) for a typical day: February 22nd 2014, with a T_{ae}= 6.24 °C (clusters for the four construction periods).



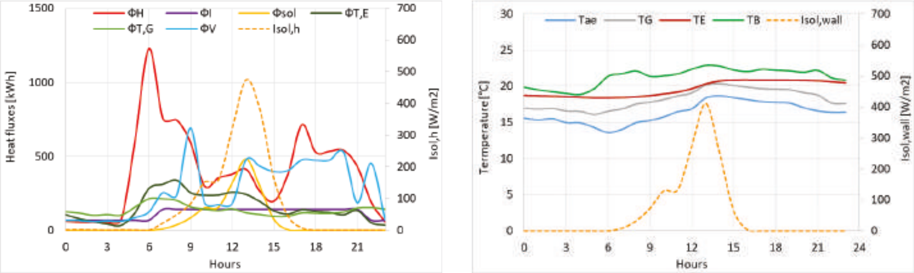
(**a**) Cluster 1 (1919—1945).

(**b**) Cluster 1 (1919—1945).



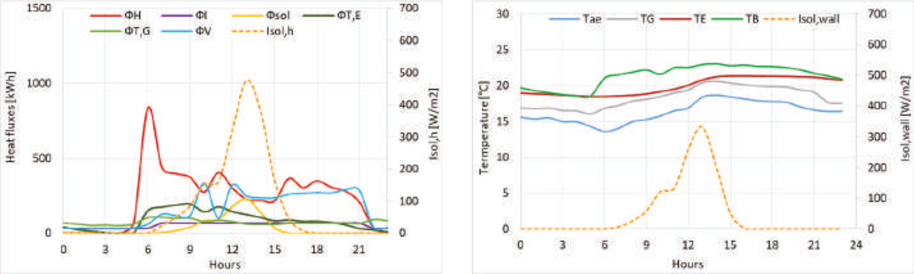
(**c**) Cluster 2 (1946—1960).

(**d**) Cluster 2 (1946—1960).



(**e**) Cluster 3 (1961—1970).

(**f**) Cluster 3 (1961—1970).



(**g**) Cluster 4 (1971—1980).

(**h**) Cluster 4 (1971—1980).

Figure 9. Heat flux components and building temperatures (with a variable number of air changes per hour and windows opening) for a typical day: October 24th 2013, with a T_{ae} = 16.3 °C (clusters with solid lines and buildings with dashed lines for the three construction periods).

Figure 10 shows a representation of the positive and negative heat flux contributions for seven typical days that have been selected from Table 6 (remember that cluster 4 has a smaller useful surface area and volume). It is possible to observe that the heat flux for space heating is higher in the cold months of December and January, the thermal losses by transmission through opaque envelope and glazing and by ventilation vary according to the external local climate conditions and are higher in cold months, the internal gains are constant, and the solar gains through windows are higher in the warmer months (October, March and April).

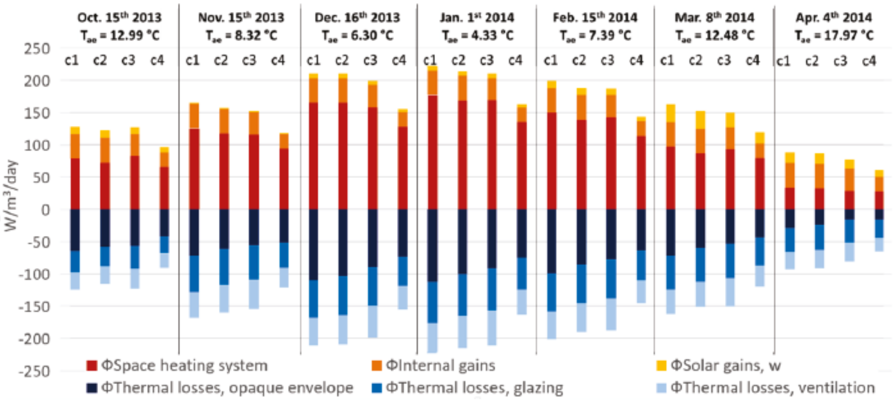


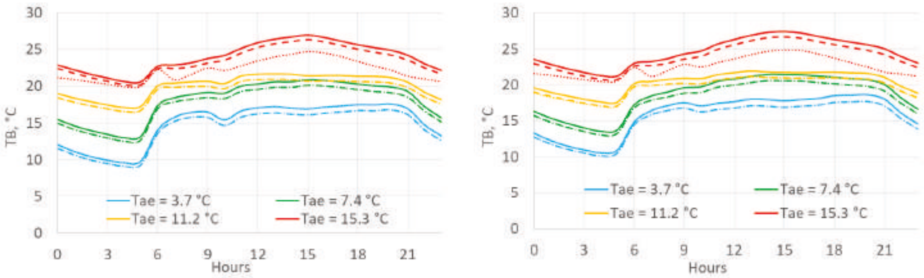
Figure 10. Positive and negative heat flux contributions with constant ventilation (*ach* = 0.5 h^{-1}) for the typical monthly days ($T_{ae,day}$), distinguishing by clusters (c1, c2, c3, c4).

The building temperatures, T_B, are represented in Figure 11, where the climate conditions for four typical days are shown, with a T_{ae} = 3.7, 7.4, 11.2, and 15.3 °C. The solid lines represent the results of T_B with constant ventilation with ach = 0.5 h^{-1}, the dashed lines refer variable ventilation between daytime (*ach* = 0.62 h^{-1}) and nighttime (0.3 h^{-1}), and the dotted lines represent the *ach* variable and windows opening. The temperature of the three ventilation models is very similar for colder days. The difference with window openings can be observed only for higher temperatures (dotted lines).

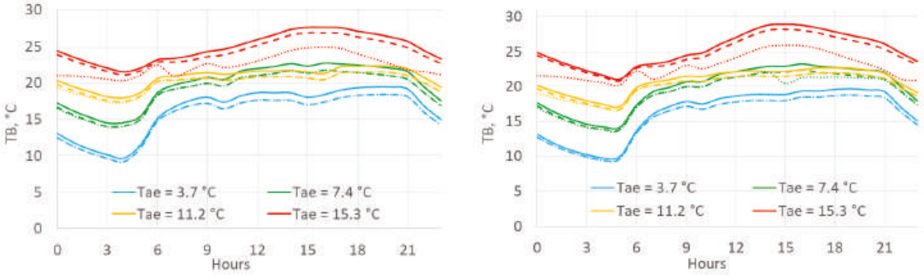
Comparing the four clusters of buildings with different periods of construction, is possible to observe that the night and daytime building temperatures are quite stable and depend on both the characteristics of the buildings and on the external climatic conditions. This behavior suggests that it would be possible to hypothesize some correlations between the climatic conditions and the day and night temperatures of the building, T_B.

The linear correlations between T_B, T_{air}, and $T_{sol\text{-}air}$ are reported in Figure 12 for the different ventilation conditions. In particular, Figure 12a,b presents the correlations with a constant *ach* = 0.5 h^{-1}, Figure 12c,d considers a variable *ach*, and Figure 12e,f considers a variable *ach* with window opening. The main results are the following:

- Good correlations with T_B are obtained for $T_{sol\text{-}air}$ throughout the day (24 h) and daytime, while T_{ae} was used for the nighttime (when solar irradiance cannot influence T_B).
- Linear correlations are obtained with a good R^2 coefficient of determination.
- Different correlations are obtained for the different clusters of buildings built in the four construction periods; the correlations with older buildings have a higher R^2 and the values deviate less from the line of correlation with lower external temperatures.
- Different correlations are obtained for the different ventilation typologies; with variable *ach* and window openings, the lines of the correlation change the slope.



(**a**) Cluster 1 (1919—1945). (**b**) Cluster 2 (1946—1960).



(**c**) Cluster 3 (1961–1970). (**d**) Cluster 3 (1971–1980).

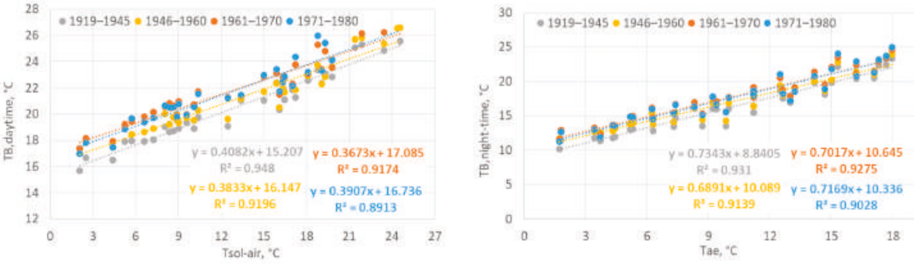
Figure 11. Building temperatures, T_B, with an *ach* = 0.5 h^{-1} (solid lines), with a variable *ach* during the daytime (0.62 h^{-1}) and nighttime (0.3 h^{-1}) (dashed line), and with a variable *ach* plus window openings (dotted lines) for four typical days (clusters of the four construction periods).

The Figure 13 shows the comparison between the simulated and measured daily thermal consumptions applying the model with the correlations for the building temperature and the three different ventilation conditions. A very good accuracy can be observed by comparing the simulated and measured values for each period of construction for the model with *ach* constant; the accuracy decreases with a variable *ach* and the last model with a variable *ach* and window openings is not accurate enough. This result attests that, in Turin, ventilation can be represented with the model of constant infiltration (during the analyzed heating period).

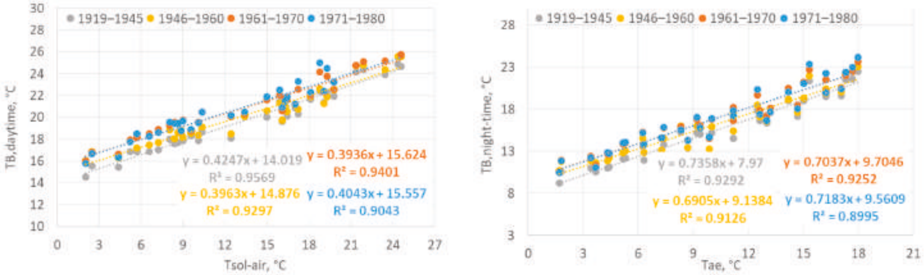
In Figure A1 of Appendix A, the comparison between the calculated and measured monthly energy consumption data are represented. The main conclusions are the same: the model that best represents the results is the one with constant ventilation; this model with a constant air change rate *ach* of 0.5 h^{-1} was chosen.

This type of model can be applied at the urban scale to represent the distribution of energy consumptions, evaluate the heat peak in every zone of a city, access the potential of renewable energy technologies that can be useful to meet that energy demand profile, and analyze the further expansion of a district heating network. All these applications can improve the security, sustainability, and affordability of the energy system and therefore the energy resilience of an urban environment.

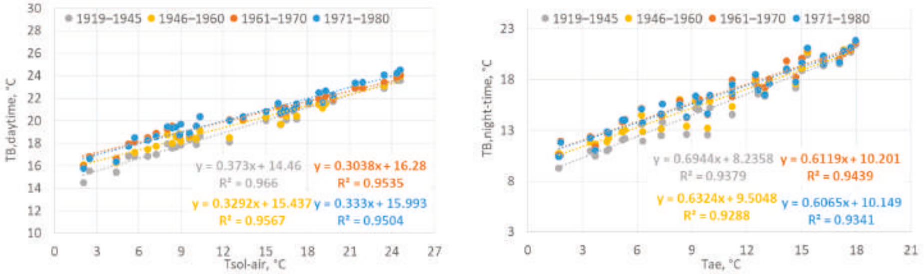
In Figure 14, an example of the hourly model application to the city of Turin is represented. By changing the building attributes on the right, the results of this solution can be obtained.



(**a**) *ach* = 0.5 h−1 day. (**b**) *ach* = 0.5 h−1 day.

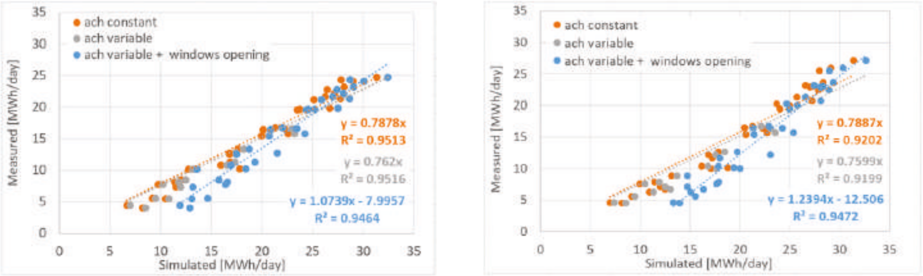


(**c**) *ach* = 0.62 h−1 daytime, *ach* = 0.3 h−1 nighttime. (d) *ach* = 0.62 h−1 daytime, *ach* = 0.3 h−1 nighttime.

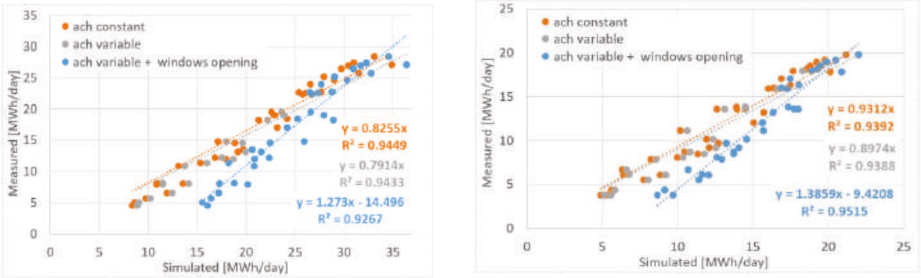


(**e**) *ach* variable with window openings. (**f**) *ach* variable with window openings.

Figure 12. Correlations between the T_B and $T_{sol\text{-}air}$ throughout the daytime from 6 a.m. to 9 p.m. (left column): T_B and T_{ae} during the nighttime, from 10 p.m. to 5 a.m. (right column). Distinguishing constant (**a, b**) and variable ventilation (**c, d**) and variable ventilation with window openings (**e, f**).



(**a**) Cluster 1 (1919–1945). (**b**) Cluster 2 (1946–1960).



(**c**) Cluster 3 (1961–1970). (**d**) Cluster 4 (1971—1980).

Figure 13. Comparison between simulated and measured typical daily thermal consumptions, distinguishing *ach* = 0.5 h^{-1} (in orange), *ach* = 0.62 h^{-1} during the daytime, *ach* = 0.3 h^{-1} during the nighttime (in grey), and a variable *ach* with window openings (in blue).

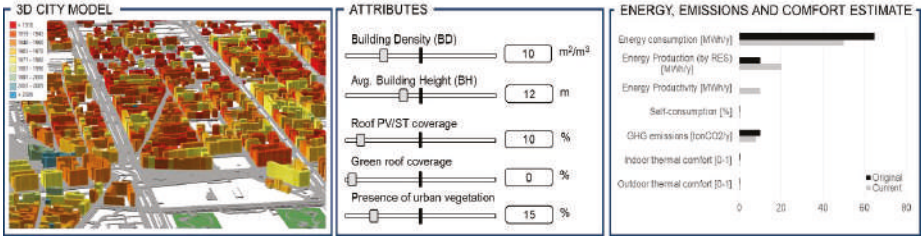


Figure 14. Example of urban-scale energy tools: 3D city model; building attributes; energy, GHG emissions, and comfort estimation.

5. Conclusions

In this work, the energy balance that has been studied for a single residential building has been simplified in order to use it at an urban scale with the existing databases (e.g., the Municipal Technical Maps that are available for every city), for groups of buildings with similar characteristics, and evaluate the distribution of space heating consumption in an urban context. The geometrical and typological characteristics of buildings were evaluated by geo-referencing information on building consumption using a GIS tool. This analysis was carried out on 92 residential buildings and on 4 groups of buildings with similar space heating consumptions and characteristics.

The main findings of the presented work can be summarized as follows:

- The presented model allows us to make fairly accurate forecasts on the consumption of buildings with the data available on an urban scale; of course, the existing tools are more accurate but do not allow analysis on cities, have much longer calculation times, and need data that is often not available.

- The best results were obtained with the building temperature variable according to the external climatic conditions and considering a constant ventilation by infiltrations of 0.5 *ach*.
- The use of a GIS tool allows us to design a very flexible urban-scale model, use data with different scales, manage the existing free databases, and map the results with a spatial distribution on the territory.
- Energy models and tools, such as the one proposed here, could be used at the territorial scale to:

    1. identify effective energy policies for the city, considering the real characteristics of buildings, population, and urban morphology;
    2. create an easily upgradable energy atlas for buildings, related to the existing territorial databases;
    3. evaluate the feasibility of establishing energy communities and grouping private and public entities, considering their energy consumptions and productions to reach energy security with a low environmental impact and good socio-economic effects.

The novelty of this simplified energy balance model concerns the possibility of applying it at the urban scale with the introduction of urban variables into the energy balance equations in order to consider the real characteristics of the urban context (with the sky view factor *SVF*, the urban canyon effect *H/W* ratio, and the solar exposition). These simplified engineering models can be used in an urban energy atlas to support decision-making in order to study how to improve the energy resilience of neighborhoods and cities with a place-based tool.

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Nomenclature

A	area, m^2	I	solar irradiance, Wm^{-2}
BCR	building coverage ratio, m^2/m^2	ID	identity code, -
BD	building density, m^3/m^2	MOS	main orientation of streets, -
c	specific heat capacity, $Jkg^{-1}K^{-1}$	R	thermal resistance, m^2KW^{-1}
C	effective heat capacity of a conditioned space (thermal capacity), JK^{-1}	S	net floor surface, m^2
DBT	territorial database, -	S/V	surface to volume ratio, m^2/m^3
DH	district heating, -	SVF	sky view factor, -
DSM	digital surface model, -	t	time, s
F	reduction factor, -	T	temperature, °C
GHG	greenhouse gas, -		
GIS	geographic information system, -	TS	thermodynamic system
h	surface coefficient of heat transfer, $Wm^{-2}K^{-1}$	U	thermal transmittance, $Wm^{-2}K^{-1}$
HDD	heating degree days, °C	V	volume, m^3
H/W	urban canyon height to width ratio, -		
Greek symbols			
α	absorption coefficient of solar radiation, -	λ	conductivity, $Wm^{-1}K^{-1}$
ε	emissivity of a surface for long-wave thermal radiation, -	ξ	shadows percentage, -
η	system efficiency for space heating, -	τ	solar factor, -
ρ	density, kg/m^3	Φ	heat flow rate, thermal power, W
Subscripts			
ae	external air	int	internal
B	building	k	building element
b	correction factor for unconditioned adjacent spaces	se	external surface
E	envelope	sol	solar
e	external	T	transmission
G	glazing	v	ventilation
H	heating	w	wall

Appendix A

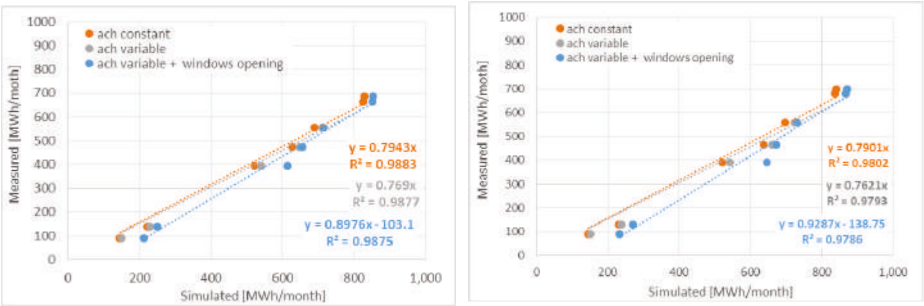
Table A1. Characteristics of the analyzed 92 residential buildings connected to the DH network with the shutdown of the heating system at nighttime.

ID	Period	Height [m]	Gross Vol. [m^3]	Occup. [-]	S/V [m^{-1}]	A_W [m^2]	A_G [m^2]	A_E [m^2]	H/W [-]	SVF [-]
213	1919–1945	22.54	4983	0.93	0.28	803	166	1245	0.57	0.66
143	1919–1945	21.31	3905	0.63	0.29	646	115	1013	0.58	0.75
157	1919–1945	18.35	4804	0.88	0.33	896	164	1420	0.50	0.74
87	1919–1945	25.00	14,113	0.88	0.27	2286	423	3415	0.50	0.74
23	1919–1945	19.14	5078	0.91	0.27	684	166	1215	0.49	0.63
28	1919–1945	28.36	6593	0.77	0.29	1234	203	1699	0.55	0.62
36	1919–1945	14.98	5514	1.00	0.36	1069	184	1805	0.54	0.64
38	1919–1945	17.64	3236	0.91	0.30	497	92	864	0.49	0.63
48	1919–1945	15.10	5871	1.00	0.35	1090	194	1868	0.54	0.64
50	1919–1945	15.92	5405	0.91	0.29	702	170	1381	0.49	0.63
51	1919–1945	24.25	7225	1.00	0.26	1069	223	1665	0.54	0.64
55	1919–1945	19.72	11,175	0.87	0.28	1625	354	2759	0.55	0.63
212	1919–1945	19.78	4311	0.93	0.28	626	136	1062	0.57	0.66
94	1919–1945	19.01	3660	0.91	0.29	568	120	953	0.49	0.63
96	1919–1945	24.25	8476	1.00	0.29	1476	262	2175	0.54	0.64
99	1919–1945	24.25	8139	1.00	0.30	1496	252	2168	0.54	0.64
129	1919–1945	22.14	6986	0.81	0.26	943	237	1574	0.59	0.63
166	1919–1945	18.94	4960	0.87	0.32	917	164	1441	0.55	0.63
179	1919–1945	14.71	5484	1.00	0.36	1050	186	1796	0.54	0.64
17	1919–1945	20.55	6442	0.76	0.25	798	196	1425	0.57	0.62
61	1919–1945	21.88	9228	0.99	0.28	1386	316	2230	0.49	0.64
242	1919–1945	18.52	3773	0.93	0.27	495	127	902	0.50	0.62
218	1919–1945	23.92	12,156	1.00	0.26	1723	381	2739	0.54	0.64
122	1919–1945	23.68	4792	0.87	0.34	1050	152	1455	0.55	0.63
62	1919–1945	19.18	8897	0.91	0.29	1323	290	2251	0.49	0.63
103	1919–1945	22.00	12,825	0.92	0.24	1482	437	2648	0.58	0.71
52	1919–1945	25.10	16,387	0.95	0.21	1498	571	2804	0.56	0.75
132	1946–1960	21.89	8871	0.76	0.27	1269	304	2080	0.57	0.62
236	1946–1960	21.37	4039	0.82	0.26	547	118	925	0.52	0.65
92	1946–1960	29.95	7912	0.98	0.27	1372	264	1900	0.55	0.70
208	1946–1960	20.00	7428	0.82	0.29	1216	232	1959	0.52	0.65
5	1946–1960	22.77	4538	0.98	0.25	605	149	1004	0.55	0.70
6	1946–1960	22.89	4355	0.98	0.31	830	143	1210	0.55	0.70
14	1946–1960	19.55	3686	0.82	0.27	506	118	883	0.52	0.65
18	1946–1960	38.34	12,935	0.80	0.22	1720	422	2394	0.69	0.67
25	1946–1960	22.39	5460	0.88	0.32	1061	183	1549	0.50	0.74
35	1946–1960	27.56	7298	0.82	0.26	1108	232	1637	0.52	0.65
108	1946–1960	19.47	6291	0.76	0.29	999	202	1645	0.57	0.62
147	1946–1960	24.28	8740	0.76	0.26	1303	270	2023	0.57	0.62
222	1946–1960	21.11	6807	0.82	0.25	874	202	1519	0.52	0.65
238	1946–1960	19.47	4930	0.76	0.27	658	158	1164	0.57	0.62
146	1946–1960	22.31	8668	0.95	0.26	1223	291	2000	0.56	0.75
187	1946–1960	19.50	3600	0.82	0.27	470	115	839	0.52	0.65
67	1946–1960	27.64	5097	0.82	0.24	698	161	1067	0.52	0.65
64	1946–1960	19.69	8927	0.93	0.28	1333	283	2239	0.57	0.66
162	1946–1960	21.77	4296	0.87	0.30	745	148	1140	0.55	0.63
198	1946–1960	27.84	8535	0.80	0.26	1346	268	1959	0.69	0.67
181	1946–1960	24.98	3743	0.91	0.27	614	112	914	0.49	0.63
177	1946–1960	19.10	5151	0.93	0.29	773	169	1313	0.57	0.63
133	1946–1960	19.28	3689	0.87	0.33	724	120	1106	0.53	0.66
3	1946–1960	20.98	4389	0.93	0.29	736	131	1155	0.57	0.63
69	1946–1960	28.00	8008	0.82	0.25	1171	250	1743	0.52	0.65
193	1946–1960	15.49	10,486	0.76	0.35	2021	338	3374	0.53	0.63
111	1946–1960	24.24	9050	0.93	0.30	1656	280	2403	0.50	0.62
88	1946–1960	23.92	9954	1.00	0.30	1843	312	2675	0.54	0.64
171	1946–1960	24.53	9472	0.76	0.26	1398	290	2170	0.57	0.62
188	1946–1960	19.60	5094	0.82	0.26	631	162	1151	0.52	0.65
130	1946–1960	25.95	5008	0.76	0.27	814	169	1200	0.57	0.62
221	1946–1960	28.41	5892	0.80	0.25	876	181	1291	0.69	0.67
74	1961–1970	24.82	11,337	0.80	0.28	1960	343	2874	0.37	0.78
240	1961–1970	23.04	3349	0.98	0.24	390	109	680	0.55	0.70
45	1961–1970	13.00	8324	0.87	0.32	1162	240	2443	0.55	0.63
9	1961–1970	28.10	6528	0.98	0.24	880	203	1345	0.55	0.70
22	1961–1970	23.95	5968	0.93	0.26	837	187	1336	0.57	0.66
72	1961–1970	29.85	8121	0.80	0.27	1378	272	1922	0.37	0.78
76	1961–1970	30.57	5743	0.95	0.28	1018	188	1394	0.56	0.75
173	1961–1970	18.68	7234	0.93	0.27	901	242	1675	0.50	0.62
185	1961–1970	24.03	4616	0.93	0.29	825	144	1210	0.57	0.66
202	1961–1970	22.55	12,232	0.76	0.26	1741	407	2826	0.57	0.62
210	1961–1970	28.10	6342	0.98	0.30	1253	197	1705	0.55	0.70
227	1961–1970	20.19	1800	0.81	0.38	454	56	633	0.59	0.63
12	1961–1970	23.39	5422	0.87	0.23	617	174	1081	0.53	0.66
83	1961–1970	18.92	3869	0.93	0.28	527	128	936	0.57	0.63
32	1961–1970	23.56	4340	0.90	0.29	738	138	1106	0.52	0.66
159	1961–1970	22.09	8191	0.87	0.31	1520	278	2262	0.53	0.66

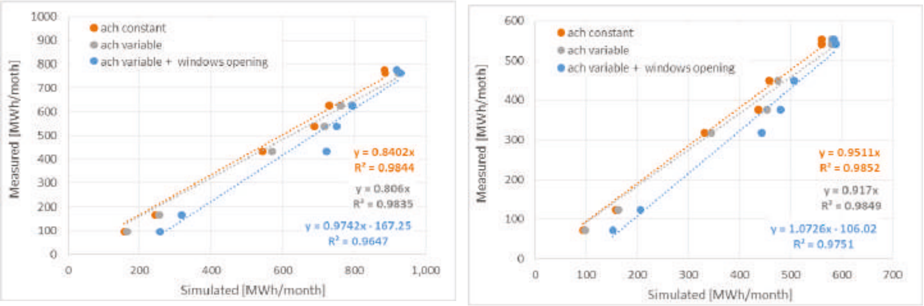
Table A1. *Cont.*

ID	Period	Height [m]	Gross Vol. [m^3]	Occup. [-]	S/V [m^{-1}]	A_W [m^2]	A_G [m^2]	A_E [m^2]	H/W [-]	SVF [-]
58	1961–1970	15.50	4179	0.99	0.41	1057	135	1596	0.49	0.64
7	1961–1970	28.10	6916	0.98	0.24	970	215	1463	0.55	0.70
97	1961–1970	26.49	28,450	0.93	0.23	3528	940	5676	0.50	0.62
201	1961–1970	24.00	25,968	0.95	0.27	3995	811	6159	0.56	0.75
77	1961–1970	28.00	28,398	0.95	0.25	4067	1014	6095	0.56	0.75
246	1961–1970	21.29	2793	0.77	0.30	490	82	753	0.55	0.62
20	1971–1980	26.23	20,994	1.00	0.33	3738	700	5339	0.57	0.69
21	1971–1980	29.78	5273	0.89	0.41	1338	177	1692	0.78	0.68
24	1971–1980	36.58	10,876	0.89	0.30	1847	372	2442	0.78	0.68
56	1971–1980	29.70	4524	0.89	0.40	1117	152	1421	0.78	0.68
58	1971–1980	36.51	6846	0.89	0.42	1911	234	2286	0.78	0.68
59	1971–1980	29.28	7514	0.89	0.39	1779	257	2292	0.78	0.68
95	1971–1980	36.72	10,537	0.89	0.37	2454	359	3028	0.78	0.68
119	1971–1980	25.00	17,362	0.92	0.27	2793	521	4182	0.58	0.71
65	1971–1980	29.00	12,364	0.93	0.32	2707	426	3560	0.57	0.66
190	1971–1980	20.36	4912	0.91	0.36	917	151	1399	0.53	0.64
100	1971–1980	17.96	13,494	0.96	0.34	2080	470	3583	0.28	0.73

Figure A1 shows the comparison between the simulated and measured monthly thermal consumptions. The simulated thermal consumptions have been calculated using the three dynamic thermal balances: (i) a constant air change rate n = 0.5 h^{-1}; (ii) a variable *ach* during the daytime and nighttime; (iii) a variable *ach* considering a quota for infiltrations and a quota for window openings.



(**a**) Cluster 1 (1919–1945). (**b**) Cluster 2 (1946–1960).



(**c**) Cluster 3 (1961–1970). (**d**) Cluster 4 (1971–1980).

Figure A1. Comparison between the simulated and measured monthly thermal consumptions, distinguishing *ach* = 0.5 h^{-1} (in orange), *ach* = 0.62 h^{-1} during the daytime, *ach* = 0.3 h^{-1} during the nighttime (in grey), and variable *ach* with window openings (in blue).

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Resilience and Sectoral Composition Change of Italian Inner Areas in Response to the Great Recession

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Abstract: This paper focuses on the response of Italian inner areas to the Great Recession. Inner areas represent the majority of the Italian territory and are very heterogeneous in terms of (unstable) growth trajectories and industrial composition. One key issue that has partially hindered a thorough empirical analysis of the development paths of these areas so far, is defining these inner areas. To this aim, we adopt the recent classification proposed by the National Strategy for Inner Areas (2014), which identified six categories based on the travel distance from service provision centers. Our purpose is to analyze the potential structural change of inner vs non-inner areas in the face of the 2007–2008 economic crisis, assessing their adaptive capacity to the recessionary disturbance and the factors underlying their industrial composition change. We found that urban poles and inner areas had different abilities to re-adapt their local industrial compositions in response to the economic crisis with obvious effects on their future resilience.

Keywords: regional resilience; adaptive capacity; sectoral industry composition; urban vs. inner areas

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1. Introduction

The body of academic contributions dealing with local and regional development has recently broadened to study the concept of regional resilience (i.e., how different regions respond and adapt to a wide array of external shocks). Seeking to understand the factors affecting the ability of a place to react to a more or less unexpected change inevitably begs the question of what influences its endogenous development, as well as what policy and governance structures are best in enabling and facilitating a positive change. One of the most intriguing facts is that while some areas manage to renew themselves, others start, or remain locked in, a path of decline.

Although many different notions of resilience have been proposed in recent years, resilience, broadly speaking, is simply meant as the ability of a socio-economic system to recover from a shock or disruption [1–8]. However, this concept has been fine-tuned, and three main interpretations of this ability to recover are now found in the literature [1,9,10]. The first one—also known as engineering resilience [11]—focuses on the resistance of a region to disturbances, and on the speed and extent of its recovery, where recovery is simply the return to the pre-shock equilibrium state or path. The second one—known as ecological resilience [11]—emphasizes the magnitude/size of the disturbance that a system can tolerate before it moves to a new state or equilibrium (i.e., it changes form, function or position). The third one—known as adaptive resilience—refers to the capacity of a system to maintain core performances, despite a shock, by adapting its structure, functions and organization to change, and hence bouncing forward. This view is quintessentially an evolutionary one. Following Boschma [4], resilience, meant as the capacity of a region to sustain long-run development, is regarded as important as the capacity of a region to respond positively to short-term shocks. Therefore, this interpretation focuses on the long-term evolution of regions and their abilities to adapt and reconfigure their industrial and institutional structures. Our paper is an initial attempt to study both dimensions of resilience. Within the evolutionary perspective, we also extensively draw on the theoretical framework built by Martin and Sunley [9], who focus on the capacity of regions to change the evolution of their structural, organizational and behavioral characteristics as an answer to any kind of shock. Therefore, recovery is just one of the aspects of a multifaceted concept such as resilience. It simply considers the return to the pre-shock equilibrium state or path, without saying anything about the capacity of an economic system to adapt or move to a better development path than before the shock [9]. We partially disagree with the limitation of excluding regional reactions to adverse processes that cumulate slowly and incrementally over long periods of time from the theoretical framework on resilience. Indeed, shocks "are often closely intertwined with the unfolding of broader, longer run and slow-burn processes of change" [12] (p. 5).

The question of how resilience to a major shock interacts with long-term patterns of economic growth is intriguing, and is the main focus of our study. This interaction is at the core of why, for instance, the same major economic shock (at the national or international scale) can have highly spatially uneven local impacts, as in the great recessions of the early 1930s, early 1980s and early 1990s. Capello et al. [13] point out that even the last crisis was characterized by a high degree of spatial heterogeneity in terms of regional and local effects [14,15]. Many studies have dealt with the evaluation of regional resilience in different countries [1,4,9,13,16–29] in response to the Great Recession. Nonetheless, there is a paucity of studies that focus specifically on the role of changes to local industrial structures as a result of regional adaptation in coping with economic crises (see [30–33]). Furthermore, to the best of our knowledge, our paper is the first that aims to discuss the relationship between the Great Recession, sectoral composition change and peripheral areas.

In fact, what is interesting in focusing on peripheral areas with long-run negative growth trajectories is that this allows us to see if a sudden, unexpected shock, such as the 2008–2009 global financial–economic crisis, makes them reach a critical tipping point that makes incremental slow-burn economic changes all at once disruptive. The underexplored issue here is whether such slow-burn processes are accelerated by shocks, or whether they could be positively reversed by them. Martin et al. [31] suggest that the resistance of a national economy as a whole is counterfactual. Regions experiencing a larger fall in employment than the national economy would be deemed as being less resistant to the shock, while regions in which the fall is lessened would be regarded as being relatively resistant. Thus, the direction of industrial change (e.g., in line with the growth of the "national champions" or not) would be intended as a proxy of the capacity of peripheral areas to better respond to shocks.

With reference to the four-part question that the concept of resilience entails, in order to more accurately define the field and scope of investigation—following Martin and Sunley [9]—the "to what" dimension is particularly relevant. We examined resilience to an acute shock (the Great Recession) in areas affected by chronic slow-moving challenges [34], such as depopulation and ageing, economic decline, contraction of the provision of essential services, which tend to be corrosive to the adaptability capacity of places [12,35]. Economic shocks can be different in their nature, and hence, in their effects and implications for resilience.

If the "to what" is an economic crisis, as in our case, to build our analytical framework we can fruitfully rely on the four interrelated dimensions identified by Martin [1] to conceptualize the notion of resilience precisely in relation to recessionary or other such shocks, which we found very salient to our purpose. These are: resistance (the capacity of a regional economy to face disruptions, such as recessions), recovery (the speed and degree of bouncing back from such a disturbance), re-orientation (the extent to which the regional economy undergoes structural realignment or adaptation) and renewal (the degree of resumption of the growth path that characterized the regional economy prior to the shock). It is worth noting that these different aspects of regional economic resilience interact in different ways with each other, but also with the various factors and characteristics that shape a region's economic landscape. The economic structure of regions is commonly thought to play a pivotal role in shaping the resistance of places to recessionary shocks in particular [1], despite also affecting the speed and extent of the recovery. More specifically, a diverse and heterogenous economic structure might provide greater regional resilience by allowing a greater resistance to the crisis, with resistance being assumed in this sense as the capacity to absorb potential sectoral unemployment through the re-distribution of the local workforce in other sectors. Investigating industrial local composition in terms of pro- and anti-trend sectors, with reference to national trajectories, could thus help in building knowledge on this specific aspect. As a potential outcome of future, follow-up research, this would help answer the fourth question inherent to the concept of resilience, which focuses on the "nature" of the recovery, exploring the direction of sectoral employment changes, the scale of shifts and whether they brought about a structural re-orientation of local economies over the long run (and if so, along which paths compared to national growing trajectories—see [31]).

Empirically, our analysis starts from the first dimension of resilience (resistance) [9] in order to gain some insight into whether a disturbance leads to rapid changes in a region's economic structure. After the initial assessment of the degree of resistance, this paper moves onto: (i) other phases that are part and parcel of the very notion of resilience to economic crises, and (ii) the urban hierarchy exploiting the classification developed within the National Strategy for Inner Areas launched in Italy in 2014 (six categories from core to ultra-peripheral areas). The assumption is that the areas so defined could be functionally meaningful socio-economic entities, providing new pieces of knowledge on the topic, and ultimately unveiling the very determinants of the capacities of different places (in terms of their prior economic growth performances and structures) to react to a nationwide disruption. This answers the crucial "of what" question, since resilience clearly depends on the consistency and relevance of the geographical units used to delimit the local economies, which we will scrutinize through the lens of this analytical framework.

Inner areas are in fact economically weak areas, because of the long-term dynamics characterized jointly by population decline, aging, reduction in employment and scarcity of local public and private services, to a degradation of cultural and landscape heritage. Therefore, these areas are potentially very exposed to decline processes accelerated by the Great Recession. Nonetheless, in comparison with urban areas, inner areas show a temporal lag in response to the crisis [36,37].

Hence, this paper explores the short–medium term shock-induced change in the sectoral composition of Italian poles and peripheral areas following the Great Recession. In particular, we look at the trend of structural change across space in comparison with the national average. To this end, we are interested—following the methodological approach by Dauth and Suedekum [38]—in the relationship between local industrial composition along the urban hierarchy. We have classified Italian municipalities according to "pro-trend" (i.e., a direction of industrial change similar to that of the nation as a whole), "anti-trend" (i.e., a direction of industrial change opposite to that of the nation as a whole) or "not-significant" growth (i.e., no clear pattern of the direction of industrial change), and we will provide a detailed comparison of these groups. Our main results show that one of the impacts of the Great Recession on inner areas was to promote a change in the local industry composition even though their local industry composition was not in line with the nationally booming sectors. This could be an intriguing research path to follow in the future, given the policy implications of such information. In fact, the high spatial differentiation that we highlight displays a need for tailored policies to improve a region's ability to rapidly react to unforeseen disruptions, while at the same time reshaping local economic environments by focusing on sectors that may drive national economic growth. This might be the case not only in the emergency post-crisis phase, but also in helping places to find and strengthen what could be the drivers of their context-specific abilities to anticipate shocks—in a word, a place-based resilience strategy.

One of the limitations of our work is that, at the moment, we do not focus on the direction of industrial change, but only on whether the Great Recession promoted a change in the composition of local industries in inner areas. Future research avenues will lead to the identification of a possible re-orientation or renewal of the inner areas of Italy in the face of a recessionary disturbance under scrutiny, possibly providing more general conclusions on the degree and nature of the resilience abilities of these areas, as well as on areas showing similar characteristics in other countries. In this sense, we look at the factors influencing a change in the economic base from one state (pro-trend/anti-trend) to another, if this were the case.

Ultimately, a follow-up of our work could contribute to filling the gap identified within the theoretical and analytical framework underpinning our study; namely, the impact that major shocks might have on long-run regional growth patterns, and thus whether disturbances could set in motion (positive) structural changes in a local economy.

Our results clearly point at a heterogenous response to the recessionary shock of urban poles and peripheral areas. Besides the relevance as a research question, from a policy perspective (especially for strategies intended to cope with uneven regional development which could be in part due to differential in resilience capacity, see [39]), this is extremely relevant to unveil the factors fostering a region's recovery trajectory with a more favorable outcome, thus with a higher growth potential than its pre-shock trend and inform policy-making in the direction of more context-tailored strategies for preparedness to and recovery from economic disruptions.

This paper is structured as follows: Section 2 outlines the data and methodology of the analysis; Section 3 describes the main results, which are further discussed in Section 4; and Section 5 concludes.

2. Data and Methodology

As discussed above, the impact of shocks on long-term growth is more deserving of study than has traditionally been recognized, a shortage acknowledged by various scholars [9,12,40]. Accounting for the evolutionary development path of places over time and disentangling the changes following a major shock brings about analytical and methodological challenges. This is due to the blurring between a single event and process-based change [12], as well as the recursive nature of the relationship between the features and structures of a region's economic growth and resilience [9].

Being aware of this, our aim is to provide some insights on the effect of a discrete recessionary disturbance on areas that have been challenged by slow-burn pressures over a time span of almost seven decades (since the 1950s). Concerning the spatial units of our analysis, we relied on the classification produced by the National Strategy for Inner Areas (SNAI), which was launched by the Italian Minister for Economic Development in 2014. This allows us to focus on clearly identified areas that are very likely to have undergone negative path-dependence processes, locking them into a socio-economic decline. As stated in the official document of the strategy [41], many inner areas have faced a reduction in the man-made environments because of aging, depopulation [28,42–46], dwindling employment and use of territorial capital, coupled with a progressive decline in offers of local public and private services. Inner areas are interpreted as areas located at a considerable distance from centers providing essential services (namely education, health and transport). Methodologically, "service provision centers" were identified as those municipalities (A: urban poles of attraction) or groups of neighboring municipalities (B: intermunicipal poles of attraction) able to simultaneously provide a full range of secondary education, at least one emergency care hospital and at least one railway station providing metropolitan/regional journeys. The identification of these centers was followed by the classification of the remaining municipalities into four bands: (C) outlying areas; (D) intermediate areas; (E) peripheral areas and (F) ultra-peripheral areas. This was carried out using an accessibility indicator in terms of the number of minutes taken to get to the nearest hub. The bands were defined based on distribution of the distance in minutes: <20 min for outlying areas (C); 20–40 min for intermediate areas (D); 40–75 for peripheral areas (E) and >75 for ultra-peripheral areas (F). The last three classes (D, E and F) are labeled "inner areas" (see Figure 1).

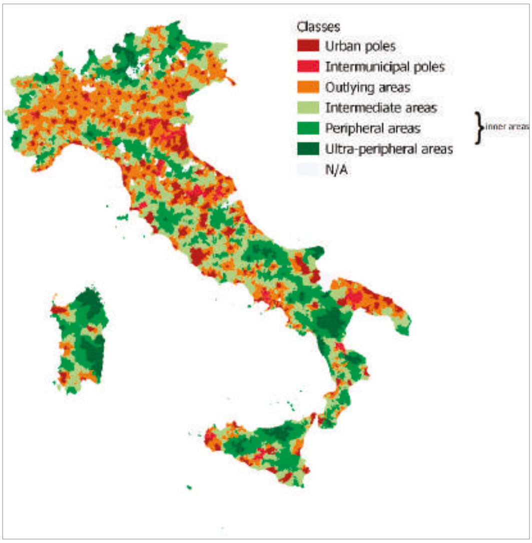


Figure 1. Italian inner areas according to National Strategy for Inner Areas (SNAI) classification.

Having defined the units of our empirical analysis, and the rationale for choosing them, we used one variable to proxy resilience: employment (no complex index) disaggregated by industry, according to the statistical classification of economic activities of the European Community, Nace (rev 2), which is provided by ISTAT (Italian National Institute of Statistics). We excluded from the analysis public and agriculture sectors as no reliable information was available for them.

The dataset provides information on employment at the municipal level (NUTS3 equivalent). In order to avoid excessive zeros and small number issues (such as high volatility over time), we focused on industrial activities at the two-digit level. Data cover a decade, from 2004 to 2014, which can be almost symmetrically split into a pre-recession (2004–2008) and post-recession (2009–2014) period.

The sectoral mix in the two sub-periods gives us a clear idea of the local level trends in industrial composition compared to the national trend. To this end, we drew on the methodology proposed by Dauth and Suedekum [38], which we found particularly useful for our purpose. We also built on a previous work of ours ([46]; see Step 1 and 2, see below).

Our empirical strategy can be classified into four steps:

1. Descriptive statistics—We started with a descriptive analysis of trends over time to identify possible differences along the urban hierarchy between areas with a different degree of peripherality, according to SNAI's terminology [41] (p. 25);
2. Defining the Excess of change—The second step, following Dauth and Suedekum (2016) [38], was to look at the changes in sectoral composition before and after the Great Recession, defining a sort of excess of change (EC_m) at the municipality (i) level—as compared with the national level—for each industrial sector (s):

$$EC_i = \sum_s \left| \frac{empl_{i,s,t} - empl_{i,s,t-1}}{empl_{i,t-1}} - \frac{empl_{s,t} - empl_{s,t-1}}{empl_{t-1}} \right|$$

where $\frac{empl_{i,s,t} - empl_{i,s,t-1}}{empl_{i,t-1}}$ is the percentage change of employment in sector s in municipality i, and $\frac{empl_{s,t} - empl_{s,t-1}}{empl_{t-1}}$ is the change of employment in sector s in the country (Please note that we adopt weighted sectoral growth rates for both class of inner areas (A, B … F) and at national level (see [16] for details).

If we divide the excess of change according to sectoral national growth, we take the null sector, $s0$, as the benchmark (see Figure 2) to obtain four different areas:

- $EC_i^{+} = \sum_{s+}\left|\frac{empl_{i,s,t}-empl_{i,s,t-1}}{empl_{i,t-1}} - \frac{empl_{s,t}-empl_{s,t-1}}{empl_{t-1}}\right|$ if $EC_{i,s} > 0$
- $EC_i^{+\prime} = \sum_{s+}\left|\frac{empl_{i,s,t}-empl_{i,s,t-1}}{empl_{i,t-1}} - \frac{empl_{s,t}-empl_{s,t-1}}{empl_{t-1}}\right|$ if $EC_{i,s} < 0$
- $EC_i^{-} = \sum_{s-}\left|\frac{empl_{i,s,t}-empl_{i,s,t-1}}{empl_{i,t-1}} - \frac{empl_{s,t}-empl_{s,t-1}}{empl_{t-1}}\right|$ if $EC_{i,s} > 0$
- $EC_i^{-\prime} = \sum_{s+}\left|\frac{empl_{i,s,t}-empl_{i,s,t-1}}{empl_{i,t-1}} - \frac{empl_{s,t}- empl_{s,t-1}}{empl_{t-1}}\right|$ if $EC_{i,s} < 0$

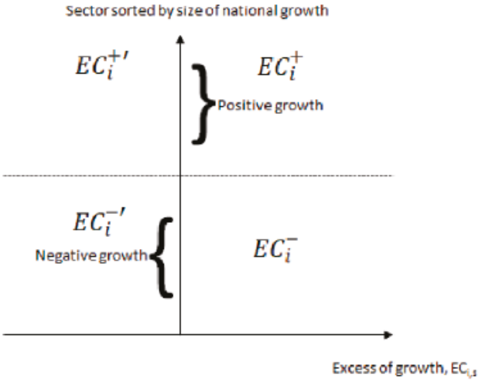


Figure 2. Visual representation of direction of local industrial change (based on [38]).

All amplitudes for area EC_i^{+} imply excess growth in sectors that at the national level have expressed positive growth in municipality i, whereas amplitudes in area EC_i^{-} imply excess growth in nationally declining sectors. On the contrary, it is possible to see above-average decline in increasing and declining industries for area $EC_i^{+\prime}$ and $EC_i^{-\prime}$, respectively.

In order to take into consideration the peculiarities of different inner areas, with particular reference to the distinction between urban and rural areas and in line with Dauth and Suedekum (2016) [38], we applied this idea to the different municipalities classified by SNAI categories (six from A (center) to F (ultra-peripheral)). Therefore, for each group $a = \{A, B, C, D, E, F\}$ with above- and below-average growth, $g = \{+,-\}$, we computed the average excess change according to their reference group and average growth ($\overline{EC}_g^{a}$).

We then calculated the following shares for every municipality:

$$\alpha_m^{\{a,g\}} = \left|\frac{EC_i^{+}}{\overline{EC}_g^{a}}\right|;\ \alpha'^{\{a,g\}}_m = \left|\frac{EC_i^{+\prime}}{\overline{EC}_g^{a}}\right|$$

$$\beta_m^{\{a,g\}} = \left|\frac{EC_i^{-}}{\overline{EC}_g^{a}}\right|;\ \beta'^{\{a,g\}}_m = \left|\frac{EC_i^{-\prime}}{\overline{EC}_g^{a}}\right|$$

Finally, we calculated the average of these shares $\overline{\alpha}_g^{\{a\}}, \overline{\beta}_g^{\{a\}}, \overline{\alpha}'^{\{a\}}_g, \overline{\beta}'^{\{a\}}_g$. The optimal rules of thumb in order to assess if the municipalities were pro-trend or anti-trend are as follows (see [16]):

Pro-trend:

if g = +: $\alpha_m^{\{a,g\}} > \beta_m^{\{a,g\}}$ and $\alpha_m^{\{a,g\}} > \overline{\alpha}_g^{\{a\}}$
if g = −: $\beta'^{\{a,g\}}_m > \alpha'^{\{a,g\}}_m$ and $\beta'^{\{ag\}}_m > \overline{\beta}'^{\{a\}}_g$

Anti-trend:

if g = +: $\beta_m^{\{a,g\}} > \alpha_m^{\{a,g\}}$ and $\beta_m^{\{a,g\}} > \overline{\beta}_g^{\{a\}}$
if g = −: $\alpha'^{\{a,g\}}_m > \beta'^{\{a,g\}}_m$ and $\alpha'^{\{a,g\}}_m > \overline{\alpha}'^{\{a\}}_g$

Figure 2, presented above, can help us distinguish areas as pro-trend vs anti-trend in this way:

- If a municipality grows more than the nation in growing sectors at the national level (Area EC_i^{+}), and declines in declining sectors at the national level (Area $EC_i^{-\prime}$) then it is "pro-trend".
- Oppositely, if most of the excess of change lines are in the Areas $EC_i^{+\prime}$ and EC_i^{-}, municipalities are defined as "anti-trend".

3. Detecting the Switch—We applied Step 2 to the pre-crisis (2004–2008) and post-crisis (2009–2014) periods, identifying whether or not the industrial composition of each Italian municipality followed the national trend. We then compared the pre- and post-shock periods to define municipalities that switched in terms of their direction of trend.
4. Finding its Determinants—Finally, we inferred which characteristics affected the pro-trend and anti-trend municipalities, and which "switched" between the two through a logit model.

3. Results

Drawing on previous empirical evidence [46] resulting from an examination of employment trends (Step 1), we found that peripheral areas had a two-year delay and a deeper recession. This double dip could be a testament of two crises of different natures: a first, financial one, more strongly affecting urban areas; and a second, economic one (namely concerning the proper real economy), more severely impacting peripheral areas. Among the poles, it was actually the areas surrounding the big cities (Outlying areas in the SNAI's nomenclature) that performed the best. This is compatible with Faggian et al. [37], but also Dijkstra et al. [47], who found that, in fact, the intermediate regions in Europe responded to the economic crisis the best. Some other studies, however, point to the underperformance of peri-urban hinterland areas compared with city cores as contrary to what could be expected from a favorable combination of urbanization economic (available in proximity to metropolitan cores) and lower prices [48,49]. Even more interesting, metropolitan cores proved to be resilient partly by pushing the recessionary shock to the outlying areas [48]. It must be acknowledged thus that, at the European level, there was no clear, uncontroversial pattern of economic growth or decline in response to the Great Recession, in regards to urban vs outlying regions.

Looking at inner areas, intermediate (D) and peripheral (E) areas showed a similar behavior, with two specular drops in growth rate in 2011 and 2013. More interesting is the trend of ultra-peripheral areas (F), which deviated from the other inner areas. In fact, the Great Recession seems to have affected them with a one-year delay, and the decline in employment growth, once started (in 2009), lasted longer (two years) and had a greater magnitude. However, recovery occurred at the same pace as the remaining inner areas, although in contrast with them (and with urban areas as well) the positive trajectory remained unaltered by the subsequent recession of 2013.

Looking at the difference in employment growth before and after the Great Recession (Step 2) of the six SNAI classes as compared with the national one, the poles clearly showed very similar trends to the national ones. This is not surprising, given that urban areas represented about 44% of the entire national employment. Moving along the urban hierarchy, from outlying and peripheral areas to ultra-peripheral ones, the differences appear to have been larger and larger. Comparing the pre- and post-shock periods, poles and peripheral areas showed a similar sectoral composition over time, with positive and significant Spearman correlation coefficients (0.24 and 0.22, respectively) between the rankings of the sectors pre- and post-recession. The recessionary disturbance did not change the economic base of urban areas, or of close belt/intermediate areas in the immediate post-shock phase. In contrast, all remaining areas showed a change in their sectoral mix due to the financial–economic crisis.

Was this change to re-align with the national trend, or to move farther away? Answering this question might pose interesting insights into policy, and hence it is the focus of the next section.

3.1. The Geography of Pro-Trend and Anti-Trend Municipalities

Table 1 shows the distribution of "pro-trend", "not-significant" and "anti-trend" municipalities before and after the Great Recession.

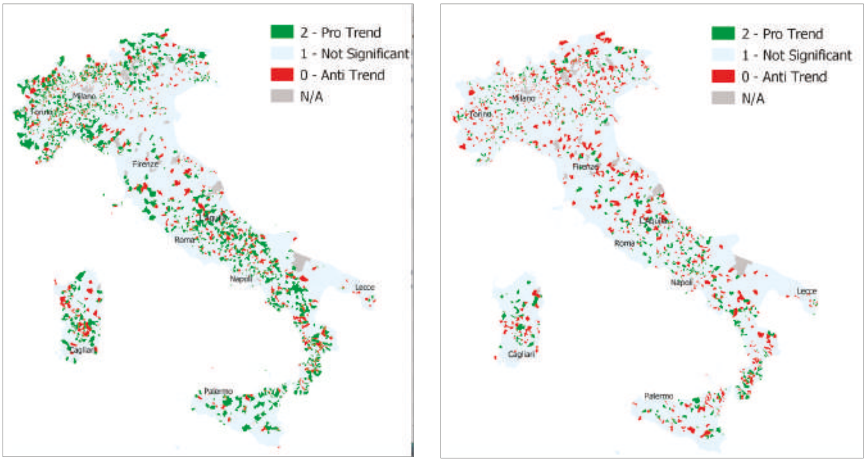
Table 1. Distribution of pro-trend, not-significant and anti-trend municipalities before and after the Great Recession.

	Trend 2004–2008		**Trend 2009–2014**	
	# Obs.	%	# Obs.	%
Pro-trend	1550	19.83	524	6.7
Not-significant	5657	72.38	6531	83.56
Anti-trend	609	7.79	761	9.74
Total	7816	100	7816	100

2004–2008	**2009–2014**			**Total**
	Anti-Trend	**Not Significant**	**Pro-Trend**	
Anti-trend	69	494	46	609
Not-significant	529	4780	348	5657
Pro-Trend	163	1257	130	1550
Total	761	6531	524	7816

The recessionary shock caused a reshuffling of the Italian municipalities within the 3 classes we are considering, with a reduction (−13.1%) of Pro-trend areas almost completely in favor of Not Significant ones.

Figure 3 illustrates the geographical distribution of pro-trend, not-significant and anti-trend municipalities in the two sub-periods we identified: (a) pre-shock (2004–2008), and (b) post-shock (2009–2014).



(**a**) Pre-shock: 2004–2008 (**b**) Post-shock: 2009–2014

Figure 3. Geographical distribution of pro-trend, not-significant and anti-trend municipalities. (**a**) Pro-trend, not-significant and anti-trend areas in the sub-period 2004–2008; (**b**) pro-trend, not-significant and anti-trend areas in the sub-period 2009–2014.

More specifically, Figure 3a shows how in the pre-shock period, pro-trend municipalities were mainly located along the two mountain ranges in Italy (i.e., the Alps and the Apennines), where many inner areas are located (see Figure 1). Many of the not-significant municipalities were located in regions leading the Italian economic system (namely Veneto, Lombardy, Emilia Romagna and Tuscany). Anti-trend areas were slightly more heterogeneously distributed across the country, but with similar patterns as in the pro-trend areas.

Following the Great Recession, the geography of pro-trend and anti-trend municipalities changed dramatically in favor of anti-trend areas and, to a lesser extent, to not-significant ones. In other words, the number of municipalities that grew more than the country in nationally growing sectors, and that declined in nationally declining sectors, dropped considerably after the shock, especially in inner areas. What is worth noting is that municipalities that showed opposite trajectories with respect to the national ones grew most significantly in the Northern–Central part of the country, which was the one closest to the national sectoral composition before the global financial–economic crisis.

These results call for a deeper investigation to understand whether—and where—the recessionary shock produced a shift in terms of local industrial profile trends.

3.2. *A Geography of the "Switch"*

Figure 4 shows the geography of "switching" municipalities; that is, those municipalities that moved from their initial state towards another one after the Great Recession as compared with "not-switching" municipalities, which remained stable following the shock. 36.3% of the municipalities (Table 2) changed the direction of their trend (pro- vs. anti- the national trajectory) after the crisis.

Most of the switching municipalities were located in inner areas, as shown in Figure 4.

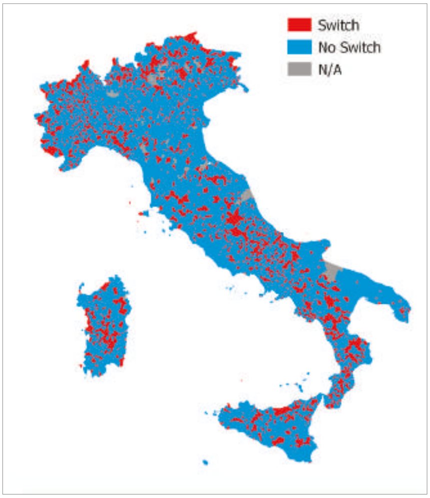


Figure 4. Geographical distribution of switching and not-switching municipalities.

Table 2. Distribution of switching and not-switching municipalities.

	Urban	Inter-Municipal	Outlying	Intermediate	Peripheral	Ultra-Peripheral	Total	
0—No switch	4979	204	104	2394	1348	791	138	4979
1—Switch	2837	7	11	1053	935	679	152	2837
% Switch	36.3	3.32	9.57	30.55	40.96	46.19	52.41	36.30
Total	7816	211	115	3447	2283	1470	290	7816

4. Discussion

Having mapped the spatial distribution of the switching vs not-switching areas, the next step of analysis is to try and uncover what were the factors underlying the "geography of the switch".

In the previous section, we showed the industrial composition changes of Italian municipalities by differentiating the peripheral gradient of the areas. We found that inner areas seemed to be more prone to reconfiguring their sectoral mix due to the Great Recession. However, we have not yet provided any explanation of this switch. The aim of this section is therefore to shed light on the determinants of this switch between the two periods. Thus, our dependent variable is the switch, which might be seen as a proxy of the restructuring of economic sectoral composition following to the shock.

We start by looking at the switch with a logit model whose dependent variable was simply 1 if the area switched, or 0 otherwise.

Our control variables included geographical, economic, social and political factors. In particular:

1. Dummies for different degrees of peripherality (SNAI categories);
2. Population and population density: number of inhabitants and inhabitants per km^2 (Census 2011);
3. Share of employment in public services: composite indicator (Atlante Prin-Postmetropoli 2011) including employees in the public administration over total population, employees in state education over total population, employees in public health;
4. Education: percentage of people aged 15–24 who did not attend a regular course of study (Census 2011);
5. Poverty: households with potential economic discomfort (Census 2011);
6. Income (log): average income per household (Ministry of Economy and Finance 2011);
7. Female condition: male employment rate over female employment rate (Census 2011);
8. Social capital (Composite indicator from Nannicini et al., 2012);
9. Density of business: number of local units per km^2 (Atlante Prin-Postmetropoli 2011);
10. Dependency ratio: age–population ratio between population in, and population not in, the labor force (Census 2011);
11. Affordability index: percentage of average annual income needed to pay an average mortgage annual payment (own calculations on Ministry of Economy and Finance 2011);
12. Inequality index: Gini index (Atlante Prin-Postmetropoli 2011);
13. Political rights: turnover of 2014 EU Parliament election (Ministry of Interior 2014);
14. Dependency on agriculture: number of cattle per person (Agricultural Census 2010).

Summary statistics are provided in Table 3 (correlation matrix available upon request).

Table 3. Descriptive statistics.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
Population (log)	7816	7.84	1.34	3.40	14.78
Institutional capacity	8080	0.00	0.61	−0.35	17.03
Education	8089	16.51	9.93	0.00	200.00
Unemployment	8092	10.14	6.31	0.00	42.20
Poverty	8092	2.02	1.87	0.00	17.90
Income (log)	8055	10.12	0.23	9.23	11.19
Female condition	8092	1.61	0.31	0.88	4.38
Social Capital	7946	0.45	0.16	0.00	1.00
Business density	8092	0.07	0.06	0.00	1.00
Population density	8092	277.34	606.79	1.4	11,346.3
Affordability index	7981	1.26	12.56	−154.76	22.00
Inequality	8055	0.19	0.02	0.11	0.33
Political rights	7869	0.31	0.08	0.07	0.63
Agriculture dependency	7581	6.99	29.97	0.00004	922.52
Peripherality class	7816	3.71	1.00	1	6

We estimated the following logit model:

$$Switch = \beta_0 + \beta\ peripherality_i + \gamma\ \text{CONTROLS} + \varepsilon_i$$

Results are provided in Table 4. It is interesting to note that the probability of switching, namely the probability for a greater magnitude of change in local industry composition over time, compared with the average national pattern of structural change, increases with the degree of peripherality of the municipality (i.e., 0.9 for outlying areas and 1.4 for ultra-peripheral areas). In other words, the more peripheral the area, the more likely it is to switch. This probability is clearly higher when looking at the basic model (model 1) in Table 4, as including more controls attenuates the effect.

Table 4. Results of the logit model. Dependent variable is the switch of industrial composition trend in comparison to the national one.

Dependent Variable: Switch (0, 1)	Model (1)	Model (2)
Intermunicipal poles (dummy)	1.126 **	0.563
	(0.498)	(0.508)
Outlying areas (dummy)	2.551 ***	0.922 **
	(0.386)	(0.398)
Intermediate areas (dummy)	3.006 ***	1.026 **
	(0.387)	(0.401)
Peripheral areas (dummy)	3.220 ***	1.176 ***
	(0.388)	(0.405)
Ultra-peripheral areas (dummy)	3.469 ***	1.380 ***
	(0.402)	(0.423)
Population (log)		−0.542 ***
		(0.0352)
Share of employment in public services		−0.105 *
		(0.0544)
Education		−0.00779 **
		(0.00326)
Unemployment		−0.00917
		(0.00831)
Poverty		0.0665 **
		(0.0298)
Income (log)		0.240
		(0.224)
Social capital		−0.433 **
		(0.218)
Business density		0.713
		(0.589)
Population density		−0.000620 ***
		(0.000158)
Dependency ratio		−0.00129 ***
		(0.000285)
Affordability index		0.00529 **
		(0.00260)
Inequality		1.439
		(1.643)
Female condition		−0.00222
		(0.120)
Political rights		−0.673
		(0.417)
Agricultural dependency		−0.000560
		(0.000904)
Pseudo r2	0.0335	0.0913
Wald chi2	240.97	611.31
N	7816	7114

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Robust standard errors are reported in parentheses. All specifications include a constant term.

Our results show that places are more likely to switch if they are smaller (in terms of population size), if they have a lower share of employment in public services, if they have a lower level of education and if they have a lower level of social capital. It is worth noting that the main determinants for switching are also the main features of Italian Inner areas, where poor institutions, prolonged high-skilled out-migration of young people and a scarce endowment, or dissipation over time, of relational capital are part and parcel of—or co-evolve with (to use an expression proper to the Evolutionary Economic Geography approach)—their long-term often precarious development trajectories.

These results show an inherent potential weakness of peripheral areas: they suffer the most from the depopulation process and youth migration, as they are not poles of attraction for the people who are more likely to confront economic shocks.

According to what we underlined above, we know that inner areas show a local industry composition that is not in line with the nationally booming sectors (i.e., manufacturing sectors are quite relevant in peripheral areas, while other key sectors at the national level are not). However, so far, we only know that one of the impacts of the Great Recession on inner areas was to promote a change in local industry composition, with no clue as to the direction of change. This could be an intriguing research path to follow in the future, given the straightforward policy implications of such an analysis.

5. Conclusions

The search for new paths to resilience of peripheral regions is a fascinating research topic from a transdisciplinary and also a policy-oriented perspective. The ultimate objective of our study is to provide insights into the diversity, variety and also unevenness of the multifaceted processes underpinning the capacity of places to restructure their sectoral composition following a recessionary shock.

Our results encourage further analysis by addressing questions into what kind of resilience these areas can cultivate, and by investigating the role played by prolonged slow-burn challenges that are often corrosive to the ability of regions to adapt or (more desirably) anticipate change.

We found that inner areas showed a higher probability to switch from the pre-shock structure of their industrial profile to another. This is very interesting, in that it indicates a higher capacity to adapt to, or a lower propensity to resist, the disturbance produced by the Great Recession. The relevant weight of manufacturing on the overall economic base of Italian inner areas, however, may underline a low propensity to innovate and transition quickly into another sectoral composition under the new conditions—in other words, it may result in a scarce ability to answer to a recessionary shock.

This calls for special academic and policy attention. If we acknowledge the idea that shocks, and the magnitude of their impact, are often closely intertwined with the unfolding of broader, long-run slow-burn processes of change [7]—which have a high spatial differentiation—then proper, tailored policies are needed to improve regions' abilities to rapidly react to unforeseen disruptions. Focusing on the notion of resilience could enhance our understanding of the factors influencing the development of regions and the scope for appropriate policy responses, not only in the emergency post-crises phase, but rather in helping regions find and strengthen what could be the drivers of their context-specific abilities to react. In a word, a place-based resilience strategy is needed.

Building on this work, several extensions and research avenues open up. Aside from refining the model, some future steps may include: studying the direction of the switch and all the possible combinations (we do not know a priori since we should look at the direction of change); progressing further in the investigation of the characteristics of the different areas and, in particular, of the differences by sub-groups classified according the degree of peripherality. Moreover, the post-crisis period is not so "post" in reality. It could therefore be useful to expand our dataset so as to account for longer post-shock times. We could divide these further in two sub-periods, to test and better explore the effects of the double dip on peripheries, and to better disentangle the impact of a first disturbance, more financial in nature, and a second one, more economic in its character. This might explain the lag in the decline of inner areas after the first financial crisis.

Knowing how the sectoral composition of these areas changes following this kind of shock could give us a clue on the untapped potential of the resistance of industrial sectors that have so far been ignored for not performing better at the national level and, within inner areas themselves, on how and to what extent the geography of a switch overlaps or interacts with the geography of resilience.

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Mainstreaming Energetic Resilience by Morphological Assessment in Ordinary Land Use Planning. The Case Study of Moncalieri, Turin (Italy)

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Abstract: Energetic resilience is seen as one of the most prominent fields of investigation in the upcoming years. The increasing efficiency of urban systems depends on the conversion of energetic production of buildings, and therefore, from the capacity of urban systems to be more rational in the use of renewable resources. Nevertheless, the integration of the energetic regulation into the ordinary urban planning documents is far from being reached in most of planning processes. In Italy, mainstreaming energetic resilience in ordinary land use planning appears particularly challenging, even in those Local Administrations that tried to implement the national legislation into Local Building Regulation. In this work, an empirical methodology to provide an overall assessment of the solar production capacity has been applied to selected indicators of urban morphology among the different land use parcel-zones, while implementing a geographic information system-based approach to the city of Moncalieri, Turin (Italy). Results demonstrate that, without exception, the current minimum energy levels required by law are generally much lower than the effective potential solar energy production that each land use parcel-zone could effectively produce. We concluded that local planning processes should update their land use plans to reach environmental sustainability targets, while at the same time the energetic resilience should be mainstreamed in urban planning by an in-depth analysis of the effective morphological constraints. These aspects may also represent a contribution to the international debates on energetic resilience and on the progressive inclusion of energy subjects in the land use planning process.

Keywords: energetic resilience; solar radiation; geographic information system; land use planning; urban regulation

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1. Introduction

The attention on urban environment and energy emerges clearly from the end of the 1980s to the early 1990s, where the importance of integrating energy and spatial planning appears to be defined [1]. Starting from milestones as the 1992 Rio Conference, Local Agenda 21 and first studies on local planning and energy parameterization [2–6], the need for a systemic approach on energy topic and physical organization of the city became relevant. Today, in the light of the exposition to adverse events, whether due to the lack of energy sources or to climate change impacts and man-made stressors, it is increasingly evident that energy systems need to become resilient too. The concept of resilience is a central topic in the debate of natural and artificial stressors affecting cites, and therefore, should be more considered in the normative framework of Sustainable Development Goals (SDGs) [7]. Indeed, as stated by Sharifi and Yamagata [8], to be resilient, urban energy systems need to develop the capacity to "plan and prepare for", "absorb", "recover from", and "adapt to" any adverse event that may occur in the future [9]. The integration of these four abilities within the systems should improve its capacity to address "availability", "accessibility", affordability" and "acceptability", which represent the four sustainability-dimensions of energy [10,11]. Within this perspective, the resilient paradigm can be applied to the planning and building design criteria [12], as they have to deal with permanent conditions of change and often also with external pressures (from both socio-economic and natural dimensions). Because of this wide spectrum of uncertainties and dynamics associated with energy supply and demand, and since adaptation approach is the key for dealing with uncertainties, improving coping capacity and learning from unexpected and new circumstances, this work adopts an adaptive approach to energy resilience, also known as "socio-ecological" resilience [13,14]. The exploration of the relevance of this concept in the urban dimension for sustainable energy can provide several benefits [15,16]. However, for a long time, despite the introduction of energy issues in the field of urban spatial planning and urban form, the topic has mainly focused on the consumption of buildings, without addressing the needs to govern complex and articulated urban districts by municipal strategies and normative solutions by land use plans which might influence renewable-energy production and energy-savings. Therefore, examining the relationship between urban planning, urban morphology, and solar energy production represents a relevant topic that highlights the complexity and multi-dimensional nature of energy resilience [17]. Furthermore, addressing these issues in the planning process of modern towns may favor the functioning of cities, as socio-ecological systems, in time.

In this sense, some steps have been done internationally, and consider renewable energy issues at different scales. This has been developed as a collective and leading response to the international political goal of sustainability, in particular through two important documents: the European Directive 2010/31/EU and the European Directive 2012/27/EU of the European Parliament and of the Council [18,19]. They introduced the EU 2020 targets that aim to reduce of 20% the Green-House Gas (GHG) emissions, to improve the energy efficiency of 20% and to use 20% of renewable sources for energy consumptions. In December 2018, the revised European Directive 2018/2001/EC on renewable energy and the Regulation 2018/1999/EU on the governance of the energy union and climate action entered into force, as part of the "Clean Energy for all Europeans Package" promoting a 40% of reduction in greenhouse emissions, a goal of 32% final consumption from renewable energy sources, and an energy efficiency target of 32.5% [20–23]. In particular, this package sets ambitious targets for all Member States in terms of energy from renewable sources by 2030 (32% share), in order to limit GHG emissions in compliance with Paris Agreement. The Regulation 2018/1999/EU provides for a structured and iterative process between the Commission and the Member States for the development and subsequent implementation of national plans. Indeed, in the new regulation, EU countries are required to develop 10-year National Energy and Climate Plans (NECPs) for 2021–2030, highlighting their strategies to meet the new 2030 targets for renewable energy.

In line with the European Directive, in December 2019, the text of the Italian Integrated National Plan for Energy and Climate (INECP) [24] was published, setting the national targets for the years 2021–2030. The INPEC establishes a percentage of energy from RES in the final gross energy consumption of 30%, a reduction in primary energy consumption compared to the PRIMES 2007 scenario of 43% and an overall reduction of GHG compared to 1990 levels of 38%. In Italy, the "Clean Energy for all Europeans Package" was implemented by the Decree D.Lgs 28/2011 and led to the definition of guidelines for energy performance certification of buildings (D.M. 26/06/2015), according to both classes of energy-performance, and economically sustainable indications for energy retrofit interventions [25,26]. Specifically, Article 11 completely redefines the criteria of renewable energy for buildings by introducing the obligation to integrate renewable sources in either new or existing buildings that are renovated by "major interventions". The article clearly states that in both cases, the transformation has to meet the need of using renewable sources to cover the consumption of space heating, space cooling, hot water and electricity, and according to the obligation of integration of the systems. Clearly, the interest in assessing the built-environment arises from all these recent European and national directives that promote renewable energy and environmental sustainability with clear goals to be achieved by each Community member [27]. At a local level, the Piedmont Region is promoting policies to facilitate the transition to a sustainable energy future also at a municipal level. Thus, the Regional Council introduced the European standards related to the Italian Decree n. 28/2011 to install and maintain energy systems powered by RES. In particular, the Regional Council of Piedmont introduced several innovations regarding the energy performance issue and in 2018 approved the regional law n.12 titled "Promoting the establishment of Local Energy Communities". Through this statute, the region promotes the establishment of Local Energy Communities (LECs), in order to facilitate the implementation of European, national and regional regulations of environmental sustainability [28]. In the so-called LECs, public and private entities are encouraged to cooperate for limiting the use of fossil fuels and facilitate the production and exchange of energy mainly generated from renewable sources [29]. Among a wide range of existing renewable energy production scenarios promoted by LECs, producing electricity from solar panels is the most popular and efficient at the urban level, since its modularity, easy installation, and relative economic affordability for private investors makes it applicable to different scales. In addition, the International Energy Agency confirms that solar energy could be the world's largest source of energy by 2050 [30], despite the strong dependence of this solution from individual choices. Therefore, collective approaches are undoubtedly helpful for promoting, facilitating and applying this solution to the largest audience. However, to optimize these collective approaches, it is necessary to prepare urban adaptation plans that regulate and facilitates the transition of the built-up system towards the more efficient and rational use of solar energy production. While doing so, cities have to prepare an analytical assessment of the relative solar-energy potential of different urban areas with the main influential urban-form features, and successively integrate that knowledge into the most effective urban planning strategies and policies; otherwise, the risk is to leave the energetic transition happening without real coordination among the land use owners, their rights to transform the urban scenario of cities while installing solar panels; thus, their potential capacity to optimize and reconvert their buildings. The question that here arises is: How can energetic resilience transition be mainstreamed by land use plans if there is no systematic assessment of the solar capacity production in cities? Moreover, how is the solar energy production affected by the morphological conditions of the city?

In this sense, land use plans may play a key role in integrating and introducing the renewable energy component in the ordinary planning activity. In response to these compelling needs and in accordance with several national and regional legislation (L. 373/1976; L. 10/1991; L.R. 31/2000; D.Lgs 192/2005; D.Lgs 152/06; L. R. 13/2007; D.P.R. 59/2009; D.Lgs 28/2011; L. 90/2013; L.R. 3/2015; D.M. 26/06/2015), on 6th April 2016, Moncalieri municipality (in Piedmont Region, Northwest of Italy) through the City Council Resolution n.34, approved the Energy Attachment to the Municipal Building Regulation [26,31–40]. In addition to the general objectives related to the efficient use of energy and water sources, reduction in CO_2 and polluters emissions, and higher quality of the indoor environment; the document promotes an improved efficiency of buildings through solar energy for planning purposes. Furthermore, it sets a series of laws referred to a minimum level of energy-quality to be mandatorily achieved in every intervention. However, despite the wide attention dedicated to the qualities of the building stock, the document still lacks a planning perspective on morphological properties of the built environment. In particular, there is a gap between the effects of Moncalieri urban form on solar energy potential, in connection with the land use parcel-zone division and the new energy purposes of the municipality. In other words, neither the physical status quo of the city nor the existing plans, fully comply with the mandatory energy incentives introduced by the new regulatory attachment and with the real morphological properties of Moncalieri built environment.

In order to overcome this discrepancy, this paper performs a comparative analysis of the existing regulations, the main morphological features and energy potentials of Moncalieri and the possible local planning perspectives. The main reference for this analysis is the local land use plan (LUP), which seeks to order and regulate municipal land uses in an efficient way. In the Italian legal system, the land use plan is a mandatory planning tool that regulates building development by different morphological units (e.g., land use zones—LUZ) within the municipal area. It provides a vision for the future possible developments in neighborhoods, cities, or any land use normative areas. Furthermore, thanks to its detailed and thematic plans, the document can zoom on specific services and public interests, as for the case of energy topic. Here, in particular, there is an opportunity to introduce more directly morphological criteria that are related to settlement types, compactness ratio, density patterns and the configuration of the urban built environment, so that their role becomes evident to mainstream energy resilience.

That clarified, the paper starts with quantifying the solar energy production potential of the buildings and continues with translating the single measures for each building to a larger geographical scale according to the land use development zones in the municipal plan. In addition, it illustrates some morphological features of compactness and density to highlight the effects of different annual solar irradiation thresholds on the energy potentials of roofs [28]. It also underlines the relevance of integrating solar energy issues in land use planning, while using GIS models to support solar urban planning practices.

The reason to work on a larger urban size (from buildings to land use zones) is mainly related to the coherence with the LUP, which divides the municipal territory in LUZ, and thus, allows for broader reflections on energy potentials at the municipal level, rather than on exclusive building scale. Subsequently, by unpacking the correlation between some common urban features and solar energy potential, it facilitates the process of revision of the renewable energy system at the municipal spatial planning level. In terms of sustainable principles, this perspective can clearly link the over mentioned levels of “availability”, “accessibility”, affordability” and “acceptability” of solar energy with a direct application on the case study. This is also possible as the work offers a comparison between the national minimum requirements of solar energy (according to Allegato 3 of D. Lgs n.28/2011) and the relative energy production based on local sources of energy [37]. The chapter ends with some suggestions for the decision-making level regarding the integration of the existing planning strategies and the real energy-production potential at the level of land use development zones. The results may represent useful support in the international discussion about the decision-making process for planning and integrating solar potential in over layered, dense and compact built environment. In addition, they also indicate the relevance of energy resilience for the urban system, not only for increasing public transparency and citizens awareness on environmental sustainability targets, but also in response to future energy requirements and to long-term perspectives of the city at economic, social and environmental levels.

2. Materials and Methods

This section starts with the introduction of the case-study and the relevant concepts such as LUZs, with the help of maps and tables to clarify the explained concepts. Subsequently, we present the indicators examined and calculated; and finally, we provide an explanation of the procedural ESRI ArcGIS (ver. 10.8) elaborations, which led to the solar energy production potential (SPP) index, considerable as the most relevant indicator of the study.

2.1. Case Study

The City of Moncalieri (IT) -represented geographically in Figure 1- directly south from the City of Turin, is part of the Metropolitan area of Turin (north-west Italy). It is located in the western part of the Po Valley at 260 m a.s.l. of altitude, surrounded by the Alps crown, and with a continental, temperate climate (Italian climate zone E). The orography is quite heterogeneous with flat fluvial areas in the southern and western sectors, while in the north-east the hills shape the landscape with its natural areas mixed with a typical sprawled settlement system (detached and semi-detached single-family houses). The municipality has a population of 57.527 inhabitants (last updated on 31 December 2019, ISTAT) [41], and consists of about 6.200 buildings [42,43].

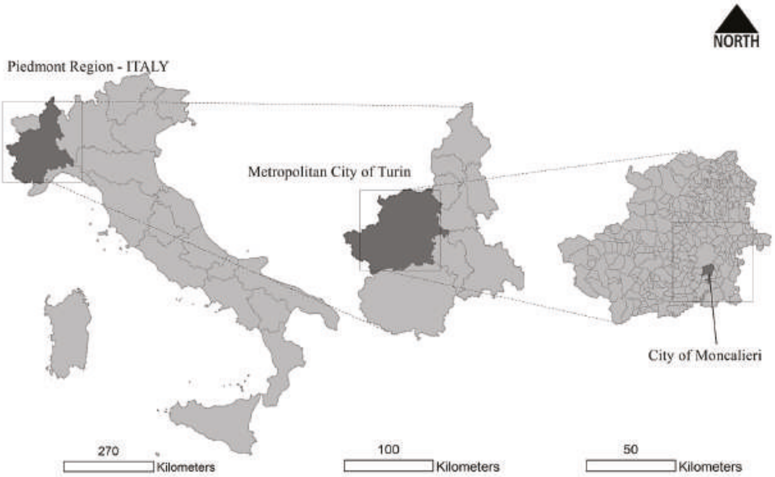


Figure 1. Geographical representation of the city of Moncalieri.

The land use is categorized as follows—34% urban areas, 39% agricultural land, 14% natural and seminatural, 4% other natural areas, 6% infrastructures, and 3% water bodies. The anthropic system, also considering infrastructures, is densely developed, covering the relative majority of land uses and threatening the environmental system (e.g., urban footprint by impermeable materials). Over the last few years, Moncalieri has experienced an expansion mainly in the hilly parts of the territory, due to a more flourishing real-estate market based on high-quality single houses in a surrounding green system and scenic view of the foothill areas.

The methodology hereafter presented is based on the calculation of two main groups of indicators, referred to (i) the energetic character of each LUZ and (ii) the morphological characters of each LUZ. Then, considering how each LUZ perform in terms of energetic production, we looked at how the potential energetic production differs from the minimum by the National Legislation.

To what concerns the morphological profile of LUZ, when dealing with solar energy in the built environment, compactness is a central parameter that influences the energy potential, and that determines different energy-performances according to the urban morphology. It is usually considered in the urban analysis, assessed in several ways, and deepened through several indicators related to the built-up environment. Furthermore, compact cities are particularly promoted in Sustainable Development Agendas and Policies of many countries, especially for reducing GHG emissions and urban-sprawl phenomena. The goal of the methodology was indeed to define a minimum solar energetic production threshold for each morphological unit linking energy production with urban planning regulation, starting from the minimum requirements of the Italian D. Lgs.28/2011 [25].

All the indicators hereafter presented are calculated using the tools of ESRI ArcGIS in a Geographic Information System environment using the digital shapefile of municipal LUZ to clip each information and extract tabular statistics at the normative-zone level. Table 1 represents all LUZ in the city of Moncalieri and gives a brief explanation about each zone and subzone.

Table 1. Land use zones in the city of Moncalieri.

Land Use Zones (LUZ)	Explanation
ZONE A—Urban settlements with historical-artistic or environmental character	
Ar1—Historical center	Built-up areas constituting the historical centers where the interventions are specified in the 1: 1000 scale works of the LUP
Ar2—Small settlements with environmental value	Smaller settlements, incorporated in the urban agglomeration or constituting the original settlement fabric of the villages of the agricultural plain
Av—Hilly areas of environmental interest	Hilly areas with relevant environmental interest. Single manufactured buildings not included in buildings of category Ar3 are also part of Av, including areas of relevance.
ZONE B—Parts of the territory largely or totally built-up	
Br—Residential areas largely built-up	Built-up areas of consolidated settlement.
Bp—Production areas	Areas with prominent existing production destination which are confirmed in their location.
Bpr1—Transformation areas with mainly tertiary use	Areas with prominent-existing production destination with a propensity for transformation from strictly productive activity to tertiary, exhibition, managerial, hospitality and residential activities (art 13, point f, LUR)
Bpr2—Transformation areas with mainly residential use	Areas with prominent-existing production destination with a propensity for transformation from productive activity to mainly residential use (art 13, point f, LUR)
ZONE C—Parts of the territory of completion or new	
Cr—Areas for residential use	Areas mainly for residential use or under construction
Crs—Areas for residence and public services	Transformation areas from public services to areas set partly to residential and partly to public services.
Crc—Areas for integrated shopping center	Transformation areas from public services to areas destined in part to an integrated shopping district and in part to services for trade and residence (V. Sestriere), art. 13, point e, LUR.
Cp—Production, commercial and tertiary areas	Production, tertiary and commercial areas
ZONE D—Parts of the territory destined to industry, artisans and tertiary sector	
D Zone	Areas with prominent production destination (art.13, point g, LUR)
LUP variant	Vadò Industrial Area
ZONE E—Parts of the territory set for agricultural use	
Ee—Free areas of the rural area in plain	Hilly and plain agricultural areas
Ep—Built-up areas used for extra-agricultural uses	Ensemble, buildings, facilities or artefacts which at the time of the adoption of the preliminary project were destined for non-agricultural production activities with the function of storage or warehouse not connected to the management of the farmlands
Es—Nurseries	Special agricultural areas for nursery activities
Es1—Permanent greenhouses	Special agricultural areas for flower activities

Table 1. *Cont.*

Land Use Zones (LUZ)	Explanation
ZONE F—Facilities and facilities of general interest (art. 22 ex LUR 56/77)	
FV—Public park areas (Urban and District)	Areas of urban and local public parks
FH—Social health and hospital facilities	Areas set for existing and projected public hospital facilities
FHP—Social health and hospital private facilities	Areas just as FH but private
FI—Higher education facilities	Areas destined to facilities for the compulsory high education public-sector
FIP—Private higher education facilities	Areas just as FIP but private
Ft—Areas for technological systems	Areas destined for technological systems of general interest (ENEL, GAS, Waste Collection, Purifiers, etc.)
Frp—PTO area set for mixed-use and leisure	Areas for sports and leisure activities included in the Environmental Protection and Valorization Area of PO river—PTO (DCR 08/03/95 n. 981–4186)
Fg—Areas for general facilities of public interest	Areas destined to other general public interest facilitates specifically indicated in the cartography section (fire department, police station, magistrate's court, library, financial offices, etc.)
Fe—Religious areas	Areas with existing buildings mainly destined for religious use (convents, boarding schools, etc.)
Fr—Areas for recreational activities included in the Po river belt	Areas for social, cultural, sporting, recreational and private activities included in the Area Plan of the System of Protected Areas of the Po River (DCR 982–4328, 08/03/95—LR 68, 13/04/95)
ZONE S—Public spaces (art.21 ex LUR 56/77)	
S—Services	Public Facilities
Sr—Residential services	Public areas and facilities related to residential settlements
Sp—Productive, commercial, tertiary and accommodation services	Public or public use areas for facilities serving the production, tertiary, management and commercial settlements
Srp—Private residential services	Existing areas just as SR but private
ZONE T—Special transformation areas	
TCR—Areas for tertiary activities, residence and services	Areas of transformation from services to residence, tertiary, and commercial activities, and services (art.13, points e–g, LUR)
TR—Areas for management and tertiary activities	Transformation area from residence, mixed industrial and handicraft uses of mainly directional and receptive areas, with residence (beginning of C. Trieste) (Art.13, point e, LUR)
TE—Areas with a predominantly exhibition tertiary sector	Areas already with services that can be transformed mainly into tertiary, exhibition and/or residential areas
OTHERS—Other zones	
Railway site	Railway site
Cemetery area	Cemetery areas
Environmental Protection Area	Areas under restrictions for the protection of natural beauty or for the protection of areas of particular environmental interest
Street furniture	Street furniture (junctions, medians, traffic circles, streamside trees, etc.)

To simplify the large collection of land use zones and represent it in a map (Figure 2). We have selected the nine macro-categories, and the four specific land uses over-mentioned: Three A areas, four B areas, four C areas, two D areas, three T areas, four E areas, four S areas, ten F areas, and four so-called "other zones".

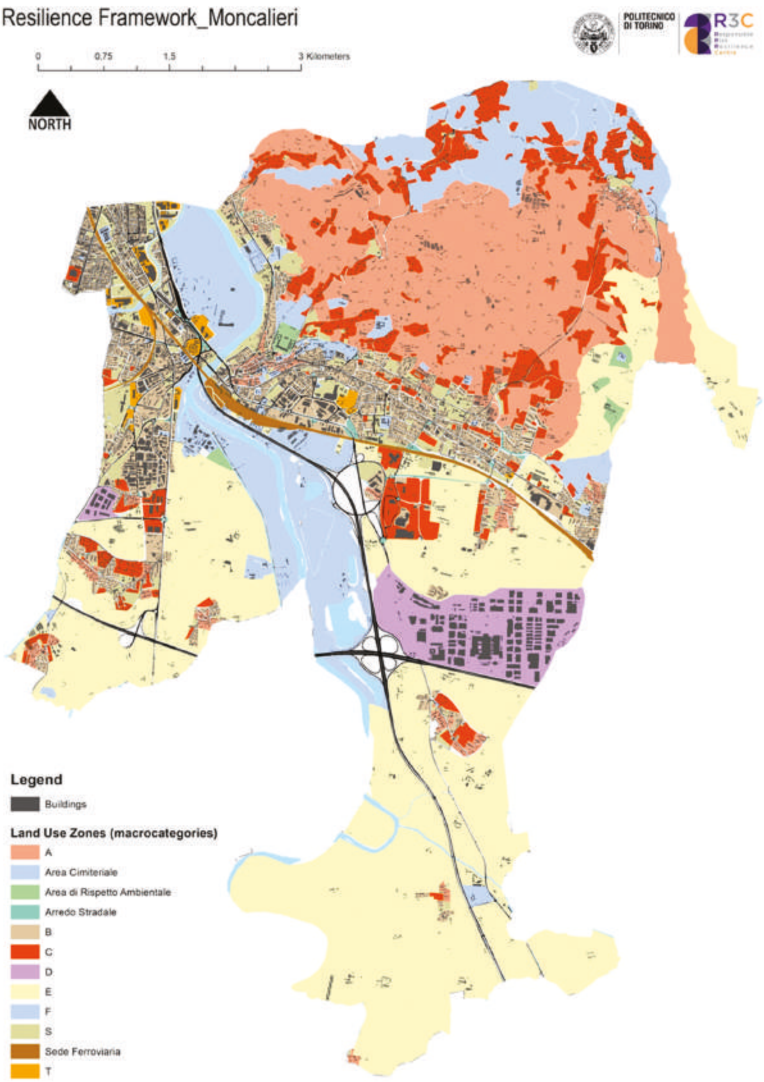


Figure 2. Graphical representation of the land use zones in the city of Moncalieri.

However, the measures for the indicators explained below will be presented for every normative zone in the city of Moncalieri in order to provide a deeper understanding of the energy potentials.

2.2. Description of Indicators

In this section, a set of indicators—to be calculated and analyzed for each LUZ—is presented and categorized in two main groups. While the first category refers to the energy performance of the buildings in each zone, the second one is related to the morphological profile of the area. This categorization enables us to make different scales of comparative analysis. The first scale relates to the comparison of different energy indicators; the second one refers to the comparison of morphological indicators with each other, and the last one is the confrontation of these two categories in order to clarify any probable correlation between energy and morphology in LUZ. To deepen the correlation between indicators of compactness and energy in different normative zones, some normalization passages have been developed, followed by regression analysis between indicators. Theoretical passages will be described afterwards and presented in the results section.

The energy indicators can be divided into two types: The indicators of solar energy production potential (E and $\overline{E}$), and the indicators referring to the regulatory minimum amount of photovoltaic energy power to be installed in each zone (P and $\overline{P}$). The first indicator is calculated by the help of GIS elaboration, in which the accumulated annual solar irradiation on the building roofs is converted to the solar energy production potential of the zones. The process of this calculation and conversion will be explained in the next subsection in more details. The second indicator is evaluated according to the Italian Decree D. Lgs 28/2011 [25]. This value is calculated using the formula of the Attachment n. 3 to the National Decree, to measure the minimum energy power of photovoltaic technology that should be installed in relation to the total building surface in a certain land zone area and the "K" coefficient equal to 50. For simplifying the calculations, the formula assumes that all buildings are installing solar panels for energetic production after the 1st January 2017. These two types of indicators are selected since the energy production potential, and the regulatory requirements are expected to follow a positive correlation. To be more specific, if the buildings of a particular LUZ are capable of producing relatively more amount of solar energy, the regulations should also comply with this potential and vice versa. Both indicators explained above are presented in total and average values in each zone. This enables us to compare both the values of the total amount of energy for the whole LUZ, and the average values for a single building, taken as a sample in each zone. This quantifies both the total amount of solar energy that each LUZ has to produce in the next future as a minimum requirement of the LUP, and the quantity of solar energy that each building have to produce averagely in each LUZ as a parameter to "set" the minimum standard for urban transformations.

The second category of indicators is related to the morphological measures in the LUZs. Although all three indicators in this category are compactness measures, each of them has specific features. While plot ratio is the outcome of the relation between total floor area and the size of land upon which it is built, site coverage represents the 2D compactness of the zones, while absolute compactness illustrates the 3D version of it since it includes the volume of the buildings as the principal variable. In order to make a comparison between these indicators possible, it is necessary to normalize all of them as they present different units of measure. Indeed, normalization is a process to organize data in a database and to make them more regular and comparable [44].

The process of normalization is done by dividing the value of each indicator to the sum of values of the same indicator and multiplying the measure by 100. In this case, the value for each LUZ is represented as a percentage of the total amount. In other words, all three indicators are normalized into a range between 0 and 100. As mentioned earlier, these three morphological indicators are also supposed to be compared with the energy indicators. In order to enable this comparison, the total solar energy production potential of the zone (E) is selected as the main indicator. This indicator is divided by the total roof surface of the zone in order to be representative of the production potential of one square meter of the building roof in each LUZ. Finally, the same normalization procedure is applied to these values to make the comparison more uniform and coherent.

Table 2 provides a theoretical overview of both energetic and morphological indicators adopted in this study. In addition, a precise description, the mathematical formula to obtain the indicators, units of measures and all the relevant variables—which are used for the calculation of each indicator—are presented.

Table 2. An overview of the indicators measured for the land use zones.

Category	Indicator	Abbreviation	Formula	Unit	Variables
Indicators of Energy	**Regulatory Minimum for Solar Power (Total Amount for the LUZ)** The indicator refers to the Minimum requirement by the Italian D. Lgs 28/2011 (KW). This value is calculated using the formula of the Attachment n. 3 to the National Decree, to measure the minimum energy power installed in relation to the total building surface in a certain land zone area and the "K" coefficient equal to 50. The formula assumes that all buildings are installing photovoltaic modules for electrical energy production after the 1st January 2017.	P	$P = \left(\frac{1}{k}\right) \times s$	kW	**S** = total building footprint of the zone (m^2) **K** = corrective coefficient (m^2/kW)
	Regulatory Minimum for Solar Power (Average Amount for a Representative Building in the LUZ) The indicator, in line with the previous one, refers to the Minimum requirement by the Italian D. Lgs 28/2011 (KW). The difference, in this case, is related to the scale: $\overline{P}$ is an average value referred to a representative building in the land use zone.	$\overline{P}$	$\overline{P} = \frac{P}{n}$	kW	**P** = Regulatory minimum for solar power (total amount for the zone) **n** = number of buildings in the normative zone
	Total Solar Energy Production Potential of the LUZ This indicator relates the annual solar irradiation in the normative zone (kWh/m^2/a) and the net surface of the panels installed in the zone (m^2), with respect to the index of the system performance and the conversion efficiency of the panel. The value represents the capacity of solar irradiation which can be turned into solar energy, without remaining simply at the minimum thresholds suggested by the national law. It has been calculated starting from the annual solar irradiation in the normative zone, and thus, represents the whole land use zone energy potential.	E	$E = PR\ H_S\ S\ \eta$	kWh/year	**PR** = index of the system performance **H_s** = accumulated annual solar irradiation in the normative zone (kWh/m^2a) **S** = net efficient surface of the panels installed in the zone (m^2) **η** = conversion efficiency of the panel (m^{-4})
	Average Solar Energy Production Potential of the LUZ The indicator, in line with the previous one, refers to the average annual solar irradiation in the normative zone (kWh/m^2/a) related to the average surface of the panels installed in the zone (m^2). Focusing on the average value, it refers to a representative building in the land use zone.	$\overline{E}$	$\overline{E} = PR\ H_S\overline{S}\eta$	kWh/year	**$\overline{S}$** = average efficient surface of the panels installed in the zone (m^2)
Indicators of Morphology	**Absolute Compactness** This indicator refers to the total building volume in a LUZ (m^3), divided by the LUZ total area (m^2). It gives the potential quantity of cube meters that are built in each LUZ, therefore representing the compactness of settlements.	Ac	$Ac = V/A$	m^2	**V** = sum of the buildings' volume in the normative zone (m^3) **A** = total land area of the zone (m^2)
	Plot Ratio The indicator refers to the total gross floor area (GLA) in a land use zone divided by the total area of a land use zone in which the buildings have been built. The average of GLA (m^2) captures the average of gross floor area per land use of a site. For instance, a one-story building that extends on an entire site has a high gross floor area which, in turn, is reduced when floors of the building increase. The indicator is a key variable to control and regulate land use zoning and development control of certain areas, since it regulates the built-up density among different LUZ.	Pl	$Pl = GLA/A$	ratio	**GLA** = gross floor area of the buildings in the zone (m^2)
	Site Coverage The indicator is based on the relation between the total building footprint on the LUZ and the total surface of the LUZ. Being based on the building-footprint and land-coverage, it can also be considered as the bi-dimensional representation of building footprints on a site. The horizontal distribution of built forms is crucial to understand the level of compactness of buildings and consequently, the physical conditions determining the solar energy producibility.	Sc	$Sc = S/A$	ratio	**S** = total building footprint of the zone (m^2)

2.3. Solar Radiation Analysis

To measure the solar energy production potential of the zone, we adopted the ESRI ArcGIS tool which is capable of detecting the annual, monthly or daily solar radiation distribution on municipal location in each pixel of the selected catchment area of about 47.52 square kilometer. The energy produced by buildings has been the output of the Solar Radiation analysis (therefore producing a Solar Radiation Index). The index E, total solar energy production potential, has been calculated for the entire catchment area (entire municipality) while enabling to analyze the effects of the solar radiation over the whole geographic zone of Moncalieri for each land use/land cover feature.

As the main input, it has been used the Digital Surface Model (DSM) (1 Band 32 Bit raster grid version, Cell-size 1-m, 99,258,750 pixels) to develop the Points Solar Radiation tool to calculate the amount of radiant energy of each pixel. In brief, our digital surface model represents the earth's surface and includes all objects on it. There, it is possible to calculate the radiant solar energy that hits the earth's surface, also called "global radiation" on a surface. This map refers to a 3D solar irradiation model of the built environment and the shadows brought by natural and artificial obstructions [45], elaborated from the monthly values of solar irradiation and the atmosphere transparency in Moncalieri. We employed the "standard" radiation parameters, setting 8 Zenith divisions, 8 Azimuth divisions the "uniform_sky" diffuse model type (meaning that the incoming diffuse radiation is the same from all-sky directions), a diffuse proportion of the sun components of 0.3 and a transmissivity of the atmosphere of 0.5. This model was corrected considering the characteristics of sun and atmosphere in Moncalieri with a seasonal interval; the annual average values were: The diffuse proportion of the sun components of 0.4 and a transmissivity of the atmosphere of 0.49. The seasonal data have been used to calculate the solar irradiation on the building-roofs and then the potential of energy producible by current solar technologies available on the market [27].

The system has stored each DSM-pixel as point features with x, y coordinates in the municipality. During the analysis, the tool internally calculates the sun position in the sky while finding the incidence of the radiated parts of the digital surface, and contemporarily, the shadowed parts. The quantity of solar energy for each pixel is delivered in point shapefiles for each month of an entire year.

Once the model provided the solar radiation, the different monthly shapefiles were joined in a single point file with the total yearly solar radiation. Then, since our focus was to calculate the energetic production for each building (thus assuming that solar panels are installed in the rooftops and not in the plots, gardens or other private properties around the buildings), the point shapefile has been intersected using the polygons of buildings, reaching a consistent reduction of fields.

The resulting shapefile has been statistically treated using MS Excel to transform the multiple point information contained for each part of the roof in an average Solar Radiation quantity. In doing so, the "pivot" function has been applied to calculate the average yearly radiation values for roof surfaces with similar values. The shift from Solar Radiation to energy production has been reached while considering the following characteristics of the used photovoltaic technology:

(i) the system performance ratio of 0.75; this parameter assumes that the in-situ performance of panels is lower than the performances in standard conditions in a laboratory; it should increase along with the years of utilization, and in this case, it has been assumed as a fixed parameter, and;
(ii) the energy production is a function of the number of panels, the peak power installed, and the energy conversion efficiency (e.g., it was considered a monocrystalline silicon technology panel with an annual average conversion efficiency of 12.5%) [46].

The final energetic production (kWh/year) has been evaluated taking into account that the average annual electric consumption of a family in the Moncalieri is about 2180 kWh/family/year [47].

For making the obtained values understandable in the context of normative regulations and make the comparative analysis possible, the single values of the energy production potential of each building have to be converted into a value of production potential of the normative zone. This passage was done through two simple mathematical operations. First, summing up all the average values for single buildings represented as E (kWh/year) and second, by dividing this indicator to the number of buildings in each zone to get the average zone value. These passages produced then an average value of solar radiation for each normative zone, useful to make comparisons and interpret the main findings. In the next session, the results obtained from these operations will be presented and comparatively analyzed.

3. Results

In this section, all measures for each of the indicators explained above are presented for the LUZs in the city of Moncalieri. For the first four indicators—which refer to energy production—the values are comparatively analyzed. In addition, the three other indicators represent the level of compactness in each normative zone. Table 3 summarizes all the results regarding the above-mentioned analysis in each LUZ.

Table 3. Obtained measures for the energetic and morphological indicators in the city of Moncalieri.

Normative Area	E (kWh/Year)	P (kW)	$\bar{E}$ (kWh/Year)	$\bar{P}$ (kW)	Ac (m^2)	Sc Ratio	Pl Ratio
Ar1	7,251,843.42	1732.97	10,664.48	1.54	2.29	0.28	0.63
Ar2	7,938,326.26	2296.66	8656.84	1.52	1.33	0.28	0.37
Cemetery area	9803.27	212.65	9803.27	0.63	0.70	0.15	0.24
Environmental Protection Area	1,826,377.54	512.91	28,990.12	3.51	0.81	0.07	0.25
Street furniture	765,407.53	143.89	12,547.66	1.27	0.26	0.05	0.08
Av	12,938,375.19	6118.48	12,722.10	2.22	0.17	0.04	0.05
Bp	25,124,828.24	7233.49	75,779.95	6.14	2.92	0.42	0.52
Bpr1	3,570,421.28	1004.90	84,064.95	5.05	3.09	0.48	0.76
Bpr2	2,245,036.75	655.04	25,104.18	3.02	2.01	0.43	0.62
Br	60,903,302.93	19,093.38	15,363.80	2.12	2.67	0.31	0.78
Cp	6,112,824.33	1393.46	105,097.36	11.81	0.27	0.15	0.20
Cr	22,701,407.24	6965.30	12,329.69	2.03	0.58	0.12	0.18
Crc	650,321.96	211.16	81,290.25	7.82	0.67	0.43	0.71
Crs	628,703.64	194.84	13,017.42	1.89	0.14	0.09	0.16
D	1,869,508.36	670.60	54,985.54	21.63	1.32	0.31	0.39
Ee	14,457,837.48	4927.15	15,546.06	1.99	0.06	0.02	0.02
Ep	1,524,901.92	389.52	30,498.04	3.61	1.74	0.30	0.35
Es	181,398.31	46.42	90,699.15	6.63	0.83	0.39	0.76
Es1	106,300.39	24.13	35,433.46	4.83	1.57	0.63	0.63
Fe	1,076,069.35	273.51	40,800.25	3.38	1.17	0.12	0.36
Fg	1,034,831.13	255.31	29,566.60	4.91	2.05	0.36	0.74
Fh	438,061.65	80.47	41,035.03	1.52	3.95	0.30	1.22
Fhp	64,626.40	14.97	64,626.40	1.00	0.20	0.02	0.06
Fi	880,981.07	282.78	51,822.42	5.54	2.62	0.23	0.83
Fip	1,182,791.57	303.96	15,906.72	2.17	1.83	0.18	0.54
Fr	1,144,473.75	319.86	34,850.70	3.20	0.07	0.02	0.02
Frp	341,091.83	96.76	10,554.40	2.85	0.26	0.05	0.08
Ft	2,843,457.26	694.14	25,857.56	2.41	2.03	0.18	0.38
Fv	3,245,660.78	1035.81	36,627.89	1.51	0.04	0.01	0.01
S	49,353.94	14.42	6169.24	0.72	0.02	0.01	0.00
Railway site	2,371,320.36	238.94	30,016.71	1.11	0.16	0.03	0.05
Sp	896,358.06	80.63	57,924.64	2.78	0.10	0.04	0.05
Sr	15,521,895.56	3463.24	29,706.28	2.31	0.79	0.12	0.23
Srp	1,352,786.36	140.73	37,860.70	2.99	1.49	0.15	0.47
Tcr	4,196,030.14	1340.97	65,318.25	5.56	2.67	0.39	0.59
Te	2,734,825.43	851.05	62,020.04	8.26	1.54	0.39	0.56
Tr	683,306.65	192.49	28,093.23	4.48	1.21	0.22	0.26
LUP variant	38,611,870.42	11,207.22	143,006.93	14.61	2.32	0.29	0.38

To clarify results, we compared the average Power ($\overline{P}$) and Energy ($\overline{E}$) production looking at how the minimum solar power required by law for each building differs from the maximum producible energy by each building according to the effective solar radiation. Since the indicators for performing the comparison are not unique, one of the two indicators must be converted to the other. Clearly, a time coefficient can be multiplied by the average power value in order to convert power to energy. Since the unit of measure for the energy indicator is kWh/year, the time coefficient is the number of hours when the solar panels have access to solar irradiation. To do so, we transformed the installable peak power into yearly producible energy multiplying it by 1200 annual utilization hours (solar hours per year). Since sunshine duration varies according to the location on Earth, in our case this indicator is extracted from the solar portal of the Metropolitan area of Turin for the city of Moncalieri [48]. Results are presented in Table 4, which represent the amount of average energy producible (E producible) for each building according to the real solar irradiation and the ones that should be minimally produced by each building every year (E minimal).

Table 4. Energy producible vs. energy required.

Normative Area	$\overline{E}$ producible (kWh/Year)	$\overline{E}$ Minimum (kWh/Year)	Difference (kWh/Year)
Ar1	10,664.48	1848	8816.48
Ar2	8656.84	1824	6832.84
Cemetery area	9803.27	756	9047.27
Environmental Protection Area	28,990.00	4212	24,778.00
Street furniture	12,547.00	1524	11,023.00
Av	12,722.00	2664	10,058.00
Bp	75,779.00	7368	68,411.00
Bpr1	84,064.00	6060	78,004.00
Bpr2	25,104.00	3624	21,480.00
Br	15,363.00	2544	12,819.00
Cp	105,097.00	14,172	90,925.00
Cr	12,329.00	2436	9893.00
Crc	81,290.00	9384	71,906.00
Crs	13,017.00	2268	10,749.00
D	54,985.00	25,956	29,029.00
Ee	15,546.00	2388	13,158.00
Ep	30,498.00	4332	26,166.00
Es	90,699.00	7956	82,743.00
Es1	35,433.00	5796	29,637.00
Fe	40,800.00	4056	36,744.00
Fg	29,566.00	5892	23,674.00
Fh	41,035.00	1824	39,211.00
Fhp	64,626.00	1200	63,426.00
Fi	51,822.00	6648	45,174.00
Fip	15,906.00	2604	13,302.00
Fr	34,850.00	3840	31,010.00
Frp	10,554.00	3420	7134.00
Ft	25,857.00	2892	22,965.00

The field "difference" represents all those LUZ where the installation of solar panel in new buildings according to the minimum requirement by law is inefficient, since the producible energy can be increased, reaching the maximum producible energy by effective solar radiation.

Comparative Analysis of the Energy Indicators

As mentioned earlier, the first indicator represents the total solar energy production potential of the zone, while the second one refers to the regulatory minimum for renewable energy production in the whole zone. Figures 3 and 4 represent the distribution of the total values of these two indicators in the LUZs. In addition, as it can also be noted in Table 2, E and P values differ greatly, with highest values always displayed in E indicators. The evidence from the two maps shows the wide gap between the distribution of renewable energy production in the land use zones and the real solar energy production of the land use zones of Moncalieri. This difference is mainly related to the capacity of the total solar energy production potential (E) indicator to get the best of the solar irradiation impacting a specific site. While E producible indicator tends to maximize the solar production setting its parameters to a real assessment of the orographic and morphological conditions of the city of Moncalieri (thus, acknowledging how the solar radiation is distributed and influenced by shaded and lighted areas and can realistically be used to produce energy), the E minimum indicator is just the empirical measurement of a sample-normative minimum requirement which does not account for the specific conditions through which each urban municipality expresses its specific character and production potential. Different from the minimum energy—thresholds required by law—the E producible measure aims to make the best of the solar irradiation according to the morphological features of each site. Additionally, it should be considered that the E minimum values consider only a portion of the rooftop to be destinated at solar energy production while it is considered that another part should be destinated to solar thermal panels while satisfying the thermic consumption and not the energetic one.

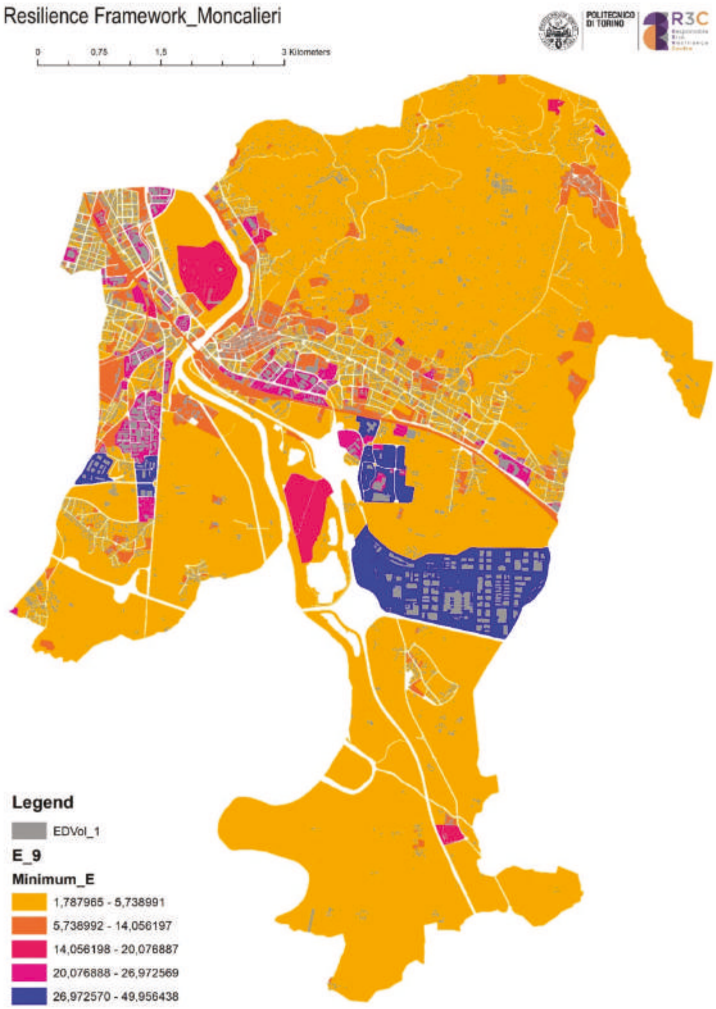


Figure 3. Graphical representation of the regulatory minimum for renewable energy production in the land use zones (P).

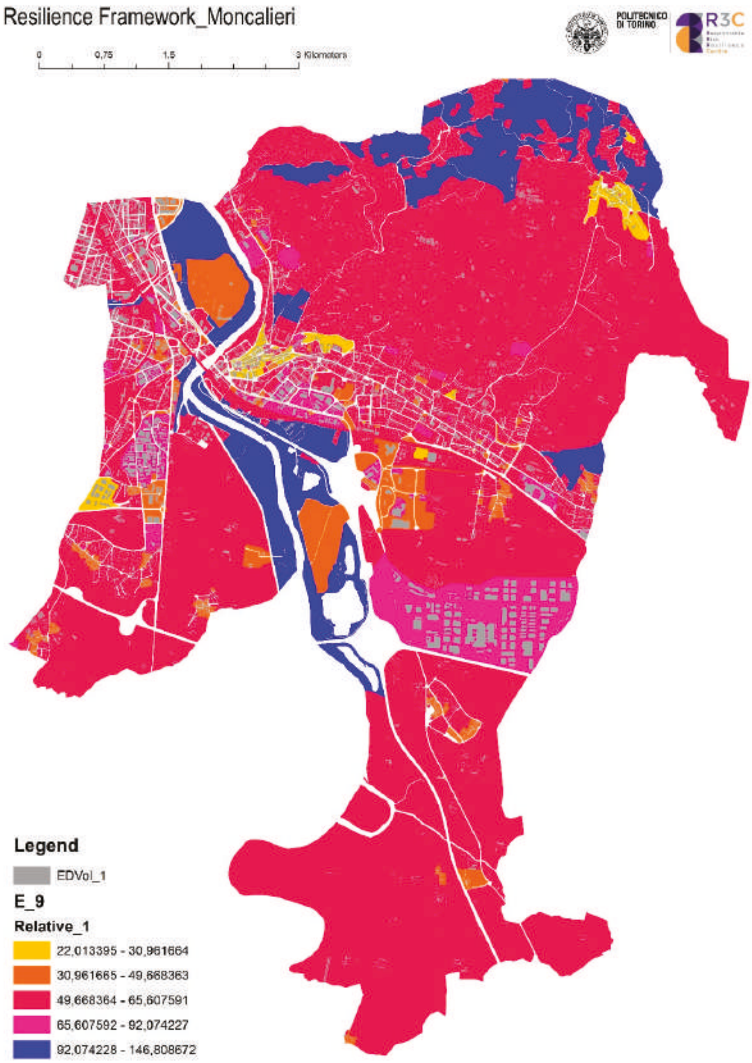


Figure 4. Graphical representation of the total solar energy production potential of the land use zones (E).

As is evident from Figure 5, a regression analysis is performed for estimating the relationship between the two indicators. The results demonstrate a great positive correlation between the two indicators in each normative zone, with an R^2 value equal to 0.98. This is due to the fact that both indicators are proportional to the roof area, but it also verifies that the zones with more solar energy production potential are also asked to produce more renewable energy according to the regulatory measures. In the urban planning field, this positive relationship can become a starting point to introduce more effective and site-specific indications of solar energy production in precise normative zones.

The next figure represents the regression analysis between the average values of E and P. A positive relationship has been verified between the average values of P and E as well. However, the significant difference between the R^2 values of the previous analysis with the latter illustrates that, although the regulatory amount of power has a positive relationship with the energy production potential, when it comes to the smaller scales (such as building scale) the relationship becomes less reliable. The R^2 value for the prior analysis equals 0.98, which means that the obtained equation is reliable for 98% of the indicators, while in the second analysis this value reduces to 0.44 which indicates that the obtained equation is valid for 44% of the indicators. Where this difference comes from, and how it can be interpreted, will be explained in the discussion section of the paper. It is also worth mentioning that, the outlier of Figure 6 refers to Zone D (industrial areas) which positions low-rise widespread buildings where huge roof-surfaces are responsible for the extremely high value of the regulatory minimum of the solar power. If this zone is eliminated from the calculations, the R^2 value increases to 0.73%, which is still significantly lower than this value for the previous regression analysis.

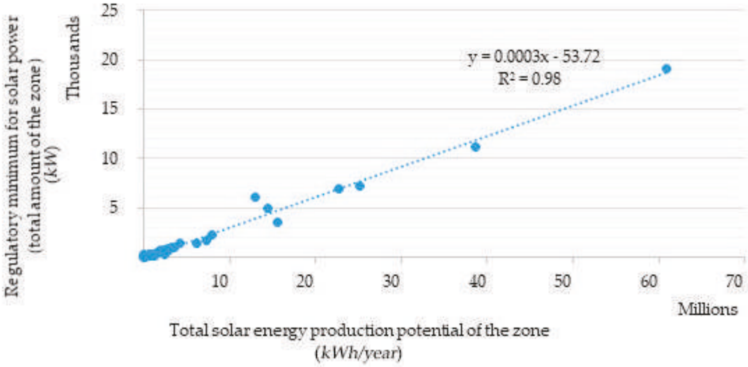


Figure 5. Regression analysis between the total solar energy production potential of the zone (E) in kWh/year, and the regulatory minimum for renewable energy production in the whole zone (P) in *kW*.

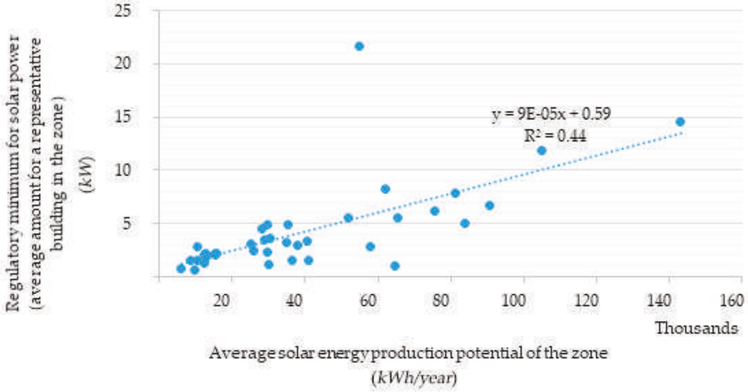


Figure 6. Regression analysis between the average values of solar energy production potential of the zone ($\overline{E}$) in kWh/year, and the regulatory minimum for renewable energy production ($\overline{\mathrm{P}}$) in kW.

In the final part of the analysis, the correlations between the indicators of compactness and the indicators of energy were examined through regression analysis. Therefore, the following three figures (a, b, c) present the regression analysis between absolute compactness, site coverage and plot ratio on the one hand, and the solar energy production potential for the unit of roof area, on the other. As it was mentioned earlier in the methodological section, the values of all indicators analyzed in this part are normalized into percentages (values between 0 and 100). The ulterior nine radar charts (d, e, f, g, h, i, l, m, n) and Table 5 summarize the results coming from the comparative analysis of these normalized indicators in the nine zones (the value for each zone is the average value of the corresponding subzones). The reason for selecting the zones instead of subzones in this section is to make the analysis more readable and coherent. The indicators utilized for the radar charts include the percentage of absolute compactness (n.Ac), percentage of site coverage (n.Sc), percentage of plot ratio (n.Pl), percentage of the regulatory minimum amount of energy to be produced in each zone (n.$\overline{P}$) and finally, the percentage of solar energy production potential in each zone (n.$\overline{E}$).

Table 5. Obtained measures for the energetic and morphological indicators in the nine macro-zones of Moncalieri. (all measures are percentages of the total amount).

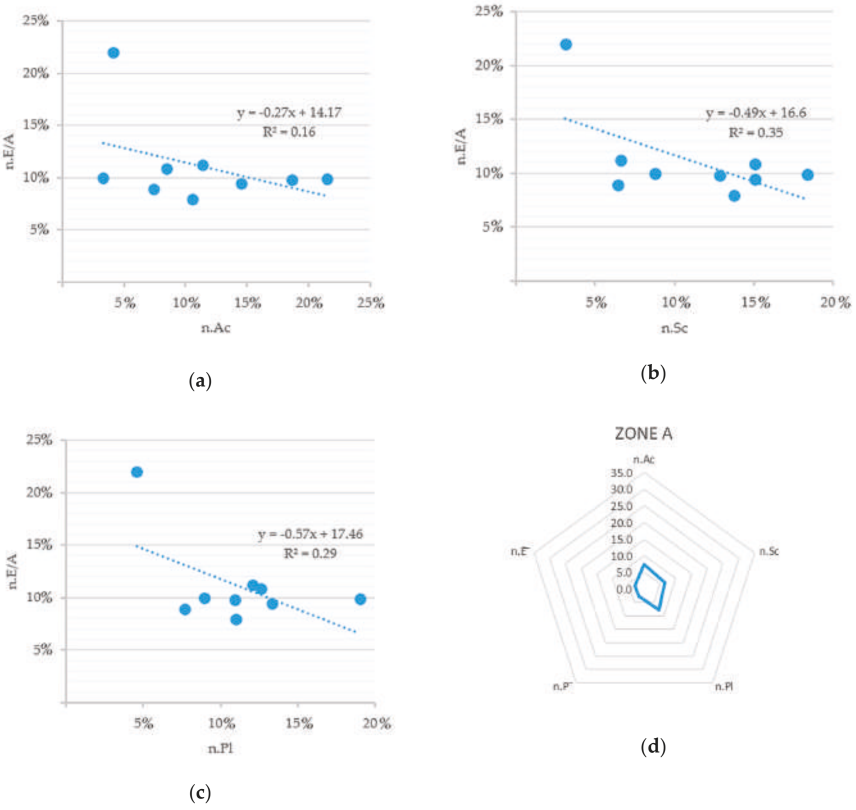
Zone	n.Ac	n.Sc	n.Pl	n.$\overline{P}$	n.$\overline{E}$
A	7.4	6.4	7.7	2.8	2.9
B	21.5	18.4	19.0	6.5	10.5
C	3.3	8.8	8.9	9.3	11.1
D	10.6	13.8	11.0	34.2	11.5
E	8.4	15.1	12.6	6.7	9.0
F	11.4	6.6	12.0	4.5	7.4
S	4.1	3.1	4.6	3.1	6.8
T	14.5	15.0	13.3	9.7	10.9
V	18.7	12.9	10.9	23.1	30.0

It is apparent from the first three figures (a, b, c) that a negative linear correlation exists between each of the compactness indicators and the energy indicator. However, this correlation is not a strong one, since the coefficient of determination (R^2), is relatively low for all three regression results and varies from 0.16 (absolute compactness) to 0.36 (site coverage). Thus, only 16–36% of the variation in the solar energy production of each normative zone of Moncalieri can be related to the variation of these compactness indicators. In general, land use zones with low compactness values produce small values of solar energy, since compactness is an indicator related to the amount of the built-up volume. As a consequence, this value can point out those urban areas where more renewable energy can be produced through the extensive installation of solar panels on roofs. If we now turn to the nine radar charts presented above, it is revealed that the changes in three compactness indicators follow the same trend for different LUZs. The energy indicators though do not follow the same trend in each LUZ. For instance, a remarkable outcome is found in the last zone (the so-called "Other Zones" in the LUP) where the value of both energy indicators is significantly higher than the other zones. Interestingly, the other indicators show that the compactness of the zone is significantly low. Although this result is meaningful for this zone, it does not lead us to conclude that any change in the compactness leads to a change in the energy indicator. This condition is highly influenced by the morphological profile of Moncalieri municipality that, being a historical over-layered city, does not present high levels of compactness and density, neither heterogeneous building-height distribution.

4. Discussion

The first significant result coming from our analysis revealed that, in the urban scale, the regulatory minimums for producing renewable energy complies with the solar production potential of the buildings in each zone. According to the formula used for calculating each of these two indicators, this convergence is due to the building footprint (S), which plays the key role for both indicators. However, the second regression analysis reports that this convergence becomes less reliable when the scale of analysis alters. Since the second pair of energy indicators are the representatives of the average values (a sample building in each zone), the significant decrease in the R^2 value demonstrates that the relationship between the production potential and regulatory minimum weakens at building scale. This implies that lots of buildings with the same value of the regulatory minimum amount of renewable energy production, in reality, have different amounts of production potential. This unanticipated finding can be explained by taking a deeper look at both indicators. The key variable in making this divergence corresponds with the accumulated annual solar irradiation in the normative zone or Hs (kWh/m^2/a). Undoubtedly, the more solar irradiation on a rooftop is accumulated, the more solar energy can be produced for the building. However, this variable is not considered in the calculation of the regulatory minimum for renewable energy production.

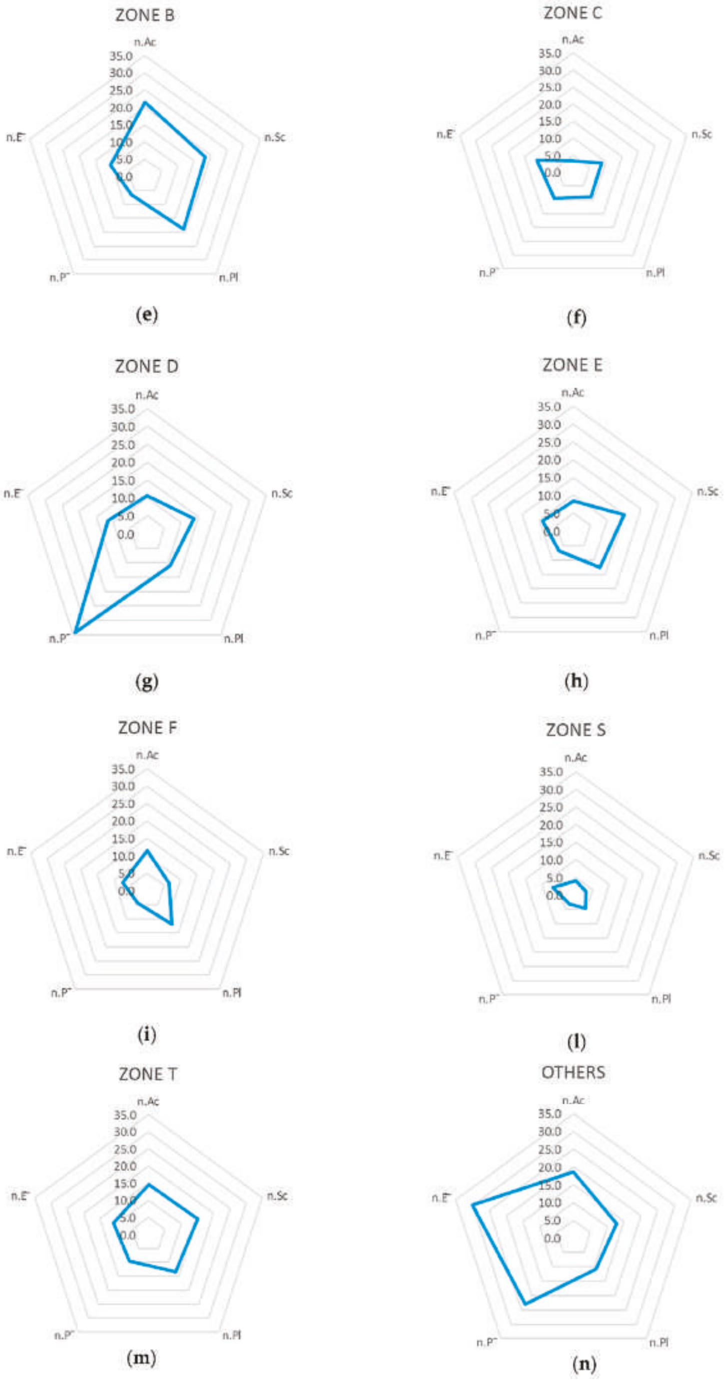
Additionally, as can be seen in Table 4, in all zones, the value of regulatory minimum for renewable energy production is considerably less than the real renewable energy production potential. The results obtained from the difference between these two values (the last column) shows an average 86.02% of the inefficiency ratio. This means that, on average, any zone is requested to produce only 13.98% of its real potential. Such observations may support the hypothesis that it is necessary to redefine the energy-related regulations and calculations in a way that the accumulated annual solar irradiation Hs (kWh/m^2/a) takes an active part in the formula of mandatory minimum for renewable energy production. Such integration between site-specific solar radiation models with the local regulations by LUZ is necessary to meet the real possibility of reconverting in an effective (achievable) and efficient way the transition to a more resilient energy proof city. It is displayed by Figure 7 that morphological conditions are quite heterogeneous in the city and that such heterogeneity poses a significant effect on the achievable quantity of energy produced by solar radiation.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. *Cont.*



(e) (f) (g) (h) (i) (l) (m) (n)

Figure 7. (**a**) regression analysis between n.E/A and n.Ac; (**b**) regression analysis between n.E/A and n.Sc; (**c**) regression analysis between n.E/A and n.Pl; (**d**–**n**) Radar chart of the comparative analysis between compactness indicators and the energy indicator in different normative zones; n.Ac is the normalized

absolute compactness, n.Sc is the normalized site coverage, n.Pl is the normalized plot ration, n.P^{-} is the normalized regulatory minimum for renewable energy production, and n.E/A is the normalized solar energy production potential for the unit of building roof area in each zone. (All values are percentages).

If the target is to produce regulatory acts that promote the transition toward a more efficient energy system, the knowledge of the "real" orographic and morphologic conditions of the urban LUZ plays a vital role in defining the reliable target, especially when the regulation concerns the minimum urban units—the buildings. Therefore, further studies to introduce the correlation between morphology and irradiation are strongly suggested, especially in those countries where solar energy is already a great and abundant source. In this way, it will be possible to realize that urban morphology represents an efficient voice to develop and transform also an old and over-layered city into an example of energy-sustainability [1]. There are several issues regarding the selection of new criteria in energy-related regulations, mainly referred to data availability to conduct calculations. Solar data access may be a relevant challenge for many local governments [7] in many countries, because they may lack adequate technical, economic and human resources to collect them.

However, the methodological implementation here mentioned is worthy of attention in the international debate, as it not only makes the required amount reasonable for the areas that cannot meet the minimum, but also can lead to an increase of the minimum required values for the zones which are more capable of producing solar energy according to their local and morphological characteristics. To be more specific, the results suggest that there is a considerable number of zones in which the minimum required amount of renewable energy production can be increased significantly. This way of realizing that the urban morphology has a strong connection with the solar potential may significantly contribute to evaluating the large-scale solar potential for roofs in existing urban areas, although it has been assessed so far for only a few countries [44]. New solar technologies may then improve the roof potential and make it evident for both public and private actors. Additionally, even if longer time is needed, the cumulative amount of solar energy produced through inclusion, modification and development of proper urban form can have relevant impacts on the energy budget at urban scale [49]. Furthermore, achieving progressive solar installation will encourage a significant amount of economic activities related to solar industries. Basically, the main economic impacts can be grouped in: "Gross impacts", which account for the activities related to the solar system construction, installation, maintenance and research spending; and "net impacts" that correspond with the difference between the solar-scenario and the current-one [50]. Within this overall background, local investments in new solar technologies may lead to specific economic impacts as: The "output", such as the value of sales considering both reductions or increases in business stocks; the "personal income", referred to the total payment to workers and business owners; the "job" impact with both full- and part- time employment; and the "tax expenses" for different national and local jurisdictions. Some benefits are also evident, as the advantages compared to an energy system without renewables, the benefits of reduced energy losses and the advantages of reduced negative environmental externalities [51]. In addition, thanks to technological improvements and cost reductions of last decades, solar panels systems are increasingly cost-competitive, affordable, and rapidly expanding [52]. The progressive understating of solar energy potentials in cities will consent to plan a priority order about the more effective interventions and economic investments [27]. It is a scientific responsibility to communicate these potentials to local authorities, professionals and citizens and to prove to them how investments today could save public and private resources in the future [7]. GIS-based assessments at a territorial scale can support this process and sensitize behaviors of both individual citizens and economic operators [27]. Urban governance needs to deal with the issues of higher initial investment costs of resilient energy technologies to reduce energy consumption and encourage local technology development [8].

Furthermore, there is a close relationship between energy production potential and urban features, such as morphological and topographical alterations. The results reveal that even in the city of

Moncalieri—which is not an extremely high compacted city—the compactness of the zones has a negative correlation with the solar energy production potential in the zones. Although this correlation was not a strong one, it underlines the importance to rethink more, in general, the role of spatial-urban planning as a strategic tool, capable of influencing land use, property rights, mobility, urban design and renewable energy production in the building sector. This new approach highlights that to understand and assess the solar energy potential in urban areas, morphology-related variables should be included in the early stages of the design and planning process [28]. For instance, this passage may highlight those LUZ where it is more convenient to install new solar panels because of the available roof-surfaces, or may introduce in the land use planning practice some "urban compactness-thresholds", "alignment of rooftops", "distance between solar-radiated surfaces" or "height of new solar energy-producing buildings". Hence, this model has the potential to slightly transform the existent city, introducing new energetic thresholds on the real/effective production capacity while maximizing the solar radiation effect. In this sense, it will become increasingly important to understand and possibly simplify the typical requirements faced by technicians, designers and planners [53]. In fact, when dealing with new design or re-design of urban areas, operators usually have to do with regulations, requirements and restrictions related to building characteristics, morphological targets, economic availabilities, etc. The integration of solar energy potential can make this process even more complicated, but the effort for a better balance is needed. To simplify the procedure, the use of some morphological features over others should be developed, according to studies that show the impact of each variable on the overall solar energy production of a LUZ or of its buildings.

Finally, our analysis is restricted to the calculation of the solar energy production from the rooftops, and this is a limit according to the most advanced solar production techniques for vertical structures (e.g., building walls, facades, and windows). Furthermore, while the area of the whole roofs is usually very high, only a fraction of it has the potential to produce an acceptable amount of energy. However, there are three main reasons that make this limitation negligible. First, the present regulations of the city and the conditions of many buildings make it almost impossible to use the facades as a potential energy source for the existing buildings. Second, usually, the amount of solar energy that can be collected on roofs is much higher than that on facades. Additionally, regardless of the roof type or slope, considering the available technologies in the region, and taking advantage of design solutions, we believe that it is possible to install solar panels on almost every roof [53]. Third, even if the calculation is restricted to the rooftops, the existence, absence, weakness, or significance of the correlation between the energy production and the real conditions of each case of study should be assessed, analyzed, demonstrated by in-depth solar radiation assessment as a minimum requirement to re-design local regulations and normative solutions at the city-level by the LUP. Finally, despite the utility of specific data on the current-percentage of buildings with roof-panels, we do not know exactly this quantity as data are not available. However, thanks to the information collected from Portale Altasole (http://atlasole.gse.it/atlasole/), we found out that in 2010 only 274 solar panel plants where installed in the city on a total of 6.200 buildings, with a total power of 6.313 kW (corresponding to 612 MWh) [54]. This information, regardless of the fact that some buildings may not be suitable for solar plants, highlights the room for a local long-term transition towards solar energy production.

In future steps of this research, we may investigate how to be more effective in such analytical results, selecting certain sample areas and providing a direct link between assessment and policy making with practical and normative implications.

5. Conclusions

Since the city is a highly-populated place with the most concentrated human activity, there is an increasing need to move towards a more sustainable development—where urban land use patterns are coherent with the morphological profile and energy producibility through solar source [27]. The growing general interest for including energy topics (in the land use planning process and in the search for sustainable urban forms) is also reinforced by the need to address future changes with more energy-efficient cities [55]. Mainstreaming energetic resilience by morphological study and assessment in ordinary municipal land use planning can become an important step for developing tools and data to drive urban energy resilience. Indicators are also useful to inform decision making by local authorities, and their outcomes can improve urban energy system's preparation, absorption and adaptation abilities [7]. In this study, we highlight the need to simplify, integrate and track solar energy issues at the local scale, in order to favor the route to resilience and to more sustainable models of urban planning. To achieve the overmentioned sustainable principles of "availability", "accessibility", "affordability" and "acceptability", any urban systems should be able to "prepare and plan for, absorb, recover from, and then successfully adapt to" any risks or disturbs over time [8]. In this sense, the proposed GIS model could become a support-tool for interactive decisions, based on the real characteristics of the municipal building stock. Moreover, looking to the model contents, we understand the need to use building regulations not only to strengthen and implement the law (specifically here, the Legislative Decree 28/2011), but also to introduce practices for "building better" than the regulatory requirements. The benefits of this approach might lead for instance to voluntary actions in favor of sustainable energy that can be recognized by the municipal land use planning with economic incentives and financial mechanisms, such as discounts on construction costs, volumetric bonus or tax benefits (for example). To reach this point, however, municipal land use regulations need to integrate progressively models like the one elaborated in this work, in order to realistically evaluate where it is convenient to adopt these actions at the local scale. Furthermore, these new elements have to be supplemented by the efforts of the local level in favor of bottom-up activities and engagement [56], in order to promote the use of good practices also at smaller scales.

One of the most evident and replicable findings of this study is that urban design has a high impact on solar energy production, through the design of buildings, forming urban geometry, determining land uses, etc. Nevertheless, the difficulty in understanding urban complexity creates limitations for intertwining theory and practice, especially in the case of the urban planning field. However, when dealing with sustainable energy issues at the local level, these aspects and results may become permanent support in the decision-making process, as well as a relevant requirement for achieving energetic resilience. For the specific case-study of this research, the Energy Attachment should not be seen as a separate and exhaustive document of the municipality, but rather part of the "corporate culture" of municipal planning in the "Era of energy transition" [1]. The energy attachment should be integrated into the municipal plan, and its technical contents should affect the localization of zones, their dimensions, their functionalities and morphologies also in the light of the urban energy strategy.

More broadly, evidence shows that the conscious installation of photovoltaic systems in large urban contests can offer a sustainable contribution to energy needs and savings, but in parallel has to be supported by proper GIS or grid models to guide the city energy balance since the early planning process [49]. Urban planners can play a central role in making these models more comprehensible, identifying the status-quo, patterns, potential threats and emergencies [8]. They should then become more and more aware of the advantages to include energy resilience among their objectives and to update development policies with renewable energy implications. Furthermore, planners should also coordinate policy makers, stakeholders and private actors in a collective strategy of sustainable and smart energy systems at territorial level.

For all these reasons, instead of focusing on short-time results, the municipal approach should also consider the morphological features (since the physical structure of cities is also relatively permanent), in order to clearly recognize the most productive areas from those more compromised, shady and geometrically inconvenient for energy purposes in the long-run. The use of realistic data may guide the exploration of future scenarios of land use and urban expansion, further integrating the solar energy potential in urban planning [57]. Finally, yet importantly, the traditional preference to keep dated policies and add plans within an already overabundant planning system hinders the reform of the way of intervening and makes it too fragmented. In relation to that, we highlight that this planning methodology risks too much of a singular focus on a single action or project, leaving the whole city "unchanged" and "unaffected" from a concrete energy-shift. On the contrary, developing the capacity to simulate the urban energy profile, starting from the morphological properties, may lead to an efficient, energetic condition capable of responding to future energy requirements, as well as to local long-term perspectives on all levels.

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sustainability

Article

Supporting Resilient Urban Planning through Walkability Assessment

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Abstract: The urban planning and evaluation literature suggests that making a walkable city means creating a resilient and healthy city. In recent years, alternative mobility has been the subject of numerous studies, showing that the concept of urban walkability can be used as an additional support in planning resilient cities. Though researchers agree that walkability assessment has a positive impact on public space planning, it is still difficult to include the topic in planning strategies because of its novelty in the scientific debate. This paper will first review the literature on walkability assessment and then propose a multi-methodological assessment framework that fills the gaps in existing assessment methods. The multi-methodological assessment framework contributes to overcoming the idea that objective and subjective aspects are "not part of the same planning project." Thanks to its combination of hard and soft methods, the assessment framework illustrated in this paper can consider physical and perceptual aspects simultaneously and represent them visually using Geographic Information Systems (GIS). It can thus provide easily readable results that can be applied in establishing guidelines for planning resilient cities.

Keywords: walkability; walkability measure; urban resilience; quantitative; qualitative and mixed models and methods; urban planning; public space

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1. Introduction

> *Let's think about how our cognitive ability and our experience will diminish, for example looking at the use of Google Maps: well, people have no idea where it is interesting to walk because they are glued to the phone to get in the most efficient way from A to B. More an experience is smooth, without clutches, more we stop learning* [1] (p. 36).

The concept of resilience originated in ecology and refers to a "measure of persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between population or state variables" [1]. The concept has gained increasing importance in numerous disciplines [2] including urban planning, [3,4] where many researchers have increasingly stressed the need for tools to support appropriate policies for creating resilient and inclusive cities [5–7].

The "city object" can be considered as a rather complex "urban ecosystem" that is vulnerable to change and external inputs [8], and needs conceptual and operational models to support its development and stability [9]. Accordingly, the challenge of urban planning is to design adaptive settlements capable of facing the threats to resilience [10]. In this perspective, the term resilient is not used to design or describe an ideal urban space [11] but to emphasize the need for urban spaces able to be safe, livable, open, accessible, healthy and designed to a human scale [12–15].

Urban mobility is one of the most significant aspects of the complex challenge that cities are facing in the areas of sustainability and climate change resilience [11,16,17]. In particular, reducing car-dependency can significantly reduce the negative impact of neighborhoods in terms of emissions and energy consumption: walkable neighborhoods can assist in climate change mitigation and adaptation plans by decreasing reliance on fossil fuels used for transportation [18].

According to this, the scientific communities and public administrations are now called on to identify development models that can reduce pollutant emissions by improving "soft mobility" [19]. As the easiest, cheapest, and socially most equal form of soft mobility, walkability presents a variety of advantages: economic, political (saving non-renewable resources), social (equity of mobility), and ecological. [20,21].

Researchers agree that walkability is first of all a measurement tool for assessing the degree of pedestrian use of a certain area [22]. It is important to stress that there is still no consensus definition of walkability [23]: some scholars define it as "the security, economy, and convenience of traveling by foot" [24], while others adopt a more qualitative perspective, regarding walkability as a "quality of place" [25].

Those differences in the definition of walkability are due to several factors. First, the action of "walking" is ambiguous: people walk for many reasons and it is difficult to determine whether walkability planning should be classified as a matter of security, health, or transport [26]. Second, walkability affects multiple stakeholders, aspects, and different spheres of reality. Third, walkability can be analyzed and measured at different territorial scales [27]. Lastly, and maybe more important, the broader concept of walkability includes a wide range of subjective elements (comfort, continuity, legibility) that are often difficult to interpret [28–30]. Moreover, subjectivity could be understood as the relationship between the perception of a space's quality and the reaction that this space is able to generate in the observer. This relationship is not readily assessed, but it is fundamental since it influences people's willingness to walk in a given place [21,29,31]. From this perspective, the subjective/perceptual factors should be assessed when planning urban spaces in order to contribute to designing more sustainable cities [28,29,32].

While past research has fully addressed the technical side of measuring and representing walkability [33,34], focusing on the objective aspects (e.g., the width and height of sidewalks), there is still a wide gap in our knowledge about how urban planning copes with the subjective aspects of walkability (i.e., the comfort of walking a road).

Based on a case study research method [35], the aim of this paper is to contribute to filling this gap by proposing a multi-methodological assessment framework able to jointly assess the objective and subjective dimensions of walkability with a view to guiding future sustainable, resilient urban development.

The multi-methodological assessment framework can be a useful tool for dealing with the issue of sustainable mobility in an approach that sees walkability as a factor in the city's sustainability and growth [32].

The study consisted of several interactive steps [36]. First, we carried out a literature review to understand the different nuances involved in walkability and the most commonly used assessment methods. Second, on the basis of the results of the literature review, we identified the main indexes and indicators for measuring the aspects of walkability. Third, we used surveys [37] to empirically test the validity of these indexes and indicators, and we aggregated the results through statistical analyses. Lastly, we performed a spatial evaluation [38,39] based on Geographic Information Systems (GIS) in order to assess the geographical representation of the indicators [34].

The remainder of the paper is organized as follows. Section 2 frames the case study research method by introducing the case study; Section 3 describes the main methods applied to assess walkability; Section 4 presents the development of the assessment framework. Lastly, Section 5 discuss the model's strengths and weaknesses, as well as future directions for research.

2. The Case Study Research Method

In order to properly develop a multi-methodological framework able to analyze both the objective and the subjective aspects of walkability, it was decided to apply a case study research method [34,40,41], which implies the in-depth investigation of a single individual or multiple events to explore the causes of underlying general principles.

Accordingly, the case study research method involves the identification of a case study, the collection and analysis of data, and the representation of the results obtained [42]. Through this method, it is possible to open up new directions for future research. In this perspective, walkability is thus assessed in a real setting.

In a case study research, selecting an appropriate case is fundamental, since a poor choice could place the entire development of the assessment method at risk [35]. Consequently, before making our choice, we listed a number of characteristics the case study should have in order to be suitable for our purpose. First, since the walkability assessment changes according to the territorial scale of analysis, an intermediate territorial scale similar to a district would provide insight into a manageable territory and would be scalable to larger and smaller areas [39].

Second, the case needed to be a public space frequented by large numbers of people so that subjective data could be collected from the area's users. Lastly, the area had to be familiar to the researchers in order to avoid lengthening the time spent in data retrieval. In view of these requirements, the choice fell to the main university campus of the Politecnico di Torino (PoliTO, Italy), hereunder referred to as the PoliTO campus.

The Case Study: Main Campus of the Politecnico di Torino

From the perspective of case study research, a university campus provides fertile ground for studying and assessing various aspects of sustainability and resilience, raising awareness among students, lecturers, and administrative staff about crucial issues of our times [43]. Here, it is possible to conduct research, undertake multidisciplinary collaborations and implement sustainability solutions that can be generalized in the future. At the same time, a university campus is comparable to an urban district in terms of size and dynamics [44].

The PoliTO campus was suitable for our purpose since it hosts the university's main activities and is used by a large numbers of students, teachers, and administrative staff. Moreover, the main campus has extensive open spaces that can only be used by pedestrians, which is an important consideration. Lastly, as indicated by the PoliTO Masterplan [45], the campus is poised to begin a new season of change in terms of growth, interaction with the territory, internationalization, and sustainable planning.

The PoliTO Masterplan, managed by a selected team of designers and experts, envisages a series of projects to increase the livability of campus spaces and the provision of services. With regard to the enhancement of open spaces, the Masterplan aims to deploy coordinated actions to create new paths, green areas and places for collective activities.

Figure 1 shows the case study area, which includes the PoliTO campus (green border) as well as the surrounding area (red border).

In talking about walkability, it is essential to think about the campus's accessibility, taking intermodality into account to consider the different modes of transport available to users. Moreover, it is important to consider that, in accordance with the "last mile theory" [46], in any communication network, the last mile is more likely to reach customers and is therefore the most reasonable area to consider in a study.

Accordingly, the case study (Figure 1) includes not simply the campus but a wider area comprising as much local public transport as possible and the main railway station of Turin (the Porta Susa intermodal station).

Figures 2 and 3 show several routes on the PoliTO campus and in the surrounding area that feature differences in walkability. In fact, a first empirical observation of the study area indicated that some routes involve more challenges for the pedestrian than others.

Figure 1. The case study area.

Figure 2. Pedestrian routes on the Politecnico di Torino (PoliTO) campus (Source: authors' photos).

Figure 3. Pedestrian routes in the area surrounding the PoliTO campus (Source: authors' photo).

The photographs in Figure 2 show two pedestrian routes that cross roadways on the PoliTO campus. Traffic signs and road markings regulate the one on the left, while the other path is devoid of signage and separation.

The photo on the left in Figure 3 shows the pedestrian crossing regulated by traffic lights leading to the Porta Susa station, while the photo on the right shows a dangerous pedestrian crossing on a linear stretch without signs or traffic lights.

3. Research Design and Data Analysis

After selecting the case study, we specified several requirements for the multi-methodological assessment framework.

The framework should be:

(1) Able to consider objective and subjective elements of walkability;
(2) Able to quantify and measure subjective elements;
(3) Mathematically robust and sensible;
(4) Flexible and adaptable. e.g., usable at different territorial scales;
(5) Able to support the urban planning design decision-making processes.

Table 1. Synthesis of the multi-methodological framework.

Phases	Steps	Activities	Results
Choice	Literature review	Definition of the keywords/search parameters Definition of the time span Database search Analysis of the 16 papers selected	Selection of 16 papers containing qualitative/quantitative assessment methods to measure walkability Identification of the most used indexes and indicators (4 indexes and 18 indicators)
Analysis	Empirical investigation	Validation of the results of the Choice phase Selection of a preliminary sample to deliver the survey test Validation of the reliability of the survey on the preliminary sample Choice of a final sample to deliver the survey Delivery of the survey to the final sample Statistical analysis	Elaboration of a survey test 40 students of the PoliTO campus + PoliTO masterplan Changing the indexes and the indicators selected in the Choice phase 4 indexes and 28 indicators) 100 PoliTO users Definition of the weights to be attributed to the indexes and the indicators
Evaluation	Spatial evaluation	Use of Geographic Information Systems (GIS) measures to spatialize the indexes and indicators Identification of the problem areas from a walkability perspective in the study area	Spatialization of the indexes and the indicators Suggestions for improvement in terms of walkability to support the PoliTO Masterplan

To satisfy these requirements, the proposed multi-methodological assessment framework is organized in three phases and several steps (Table 1) in an interactive and iterative process in order to achieve solid results [47,48].

According to Table 1, the multi-methodological assessment framework is structured as follows:

(a) Choice phase, where indexes and indicators were preliminary chosen through an in-depth analysis of the literature. First, we selected three keywords to compose the string search viz., walkability + walkability measure + walkability indicators. Second, the string has been inserted in both Scopus and Google Scholar databases to identify scientific papers in the timespan 2000–2019 (Figure 4). This research has given rise to numerous papers. Third, basing on abstract and keywords, we selected only the papers that appeared in both databases and simultaneously related to the 3 subject areas of interest: urban planning, urban planning measure and qualitative/and quantitative assessment methods). This systematic literature review provided 16 (Table 2).

Figure 4. Distribution of the 16 papers in the timespan of the research.

Figure 4 shows that, although the timespan is related to 19 years, it is only since 2009 that we found scientific papers actually corresponding to our research interests. This underlines the topicality of the walkability measurement from an urban planning perspective.

Table 2. Quantitative and qualitative assessment methods in the 16 papers analyzed.

Papers	Quantitative Methods		Qualitative Methods		
	Weighting of Indexes and Indicators	**Statistical Analysis**	**Empirical Investigation**	**Assessment Survey**	**Visualization through GIS and CAD (Computer-Aided Drafting) Tools**
Ewing and Handy, 2009		✔	✔		
Cerin et al., 2011		✔		✔	
Galanis and Eliou, 2011		✔			✔
Cambra, 2012	✔	✔			
Ford, 2013	✔				
Moayedi et al., 2013	✔				
Domokos, Wiitala and Tier, 2014			✔	✔	
Lee and Talen, 2014		✔	✔		✔
Blečić et al., 2014	✔		✔		
D'Alessandro, Apolloni and Capasso, 2016	✔				
Keat, Yaacob and Hashim, 2016			✔	✔	
Yin, 2017		✔	✔		
Chiantera et al., 2018	✔				✔
Shatu and Yigitcanlar, 2018		✔		✔	
Wibowo and Nurhalima, 2018			✔		
Ussery et al., 2019		✔			

In Table 2, the 16 papers are summarized according to the assessment method used. According to the literature, the main quantitative methods are:

(1) Weighting indexes and indicators to produce a global index. Indexes and indicators are chosen by researchers on the basis of the literature or empirical analyses. The method is very flexible and can be applied at several territorial scales [39];

(2) Statistical analyses, which provide a robust evaluation by using highly objective analytical attributes such as averages, maximum and minimum values, correlation, and agreement coefficients and standard deviation [49];

The main qualitative methods are:

(1) Empirical investigation, which can assess both measurable and perceptual elements by direct observation in the analyzed area [50].

(2) Assessment survey, which aims to capture the subjective aspects of a problem. The difficulty here lies in selecting the correct survey structure [37];

(3) Visualization through GIS [50] and CAD tools [34] to visualize the current state of the study area and to represent future scenarios.

The literature review indicated that the choice of one method rather than another depends on two main factors: the geographical scale of the analysis and the purpose of the assessment. Currently, it is very difficult to identify an assessment method that is suitable for every situation in a multi-scale perspective [27].

Nevertheless, researchers have begun to advance proposals for overcoming these problems. The most widely used solution is to combine qualitative/quantitative assessment methods [47,51] in order to include both aspects of the assessment while making the method more flexible. However, there are still few studies that propose all the assessment methods simultaneously (Table 2). For example, statistical analyses are often employed after all the other assessment methods to verify the robustness of the results [28,34], while assessment surveys are usually used before weighting indexes and indicators to gauge the level of satisfaction with the indicators [52].

(b) Analysis phase, consisting of an empirical investigation of the case study area and a survey administered to the main categories of PoliTO campus users. In order to verify the reliability of the survey, a preliminary test was made on a sample of 40 students. Subsequently, survey data were analyzed using different statistical techniques. Through the survey, the results of the Choice phase were tested, making changes and enriching it with data, thus making the model more robust and objective;

(c) Evaluation phase, where the current status of the PoliTO campus was assessed. This phase employed a GIS software application called Quantum-Geographic Information System (QGIS) [53] to assess potential associations between a number of built environment characteristics and walking [54] and to have a visual representation of the evaluation problem [55]. Among the many available visualization tools [39,50,56], we decided to use QGIS [53] since it is an open-source software system that does not require a license, uses readily consulted open data, and georeferences objects to be assessed on any geographic scale (city, neighborhood, or single street), providing easy-to-read output. Moreover, it is widely used, making the method presented here easily replicable.

In general, using visualization tools can promote a shared understanding among the stakeholders involved in a decision process [57–60] and is useful in complex problems such as walkability, which involve many different stakeholders and aspects.

Thus, the QGIS tool in the third phase (Table 1) contributes to the assessment by helping stakeholders to "get on the same page" [61] and to have a collective insight [62] about the issues involved.

4. Findings

4.1. Choice Phase

To identify the main walkability indexes and indicators to be used in the proposed multi-methodological assessment framework, we studied and analyzed the 16 papers selected through the literature review discussed in Section 3. The analysis yielded 18 indicators divided into 4 indexes (Table 3).

Table 3. Indexes and indicators resulting from the literature review.

Indexes	Indicators	References
Security	Presence of intersections Drivable speed Existence of conflict area between pedestrian and vehicular traffic Types of roads	[33,39,52,63–66]
Quality of routes	Sidewalk's length Condition of the pavement Non-sliding paths (with obstacles) Well connected Slope	[21,28,29,31,33,34,39,52,63–66]
Intermodality	Presence and coverage of public transport stops Cycling	[31,63]
Comfort	Presence of trees/meadows Adequate lighting Possibility of stopping due to benches Architectural variety Buildings with monotonous colors Possibility to see the continuity of the route Presence of commercial activity	[21,29,31,33,37,39,49,50,52,63–66]

As shown in Table 3, according to the revised literature, the most commonly used indexes for assessing walkability are Security, Quality of route, Comfort, and Intermodality. Moreover, each index can in turn be measured with different indicators. In detail, the Security index can be measured through 4 indicators (7 papers), the Quality of routes contains 5 indicators, the Intermodality index contains 2 indicators (2 papers), and Comfort has 7 indicators (12 papers). Unsurprisingly, the majority of the indicators refer to the Quality of routes and Comfort indexes. This is probably because it is difficult to identify general indicators capable of measuring these indexes' high subjectivity.

4.2. Analysis Phase

The first step of the analysis phase was an empirical investigation of the PoliTO campus (Table 3) to determine which of the indexes and indicators found through the literature review were most appropriate (Table 1). For this purpose, we interviewed a first sample consisting of the PoliTO Masterplan Team together with a selected group of 40 students. They were asked to analyze the indexes and indicators shown in Table 3 in terms of their applicability to the PoliTO campus. The interviewees found that the Security, Quality of routes, Comfort, and Intermodality indexes perfectly fit the PoliTO campus's needs. By contrast, the indicators found in the literature review were too generic to correctly assess the current situation of the PoliTO campus or for use in planning projects. Accordingly, each indicator in Table 3 was further specified to better reflect the case study's needs. For instance, the "cycling" indicator in the Intermodality index (Table 3), which referred simply to the presence of cycle paths, was divided into two indicators, namely "parking spaces for own bike" and "bike sharing stations" (Table 4) denoting that the area in question has provision for users to park their own bikes and features bike sharing stations (Figure 1).

Table 4. Indexes and indicators selected in the analysis phase.

Indexes	Indicators	
Security		Presence of busy roads
		Traffic light pedestrian crossings with sufficient time
		Non-lighted pedestrian crossings in neighborhood streets
		Separation of pedestrian/cycling/cable/accessible routes
Quality of routes	Internal	Tightening of sidewalk
		Condition of the pavement
		Non-sliding paths (with obstacles)
		Well connected with the outside
		Slope
	External	Tightening of sidewalk
		Condition of the pavement
		Non-sliding paths (with obstacles)
Intermodality		Parking spaces for own bike
		Easy accessibility by public transport
		Own car parks
		Bike sharing stations
		Car sharing stations
Comfort		Acoustic pollution
		Covered routes
		Presence of trees/meadows
		Presence of baskets
		Adequate lighting during night/evening hours
		Possibility of stopping due to the presence of benches
		Presence of water points
		Presence of tall buildings
		Buildings with monotonous colors
		Possibility to see the continuity of the route
		Refreshment points of the PoliTO campus
		Study points in the PoliTO campus
		Spaces where crowding is created in PoliTO campus
		Spaces where crowding is created outside PoliTO campus

In addition, the indicators for the Quality of route index were split into two macro categories, internal and external, to better analyze the situation on and off campus (see green and red borders in Figure 1). With the same rationale, some indicators were eliminated from the analysis: the "presence of commercial activity" indicator in the Comfort index was considered unnecessary for the PoliTO campus.

The 28 indicators resulting from the empirical investigation are listed in Table 4.

As shown in Table 4, the final selected indexes are: Security, Quality of routes, Intermodality, and Comfort. Despite the changes made, according to the first interviewed sample, we have classified the indicators into indexes based on the analysis of the literature as for example: the indicator "tightening of the sidewalk" has been associated with the Quality of routes index because it refers to the specific structural characteristics of the pedestrian area.

The second step of the analysis phase used surveys (see in Supplementary Materials) and statistical analyses to test the sensitivity of the indexes and indicators (Table 4) and understand the weights of each index and indicator in the users' subjective perceptions.

The surveys consisted of 36 closed questions in order to facilitate completion and reduce the dispersion of responses [67]. Respondents were asked to rate their agreement with each question on a 5-point Likert scale [68,69] ranging from 1 (strongly disagree) to 5 (strongly agree).

A sample item is reported in Table 5.

Table 5. Example of closed question provided in the questionnaire

There are many busy roads in the area inside the PoliTO campus with heavy vehicular traffic.						
Strongly Disagree	**1**	**2**	**3**	**4**	**5**	**Strongly Agree**

After an internal test to verify the reliability of the survey structure, the surveys have been sent by e-mail to the daily employees and users of the PoliTO campus including students (from 4 master's degrees), faculty members (professors, researchers, and research fellows) and technical/administrative staff. The completed surveys collected have been 100. This sample size corresponds to the non-statistical sampling method called "judgmental sampling" [70], according to which the choice is entrusted to the researcher with criteria of representativeness and convenience: the increase of the empirical basis ends when the addition could give a null contribution [70].

Based on the 100 surveys, statistical analysis was performed in order to analyze the data and assign weights for indexes and indicators as suggested by the literature [33]. After applying several simple statistical analyses including mode, arithmetic mean, weighted average, and standard deviation [71], we decided to focus on calculating the weighted average since it is better able to reflect the priorities of the users' real preferences by assigning each value its own degree of importance, producing more sensitive results [52]. In fact, according to the definition of the weighted average, the values in analysis are summed, each multiplied by a coefficient that defines their "importance" and the result is divided by the sum of the weights [71]. The aggregated weights of the indexes and of the indicators obtained through the weighted average are shown in Table 4.

As shown in Table 6, Security is considered the most important index (29%) and also contains the most important indicator, e.g., "presence of busy roads" (31%), given that from the individual's point of view, being able to walk in a safe place is an extremely important aspect of sustainable public space planning. Almost equal to the first index is the Quality of routes (28%), whose most important indicator is "non-sliding paths" (15%). This highlights the importance of eliminating architectural barriers in public spaces. The third index is Intermodality (22%), where the "easy accessibility by public transport" indicator is emphasized (23%). Public transport is widely used in Turin. Most users of the PoliTO campus reach it by train or bus rather than bikes or private transport. This means that being able to reach a train or bus station quickly is very important. The Comfort index came last in the rankings (22%). This does not mean that comfort is not an important aspect for the PoliTO campus, but that any associated problems have to a certain extent been solved. Currently, users perceive the PoliTO campus as comfortable, except for a problem highlighted by the "spaces where crowding is created in PoliTO campus" indicator (10%) which reflects the need for a more rational and planned use of space to avoid overcrowding.

Table 6. Indexes and indicators with weights obtained in the analysis phase.

Indexes	Weights of Indexes	Indicators		Weights of Indicators	
Security	**29%**		Presence of busy roads	31%	Minimize
			Traffic light pedestrian crossings with sufficient time	23%	Maximize
			Non-lighted pedestrian crossings in neighborhood streets	19%	Minimize
			Separation of pedestrian/cycling/cable/accessible routes	26%	Maximize
Quality of routes	28%	Internal	Tightening of sidewalk	12%	Minimize
			Condition of the pavement	13%	Maximize
			Non-sliding paths (with obstacles)	15%	Minimize
			Well connected with the outside	12%	Maximize
			Slope	11%	Minimize
		External	Tightening of sidewalk	13%	Minimize
			Condition of the pavement	12%	Maximize
			Non-sliding paths (with obstacles)	12%	Maximize
Intermodality	22%		Parking spaces for own bike	20%	Maximize
			Easy accessibility by public transport	23%	Maximize
			Own car parks	17%	Maximize
			Bike sharing stations	21%	Maximize
			Car sharing stations	19%	Maximize
Comfort	21%		Acoustic pollution	8%	Minimize
			Covered routes	5%	Maximize
			Presence of trees/meadows	6%	Maximize
			Presence of baskets	7%	Maximize
			Adequate lighting during night/evening hours	7%	Maximize
			Possibility of stopping due to the presence of benches	6%	Maximize
			Presence of water points	6%	Maximize
			Presence of tall buildings	8%	Maximize
			Buildings with monotonous colors	8%	Minimize
			Possibility to see the continuity of the route	7%	Maximize
			Refreshment points of the PoliTO campus	8%	Maximize
			Study points in the PoliTO campus	7%	Maximize
			Spaces where crowding is created in PoliTO campus	10%	Minimize
			Spaces where crowding is created outside PoliTO campus	8%	Minimize

Moreover, while some indicators refer to positive elements from the walkability point of view, others are negative. Therefore, the corresponding weights should be minimized or maximized (Table 4) depending on these characteristics (e.g., “presence of busy roads” refers to a negative characteristic therefore should be minimized, as opposed to “traffic light pedestrian crossings with sufficient time” that should be maximized—Table 6).

4.3. Evaluation Phase: QGIS Measure

The Evaluation phase involves the visual representation of the objective/technical and subjective/perceptual elements of walkability. This phase employed QGIS and sought to provide a complete picture of the current walkability situation on the PoliTO campus.

To this end, the 28 indicators found in the literature and weighted through the surveys (Table 4) were first georeferenced. Here, some indicators required special attention. For example, the “bike sharing stations” indicator cannot be represented in a single way, since the footprint of each bike sharing station differs according to the number of stalls. Similarly, we decided to georeference “adequate lighting during night/evening hours” by representing the footprint of the light cast by the lamps.

Lastly, georeferencing the “non-lighted pedestrian crossings in neighborhood streets” indicator proved particularly problematic. In fact, according to the Torino Sustainable Urban Mobility Plan (PUMS) [72] and a site inspection (Figure 1), some non-lighted pedestrian crossings in the area in question cannot be considered dangerous, as alternative routes such as pedestrian overpasses are provided for crossing the roads. A different level of danger was thus assigned to each non-lighted pedestrian crossing on the basis of the information provided by the PUMS.

Georeferencing all the indicators with QGIS created a number of shape files, which are vector drawings using geometric shapes [73]. The shape files were then converted into raster maps [73], which are digital drawings that can store different kinds of data.

Punctual, linear, and spatial raster were produced, depending on the footprint and the spatial distribution of each indicator (Figure 5). This step resulted in 28 raster maps, one for each indicator.

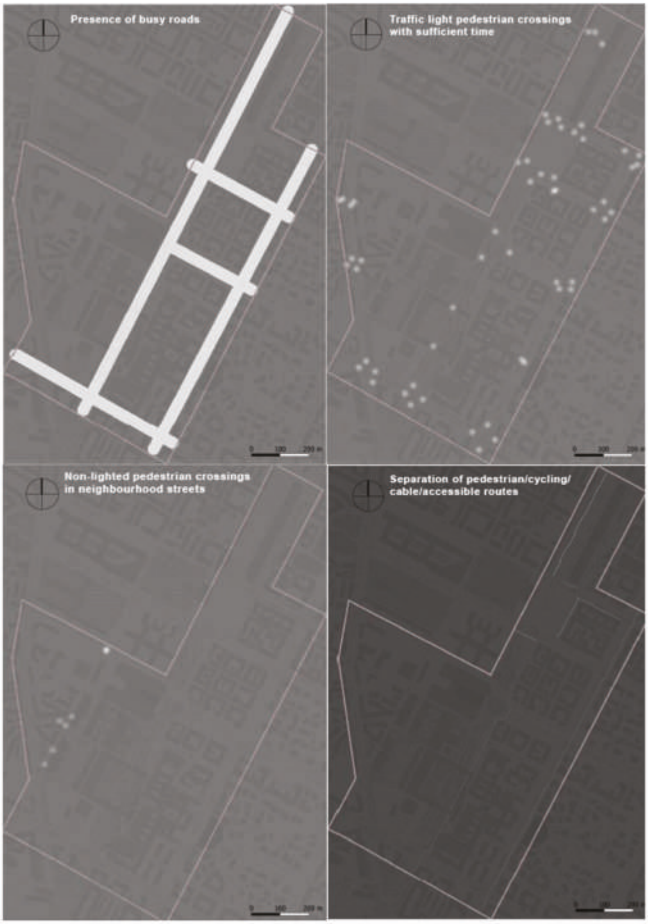

Figure 5. Examples of raster maps (Security index).

Figure 5 shows examples of raster maps for the Security index indicators: "presence of busy roads" and "separation of pedestrian/cycling/cable/accessible routes" maps use a linear raster created using the QGIS "Rasterize from vector to raster" tool. The "traffic light pedestrian crossings with sufficient time" and the "non-lighted pedestrian crossings in neighborhood streets" maps use punctual raster, which have been spatialized using the QGIS Kernel Density Estimation (KDE) tool [39]. This tool reports the diffusion of a phenomenon in a circular point with a radius defined appropriately according to the phenomenon represented [39] (e.g., for the indicator "traffic light pedestrian crossings with sufficient time" a radius of 20 m was used, considering it appropriate according to the phenomenon analyzed).

Moreover, the "adequate lighting during night/evening hours" indicator was an exception and it is represented by a spatial raster, due to the fact that it was important to highlight the streetlamp's different levels of light ray refraction (RN) using a spatial buffer to better highlight the differentiation of some areas compared to others (Figure 6).

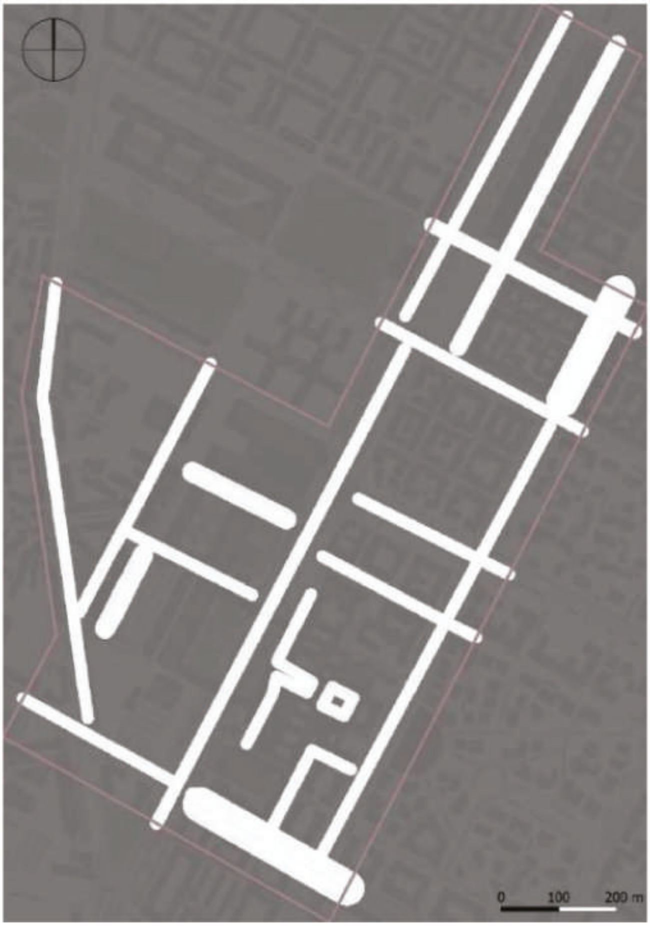

Figure 6. Raster map of the "adequate lighting during night/evening hours" indicator (Comfort index).

As Figure 6 shows, for this indicator we first made a buffer with the QGIS "Variable Distance Buffer" tool using a width based on the different levels of light ray reflection. Then, we generated the raster with the QGIS "Rasterize" tool.

Each raster map was assigned the weight established for the associated indicator in the previous phase (Table 5). All indicators referring to a specific index were then summed to produce four cost raster maps, which represent the cost in terms of walkability of traveling through a certain route [39].

Figure 7 shows the cost raster map for the Security index. The red areas are those in which it is less safe or pleasant to walk.

Figure 7. Example of a cost raster map (Security index).

Figure 8. Walkability index.

After producing a cost raster map for each index, the overall weights of the indexes were considered (Table 5) and inserted in the analysis. Each cost raster map was assigned the weight of each index, and the maps were then summed to produce the final cost raster map, also called walkability index [39]. Unlike the previous maps, the walkability index represents only the pedestrian areas (Figure 8).

In Figure 8, the red areas are the most problematic in terms of walkability, considering all four indexes together, while the green areas are the most walkable one.

5. Discussion

Through the application of this multi-methodological assessment framework, we are better situated to provide some initial reflections about the indexes and indicators used as well as about the raster maps, highlighting how some elements could affect the improvement of the quality of walkability while also having a positive impact in relation to urban resilience. This is the case, for example, of maximizing the "covered routes" indicator (Table 5), since implementing shading is essential both to create more comfortable spaces for walking and to contribute to the reduction of heat islands in terms of resilience [11,74].

In details, Figure 8 allows to draw an overall picture of the critical issues related to walkability, which can be mostly analyzed in detail through the cost raster maps of each index (Figure 7).

Accordingly, the cost raster map of the Security index (Figure 7) clearly shows some critical values of some indicators applied to the study area (Figure 1). Figure 7 highlights the indicator "Presence of busy roads" that disturb the usability of users who reach the PoliTO campus (red lines), together with the "Non-lighted pedestrian crossing in neighborhood streets" (red point). The red dot therefore highlights a pedestrian crossing without traffic lights in the area under investigation. Although the intersection is not located on a road classified as busy, it still constitutes a danger, because it is also an important junction point for pedestrian flows that reach the PoliTO campus from the north of Turin.

In agreement, the aforementioned critical pedestrian crossing appears particularly evident also in the Walkability Index map (Figure 8), bringing the attention to an area that is generally considered quite good in terms of walkability (yellow areas).

The analysis of the cost raster maps of each index jointly with the overall Walkability index map allows to study future design solutions in order to mitigate the current negative impacts, enhancing pedestrian security and the usability of walking space.

The study and the observation of the raster maps has brought to light critical morphological aspects that can be corrected in order to design a more resilient environment, which can contemplate solutions attentive to individual specificities by enhancing the use of the roads as a public space [75].

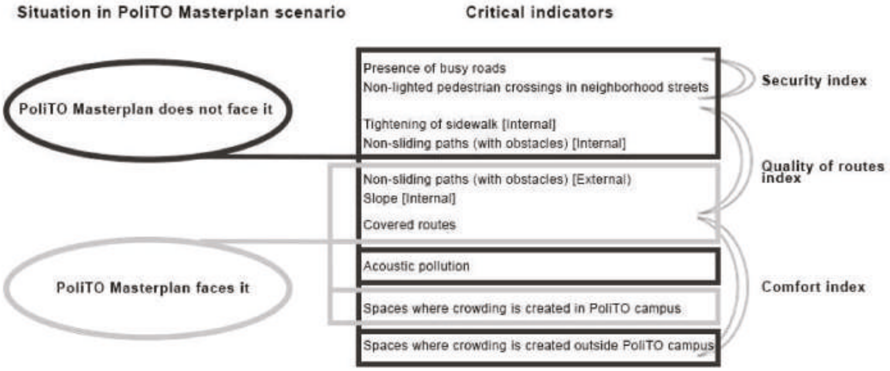

Figure 9. Most critical indicators and current situation in the PoliTO Masterplan.

Moreover, the value of the maps does not only concern morphological aspects, but also allows to highlight sociological elements. This is the case of the indicator "Spaces where crowding is created outside PoliTO campus" resulted critical (Figure 9) in the analysis, underlying the users' discomfort in walking to the PoliTO campus. With the same reflection, the indicator "Adequate lighting during night/evening hours" is not a critical element (Table 5), pointing out a minimum social discomfort in walking during night/evening hours.

Starting from those reflections, we analyzed in depth the ongoing PoliTO Masterplan process. We look at the PoliTO Masterplan documents in light of the calculated walkability index (Figure 8) and discussed them with the team in order to fully understand whether or not the most critical indicators shown in Table 4 were directly or indirectly taken into account in the Masterplan project proposals. (Figure 9).

As can be seen from Figure 9, the PoliTO Masterplan projects address 4 out of 10 critical indicators, namely: "non-sliding paths," "slopes," "covered routes," and "spaces where crowding is created in PoliTO campus." This is a strong improvement in terms of walkability and resilience of the PoliTO campus, although it is not enough for the campus to be considered totally walkable. However, it is important to underline that the PoliTO Masterplan projects are still ongoing and the PoliTO team could use/apply the results of our analysis to further improve the PoliTO campus situation. Moreover, some of the aforementioned critical indicators are not currently a responsibility of the PoliTO Masterplan being concentrated in areas outside the campus and therefore managed by different subjects. This is the case of the indicators "presence of busy road," "non-lighted pedestrian crossing," and "spaces where crowded is created outside PoliTO campus."

6. Conclusions and Future Developments

This paper analyzed one case study dealing with resilient urban planning aiming to understand the possible contribution of walkability assessment. In this section, we summarize our answers to the research question we formulated in the introduction: Is it possible to design a multi-methodological assessment framework able to jointly assess the objective and subjective dimensions of walkability?

The case study deals with a university campus in Italy (PoliTO), allowing to investigate various aspects of sustainability, resilience, and walkability. Concerning our research questions, we could report that:

1. The Masterplan addresses the issue of walkability indirectly, namely it is not explicitly mentioned in the documents;
2. Among the 10 critical indicators identified by our framework, the Masterplan projects address 4 of them ("non-sliding paths," "slopes," "covered routes," and "spaces where crowding is created in PoliTO campus"), showing particular attention to the morphology of the pedestrian streets, an attitude quite consistent with the training of the experts who drafted the Masterplan;
3. The PoliTO Masterplan Team is determining whether the Masterplan's scope can be broadened to reflect the findings that emerged from applying the multi-methodological assessment framework presented here. The idea is to be able to include roads and sidewalks around the PoliTO campus since they have a significant impact on its accessibility and walkability.

Thanks to the analysis of the above case study and the strong literature review, we have tested that the multi-methodological assessment framework is functional in terms of scientific robustness and flexibility, given its combined use of hard (quantitative) and soft (qualitative) assessment methodologies [76]. This combination provided the study with the solid underpinnings needed to take an integrated approach to elements belonging to different decisional domains and to apply the model at different scales. It is worth underlining that, as it is organized in successive interactive/iterative phases, the proposed framework is flexible: each phase can be seen as the basis for subsequent or previous phases, so that the process can be re-thought as new or more accurate information becomes available.

In terms of completeness, the multi-methodological assessment framework contributes to overcoming the idea that objective and subjective aspects are "not part of the same planning project" [77]. Thanks to the combination of hard and soft methods, the framework can consider objective (physical) and subjective (perceptual) aspects simultaneously and represent them visually using GIS. It can thus provide easily readable results that can be applied in establishing guidelines [78] for future plans and projects.

With regard to the type of contribution that walkability assessment can provide to resilient urban planning, it has been pointed out that public space planning and walkability are intertwined in a relationship of non-negligible causality: each one involves and enhances the other, adding psychological well-being, aesthetic pleasure, promoting social exchanges or simply spending free time outdoors. Correct walkability planning is an essential part of planning sustainable cities, as it controls the way people move and determines the way they will move in the future [21,79]. In this perspective, walkability assessment can be part of a planning process, useful in understanding all its phases: from the current status to the planning proposals, up to the design of possible future scenarios [80].

It should be emphasized that the multi-methodological assessment framework presented here leaves room for future developments. In future work, we plan to verify how the indicators would change and what dynamics would be involved when a wider territorial scale is considered. Moreover, it would be interesting to carry out surveys on the "intermodality" index in greater depth by including analyses about users' movements and preferences stemming from the cost of the trip, not only in terms of money and time. Results could thus be organized in relation to users' preferences, according to more specific indicators that better frame the situation of the Intermodality index.

Lastly, the proposed multi-methodological assessment framework will be tested to determine whether it can be applied not only to assess an area's current walkability status, but also to compare different project scenarios.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/19/8131/s1, The Attached 1: Walkability Evaluation of the Main PoliTO Campus. Survey—Walkability evaluation in PoliTO campus consisted of 36 closed questions and was delivered to a sample of 100 users. Respondents were asked to rate their agreement with each question on a 5-point Likert scale [68,69] ranging from 1 (strongly disagree) to 5 (strongly agree). This survey was used during the Analysis phase (Section 4.2).

Author Contributions: Conceptualization and methodology F.A. and I.M.L; software—methodology L.L.R.; software—maps, L.L.R. and M.G.; writing—original draft, M.G.; writing—review and editing, F.A. and I.M.L. All authors have read and agreed to the published version of the manuscript.

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Evaluating and Planning Green Infrastructure: A Strategic Perspective for Sustainability and Resilience

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Abstract: In the light of the current changing global scenarios, green infrastructure is obtaining increasing relevance in planning policies, especially due to its ecological, environmental and social components which contribute to pursuing sustainable and resilient planning and designing of cities and territories. The issue of green infrastructure is framed within the conceptual contexts of sustainability and resilience, which are described through the analysis of their common aspects and differences with a particular focus on planning elements. In particular, the paper uses two distinct case studies of green infrastructure as representative: the green infrastructure of the Region Languedoc-Roussillon in France and the one of the Province of Turin in Italy. The analysis of two case studies focuses on the evaluation process carried on about the social-ecological system and describes the methodologies and the social-ecological indicators used to define the green infrastructure network. We related these indicators to their possible contribution to the measurement of sustainability and resilience. The analysis of this relationship led us to outline some conclusive considerations on the complex role of the design of green infrastructure with reference to sustainability and resilience.

Keywords: green infrastructure; resilience; sustainability; social-ecological indicators

1. Introduction

In the context of the current changing global scenarios and overwhelming urbanization, the concepts of sustainability and resilience can help us to understand and adequately shape all the global transformations (environmental, social, energetic, climatic). These two concepts can be both read as major potential shifts in the understanding of the global territorial system and as key drivers of a more desirable future. Starting from the assumption that the two concepts have to be distinguished, we reflect on their implications in planning, design, and evaluation, with a particular focus on social, ecological and environmental issues. Since the literature on sustainability and resilience is quite extensive, we decided to select the most suitable references which attempt to conceptualize similarities and differences between sustainability and resilience. Such a focus on sustainability and resilience is necessary because there is often a common belief that "the resilience approach is a subset of sustainability science" [1] (p. 5) or is just a renewed system approach for sustainability science [2].

In particular, the focus of our research is twofold: on the one hand, we want to highlight the main similarities and differences in sustainability and resilience discourses, and on the other hand, we attempt to fill the gap between evaluation methods, measurements, and planning tools. In order to achieve these objectives, the paper analyzes some specific methodologies in the French and Italian planning frameworks which use indicators and/or multicriteria analysis as tools for designing green infrastructure (GI). We have chosen the GI strategy because it is a nature-based solution capable of enhancing the social-ecological quality of a specific territory, both in a sustainable and resilient way [3].

The methodologies and approaches will be compared in order to identify which elements of each case study fit better in the framework of the two concepts of sustainability and resilience.

The concepts of sustainability and resilience have been discussed and used in different disciplines, such as ecology, engineering, and sociology, and have been subject to multiple interpretations which cannot be interchangeable, but they can be both used to understand system dynamics and to promote strategic capabilities [4,5]. In literature, these multiple interpretations have resulted in a general fuzziness, unclearness, and malleability on the meaning of the two concepts. For instance, the malleable meaning of resilience has led to the interpretation of resilience as a "boundary object" [6] which allows a common background for different disciplines and stakeholders. This common background can enable the production of visions or consensus in decision-making and in implementation processes [7] and the creation of a common and shared communication across disciplinary borders.

In a nutshell, for our purposes, on the one hand, we can identify how the concept of sustainability is mainly referred to as a perspective issue which cities and societies attempt to reach in the face of a relevant societal transaction. In this sense, sustainability is an objective and a principle of spatial and temporal equity and "an overarching goal that includes assumptions or preferences about which system states are desirable" [2] (p. 128). On the other hand, differently from sustainability, resilience describes the system, its functionality and its behavior after a shock [8].

2. Materials and Methods

As mentioned in the previous section, the paper has a double objective: on the one hand, the analysis of sustainability and resilience, and on the other hand, the compared evaluation of GI's indicators.

Given this as a general statement, the first step of the investigation process is a literature review on sustainability and resilience. Literature was identified by focused searches in major scientific databases (such as Scopus and Google Scholar). This analysis has its main focus in the identification of the key characteristics which compose a social-ecological system, where "social and ecological systems are deeply interconnected and co-evolving across spatial and temporal scales" [9] (p. 14). Social-ecological systems are particularly relevant nowadays in the understanding of resilience [10] and have inspired advances in sustainability science and practice [11]. In the social-ecological systems approach, where the "delineation between social and natural systems is artificial and arbitrary" [12] (p. 4), it is emphasized that "people, communities, economies, societies, cultures are embedded parts of the biosphere and shape it, from local to global scales" [13] (p. 1).

In the social-ecological context, an important strategy is the one of GI which, if provided with high multifunctionality and connectivity quality, can help to reach the objective of sustainable and resilient regions [14]. The multifunctionality of GI is intended as a necessity to "combine ecological, social and economic/abiotic, biotic and cultural functions of green spaces" [15] (p. 517) while the connectivity is represented by "the physical and functional connections between green spaces at different scales and from different perspectives" [15] (p. 517). GI is developed using different methods: for example, land-use analysis, visual interpretation, permeability studies, and multicriteria analysis. Despite the importance of considering stakeholder preferences [15] and different functionalities, there are still few studies that apply a spatial multicriteria evaluation to GI [3,16]. The majority of these methods use available territorial and environmental data (for example, Corine Land Cover data or regional database) in order to develop suitable indicators.

In the vast range of GI experimentations, we have selected two case studies: the first one is the GI developed by the French former Region of Languedoc-Roussillon (since 2015, it is part of the Occitanie Region) and the second one is the GI developed by the Italian former Province of Turin (since 2014, it has been converted into a Metropolitan City) with the contribution of the research group of Politecnico di Torino. We chose these two case studies because they are representative of two distinct European planning systems which share a long tradition in planning but have a different approach toward GI. Indeed, the two case studies represent two evaluation models based on a range of diverse social-ecological indicators. On the one hand, the Region of Languedoc-Roussillon developed its GI using a multicriteria analysis which applies indicators based on available data (homogeneous and spatially linked on the regional scale). Since the diverse resolution of available data, the regional territory has been divided into hexagonal patterns which correspond to the best compromise. The database input OCSOL (soil occupation) of the regional agency SIG-LR is available online for free and it is specifically related to the regional territory of Languedoc-Roussillon.

On the other hand, the former Province of Turin proposed a specific methodology for the identification of the ecological character of the territory and defined a set of criteria for the evaluation of different land use typologies. In this case study the data used were the ones of Corine Land Cover. Both of the two case studies have spatialized the indicators through GIS; this spatialization is useful to interpret and analyze the two methodologies in a cross-comparative perspective.

In order to fill the gap between planning and measurement in the framework of sustainability and resilience, the comparative analysis of the two methodologies is useful for the construction of a strategic GI framework through the selection of the advantages of each case study.

3. Sustainability and Resilience in Planning Debates

Many scholars have long argued on the differences which can inhabit the two concepts [4,5,17–19] but there is also a branch of research which highlights the possible links between the two concepts (Table 1), while considering resilience as a possible way to conceptualize sustainability by describing its typical features [20]. In other cases, resilience is described with reference to its implications on sustainability [21], for the fact that, if cities are understood as dynamic and self-organizing, the concept of sustainability has a different connotation than the original one; in this case "sustainability is challenged to build the resilience capacity of cities" [21] (p. 1203).

Table 1. Features of sustainability science approach and resilience approach.

	Sustainability Science Approach	Resilience Approach
Peculiarities	Overarching goal for social justice, environmental protection and economic efficiency Radical reorganization of the social-ecological system	Capacity to change, adapt and transform over time with or without disturbances Overcome social-ecological limits
Common elements	Integrate environmental and planning management Need of a reflective capacity Need of flexibility of the process Inclusion of stakeholders Robustness Biological diversity	

On the one hand, the wide literature shows how there are many definitions of resilience related to risks, climate, socio-economic, environmental and landscape changes which are taking place in the current global scenario, determining actions and transformations in the territorial system, conceived as "complex, non-linear and self-organized, permitting by uncertainty and discontinuities" [12] (p. 12). Within this framework, resilience refers to the capacity of the territorial systems and of their components to change, adapt and transform over time with or without external disturbance [22]. In particular, for our aims, we assume that one of the most prominent resilience theories has its focus on social-ecological system dynamics and interactions [10], which originates from ecological studies [23]. In this theoretical perspective, the human component must be seen as a part of nature, not separated from it. The main aspect of resilience is the ability to adapt or transform in unexpected cases of environmental and climate changes, and to transform the systems in the attempt of overcoming social-ecological limits [24]. This approach to resilience is connected to a "strong sustainability" understanding [25].

On the other hand, sustainability has become a mainstream topic since its first recognized definition of the Brundtland report "Our Common Future" [26], which focused on three pillars of sustainable development: economic, social, and environmental. This model is usually interpreted with reference to the simultaneous consideration of three main issues: economic efficiency, environmental protection, and social justice [27–30]. This model also stresses the need for integration of environmental and territorial policies for improved quality of life by relating humans to the environment. Recently, in 2015 this concept was resumed by the United Nations in setting the Sustainable Development Goals (SDGs); such a decision shows how sustainability aims at reaching certain goals which are specified in advance and can be achieved through the transformation of a system [31]. In such a perspective, sustainability can be a transformation, intended as a "radical reorganization of the social-ecological system" [17], measurable through policies and projects, while the adaptive character of a system is not always evident. In addition, it is argued that "the difference between adaptation and transformation can also be seen through time and space cross-scale interactions" [17] (p. 6). So, in some specific cases, adaptation can also include transformation, but they are not always directly linked at each scale.

With the aim of framing these concepts within the planning debate, it is essential to integrate environmental planning and management, and integration between environmental policy and spatial planning [30] and to identify the importance of a multi-level governance in order to recognize "the ubiquity of changes, the inherent uncertainties, and the potential of novelty and surprise" [32] (p. 304). In planning and design for sustainability and resilience [33], there is an evident need for a reflective capacity, linked to the recognition and management of territorial resources in order to adapt and maintain ecological and cultural diversity, maximizing environmental benefits; the flexibility of the process, that allows adaptation of decisions to the territorial needs and implementation of strategies over time [34]; the creativity that gives space to individual initiatives and to the integration with institutional practices; the inclusion of stakeholders, local actors and self-organized protagonists in the decision-making process empowering local self-reliance; the integration of different action scales and multiple policies, focus on river, rural areas, city, nature and agriculture; the robustness, the ability to converge the society toward a common evolutionary perspective, widely shared, through the guarantee of quality and effectiveness of results.

Considering the concepts of sustainability and resilience, it is possible to interpret them with reference to some of the abovementioned characteristics, which can fit both. In particular, the two concepts gather robustness [35] as an important factor for addressing social-ecological problems at different scales and levels of organization. In sustainability, robustness is related to the need to measure the persistence of a territorial system and the performance in the transformation of complex social-ecological structures. In fact, robustness is the capacity of a system to preserve its stocks and identity after a shock [35] through its reorganization and innovation abilities [36].

On the one side, robustness is a key concept while considering the preservation of a specific component of a social-ecological system (i.e., the system capital stocks including natural, human, and human-made) in the face of innovation, stress or transformation processes. On the other side, sustainability is a framework to legitimate the performance of the transformation of a system, recognizing that the functionality of the system is the precondition for economic and social development [37]. The functionality of the system depends on the quality and the persistence of the system capital stocks over time embracing inter and intra-generational equity [38].

Another common aspect is related to the specific role of biological diversity for resilience and sustainability, as a way for enhancing, for example, ecosystem quality. In biological systems, diversity must respond to the necessities of different species, which have diverse reactions towards disturbances and shocks. In this context, biological diversity (biodiversity) is furthermore essential for the self-organizing ability of complex adaptive systems [39] in terms of absorbing the disturbance and regenerating itself, but the social, the economic and the physical diversity are also effective strategies for the support of resilience. The adaptive cycle [40] is often considered to be a central metaphor in the conceptualization of the dynamics of change in social-ecological resilience. Adaptability is indeed a key aspect of resilience of social-ecological systems as it considers the interrelation between concepts of "diversity (biodiversity), redundancy (ecological variability), cycles of adaptation (multiple equilibrium states), and interaction between spatial scales (hierarchy) and temporal (activation of different times responses)" [41] (p. 780).

In social-ecological systems approach and in planning discourses, in order to enhance both sustainability and resilience, the role played by GI is highly relevant. Addressing this statement, we assume that GI can reinforce the characteristics of robustness and biological diversity of the territorial system besides fostering sustainability and resilience by increasing flexibility, redundancy, modularization and decentralization [40,42]. With reference to GI, evidence on these resilience characteristics has been mainly applied to stormwater management [21,43]; for example, a modular approach, characterized by a functional redundancy and decentralized elements, in planning and design helps to be prepared and to preplan in the event of a system's failure [21]. GI can also contribute to perform connectivity besides functionality; connectivity is indeed a trigger of sustainable and resilient urban forms [44,45] by providing cities, from macro to micro-scale elements, with an enhanced biodiversity, improved hydrological processes and a healthier life.

4. Green (and Blue) Infrastructure in Sustainability and Resilience Discourses

GI, originally inspired by the principles of landscape ecology [46,47], has been widely recognized and promoted as the "ecological framework needed for environmental, social and economic sustainability" [48] (p. 5), thus connecting and supplying ecological, economic and social benefits which are at the basis of sustainable development; this definition of GI can indeed be considered as the first one that explicitly links GI to sustainable development. By reviewing international literature on GI, we can identify different definitions but, generally, there is a consistent presence of both natural and human-made components as essential elements. GI has firstly developed in response to different needs and, in recent years, has also influenced and entered into planning theories and policies [49] and design practices; for example, its strategic role is underlined by the European Commission, which recognized GI as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" [50]. In this context, GI can be considered as a producer of multiple benefits [15,42,51] for health and life quality. Furthermore, the concept of GI "differs from conventional approaches to open space planning because it looks at conservation values and actions in concert with land development, growth management and built infrastructure planning." [48] (p. 5) thus including also a sustainable development perspective in addition to a preservative one. There is also increasing evidence in literature, even though not always unambiguous, that GI contributes to climate change mitigation and adaptation by supplying several benefits and services to urban environments [52,53]. With this in mind, the multifunctionality of GI can mitigate the urban heat island effect, flood risk management and ecosystem resilience [53].

The growing popularity of GI is also detectable in pioneering climate change adaptation policies of some cities, such as London, New York, Copenhagen and Paris [54,55]; these policies have indeed introduced green infrastructures in their planning and design tools for climate change adaptation and biodiversity preservation.

Since our focus is on social-ecological systems, sustainability, and resilience, we can notice (Table 2) how literature applies GI mainly to stormwater management and design even though they can contribute to provide other several benefits, such as improved air quality, urban heat island mitigation, improved communities and reduced social vulnerability, greater access to green space and increased landscape connectivity [3].

Table 2. Sustainable and resilient solutions of GI.

		Resilience	**Sustainability**	**References**
Governing climate change	Managing and regulating stormwater hazards	x		[21,42,52,55]
	Improving soil, air and water quality	x		[52]
	Regulating urban heat island effect	x	x	[53,56]
	Limiting land take and soil sealing		x	[57,58]
Enhancing landscape quality	Supporting landscape connectivity and fruition (slow mobility)		x	[3,59]
	Supporting ecological functionality and accessibility to green space	x	x	[3]
	Recovery of degraded and vacant land		x	[59–61]
Promoting well-being	Reducing social and ecological vulnerability	x	x	[3]
	Developing healthy communities	x	x	[52,56]

The literature review (Table 2) shows how GI can help trigger some sustainable and resilient solutions. In particular, GI can:

(1) be a flexible and adaptable answer to climate change through actions of stormwater management [21,42,52,55], improvement of soil, water and air quality [52], regulation of the urban heat island effect [53,56], and limiting of land take [57,58];

(2) enhance landscape quality by favoring landscape connectivity and fruition [3,59], supporting ecological functionality and accessibility to green space [3], and recovering degraded and vacant land [59–61];

(3) promote well-being in favor of a reduced social and ecological vulnerability [3] and the development of healthy communities [52,56].

In our view, GI is a strategy which combines both natural and social elements and can be conceived as a landscape network [62,63] that can enhance ecological quality through an integrated and socially inclusive approach to territories as requested by the European Landscape Convention. At the same time, it can help to overcome habitat fragmentation and promote healthy communities and, in order to be equally recognized and accessible, it must have extensive public support in policy decision-making and realization.

The project of GI needs to be based on a social-ecological evaluation of the territorial system based on index and indicators essential for the identification of quality aspects of ecosystem diversity and for the interpretation of possible pressures of human activities.

The index and indicators are used to interpret the social-ecological system with respect to the capacity of the system to preserve the ecological functionality but also to consider the impacts of human activities and the possible adaptation strategies capable of enhancing resilience and sustainability. In fact, they can measure the robustness and the persistence of a system, relating it to the capacity of maintaining their functions acting in buffer areas around the naturality core areas and in the case of withstanding shocks. They can act as interpreters of the interplay disturbance between nature and human activities, favoring a reorganization or a development of the system. By using these indicators in promoting GI, it is possible to develop an integrated social-ecological system capable of acting in a cross-scale dynamic interaction.

The spatialization of the integrated measurement of potential ecological functionality is used to evaluate the vulnerability of a territory and the loss of biodiversity, to define possible design scenarios able to contrast potential irreversible transformations and unexpected shocks. It can also be used to envision possible future directions.

5. Two Case Studies in Comparison

Towards this perspective, as mentioned in paragraph 2, we analyzed the methodologies used for the identification of two case studies of GI in France, the Region of Languedoc-Roussillon, and Italy, the Province of Turin. The two case studies, and their referring planning system, differ in some elements but the interpretation of their methodologies for GI help to demonstrate the link between the measurement of ecological functionality in terms of sustainability and resilience and the GI design.

On the one hand, the French case study is representative of a multiscale design from the national scale to the local one and it is based on a participatory multicriteria analysis of the ecological value of the territory and of the human impacts on naturality. The methodology of the Region of Languedoc-Roussillon provides a wide range of indicators for the evaluation of both ecological and social aspects of the territory. This analysis can be used to define design scenarios of the GI at a vast scale and can be redefined at the local scale, contributing to adaptation and sustainable use of territories.

On the other hand, Italy is characterized by a jeopardized approach in the different regional landscape plans and has no national disposition towards GI. Despite this national situation, some Regions and Provinces have attempted to define their own methodology for developing ecological networks, such as the Province of Turin. In this particular case the active participation of stakeholders was fundamental for the definition of connectivity scenarios. Despite the active participatory process, no social indicators were included in the process, thus leading us to state that this methodology is less comprehensive and overarching.

5.1. French 'Trames Vertes et Bleues'

France in its planning system has always given great relevance to environmental and ecological elements; since 2009 this relevance has even been more strongly emphasized with the promulgation of two specific laws: the Grenelle laws I and II (the second is an extension of the first one and has been promulgated the year after, in 2010). These laws, implementing and modifying both the Code of Urbanism and the Code of Environment in line with the principles of sustainable development, can be considered as a turning point in the French planning system as they introduce new issues connected to ecological preservation.

Grenelle laws introduce a new planning tool, the *Trame Verte et Bleue* (TVB). It resumes the principles of landscape ecology [46,47] and shapes its characteristics in order to properly fit it into planning tools. TVB are indeed applied to different scales of planning, from the national to the local one (Figure 1). The French National State in 2014 defined and approved the "*Orientations nationales pour la préservation et la remise en bon état des continuités écologiques*" (National orientations for the preservation and maintenance of ecological continuities) which must be taken into account at lower scales: the regional and the local one. Regions are indeed in charge of developing a *Schéma régional de cohérence écologique* (SRCE), a new planning tool introduced by the Grenelle laws which must define the stakes of TVB at a regional scale.

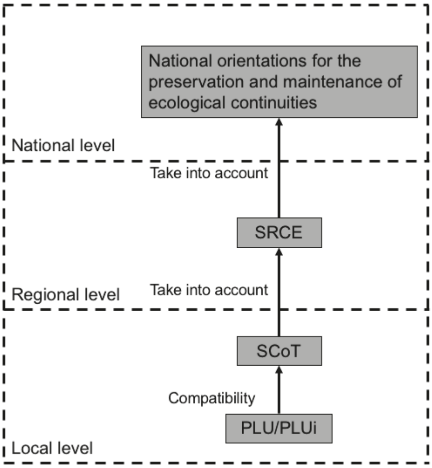

Figure 1. The structure of TVB at different levels.

The SRCE can appear to be juridically fragile as it has no prescriptive value (such as in the sense of granting building permits); in this sense it is neither a brake or an obstacle to land use planning but rather a functional framework for the ecological coherence of a territory and its planning tools. In this context, it gives some recommendations for raising awareness on ecological issues, for managing and protecting ecological continuities and for allowing a sustainable development and management of territories. The only legal and regulatory obligation is the necessity to be taken into account (*prise en compte*) by subordinate urban plans (principally *Schéma de Cohérence Territoriale* - SCoT). The most operational scale for a more precise specification of TVB elements is the local one, SCoT and *Plan Local d'Urbanisme* (PLU) or *Plan Local d'Urbanisme Intercommunal* (PLUi). In this context, indeed, these territories (they are often an ensemble, big or small, of municipalities) became strategic in the operational implementation of TVB for their competences in urbanism and territorial planning and projects.

TVB are composed of two main elements: biodiversity reserves and ecological corridors. In order to define and map these two elements, the National orientations document provided a methodological guide which identifies the areas that are automatically integrated in the network as biodiversity reserves or ecological corridors (for example: the core of national parks, national and regional natural reserves and spaces assigned to the conservation of specific biotopes, etc.). In order to define "extra" biodiversity reserves and ecological corridors, in addition to the ones identified by the national orientations, some Regions have identified specific methodologies, such as multicriteria analysis. The multicriteria analyses developed by some Regions (such as Aquitaine, Auvergne, Languedoc-Roussillon, etc.) have interpreted some elements of landscape ecology in the form of indicators and indices. These analyses are indeed based upon specific ecological notes, values and criteria which are applied to the single land pattern or to a network; this modeling allows us to reach a global value of functional or ecological quality of a specific territory.

Some Regions (such as Languedoc-Roussillon) have combined different indicators, not only the ones strictly connected to ecological importance but also sociological ones, linked to the presence (or absence) of human activities and their related impacts.

The Region of Languedoc-Roussillon, an Example of Ecological Functionality

The Region of Languedoc-Roussillon, situated in the south of France, has a high percentage, almost half of its total surface (48%), characterized as natural protected areas [64]. Despite this positive outcome, the Region is facing the process of land take and artificialization at a rate of almost 830 ha per year [64]; the most affected lands are the agricultural ones, with a loss of 51% of lands with high agronomic value between 1997 and 2009 [64].

The SRCE identifies 23 *grands ensembles paysagers* on the basis of their characteristics which in turn have been further detailed in 175 landscape units, thus dividing the territory into different geographical categories (such as littoral, plain areas, mountain areas, etc.).

In order to define a regional TVB, the methodological choice made by the SRCE of Languedoc-Roussillon was to qualify the ecological value of the territory by a global approach, through the identification and implementation of some indicators.

The Region of Languedoc-Roussillon in its SRCE proposed a spatialized multicriteria analysis based on the identification of a global index of potential ecological functionality of the territory, which is the result of a combination of ecological indicators (index of ecological importance) and social-ecological ones (index of human footprint).

The index of ecological importance (*indice d'importance écologique*) corresponds to the importance that an area is likely to have for biodiversity and ecological continuities preservation. This index is based on a spatialized multicriteria analysis which attempts to qualify the landscape mosaic. It is made up of 5 different indicators (Figure 2): ecological functionality of natural milieu, density of remarkable landscapes, patrimonial responsibility, ecological functionality connected to agricultural practices and ecological functionality of continental water milieu. These indicators show how they embrace different land uses and landscapes typologies, which are strategic for the social-ecological effectiveness of GI.

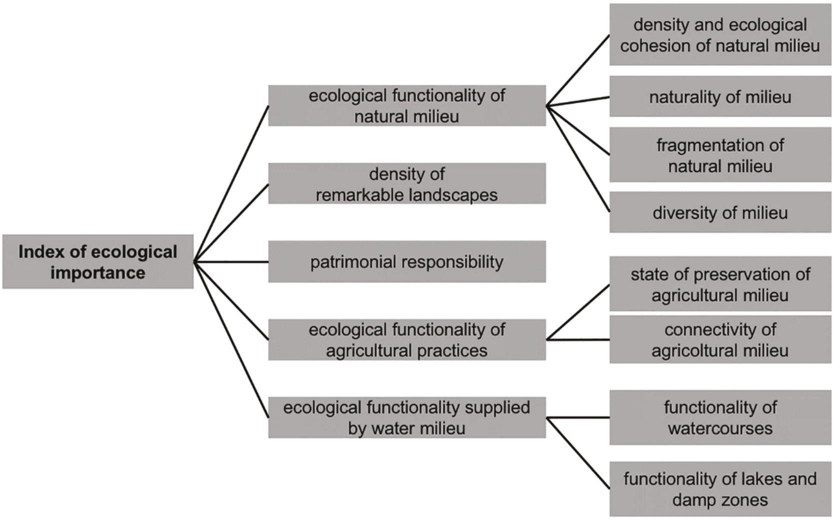

Figure 2. The index of ecological importance and its indicators.

The first indicator, ecological functionality of natural milieu, gives an approximation of the ecological functionality of natural terrestrial milieu; it takes into account the surface of natural habitats and their potential inclusion in a specific protected zone, called ZNIEFF of type 2 (*Zone naturelle d'intérêt écologique, faunistique et floristique*). Due to the presence of different contexts (degree of naturality, differences in habitats, alteration of natural milieu by human activities and fragmentation), the indicator relies on different indicators. In a situation of a network characterized by a different natural milieu that is not so fragmented or altered by human activities, the ecological functionality is considered to be high; as a first input, since the area of natural milieu is the most relevant factor in terms of ecological functionality, it is assigned the highest weighting. In addition, the indicators concerning the diversity of the milieu (with a diverse resolution and based on categorical values) have a lower weighting in order to limit bias induced by different geometries and themes of data. The weight of naturality is furthermore reduced so as not to overestimate its importance; in identifying stakes there finally is a crossover with the global index of the human footprint.

As shown in Figure 2, the first indicator is made up by:

- the density of the natural milieu and its ecological cohesion with ZNIEFF of type 2 (considered to be a milieu of high ecological integrity);
- the naturality of the milieu, translating the level of human interventions or artificialization of a determined milieu. A low weighting is given to this indicator in the calculus of the indicator of the "integrity of natural milieu" in order to avoid an overestimation of the socio-economic factors related to the human footprint (it is strictly connected to factors used in the evaluation of the indicator of human footprint);
- fragmentation of a natural milieu;
- diversity of the milieu measures the spatial subdivision (including elevation) of different milieus which are present in a single pattern.

The second indicator expresses the density of remarkable landscapes within a parcel; different types of zoning have been included (such as cores of UNESCO sites, protection zones previously defined by law). The third indicator, the patrimonial responsibility, reports on the presence of species and/or habitats of regional, national or European interest.

The fourth indicator, the ecological functionality of agricultural practices, is based on data on land use, agricultural practices and according to experts, gives an estimation of the state of preservation and intra-network connectivity of agricultural milieu. The last indicator is connected to ecological functionality supplied by water milieu (rivers, lakes and damp zones).

The index of human footprint (*indice d'empreinte humaine*), aims to translate the intensity of human activities on biodiversity and, likewise the index of ecological importance, is estimated by a combination of different indicators which are weighted on the basis of supposed impacts on biodiversity preservation and ecological continuities. In this context, the index takes into account potential risks on biodiversity and ecological functionality of each single pattern. The indicators which concur with the definition of this index are: an indicator of soil artificialization, an indicator of transport networks, an indicator of demography, density of energetic network, and planning and transport projects (Figure 3).

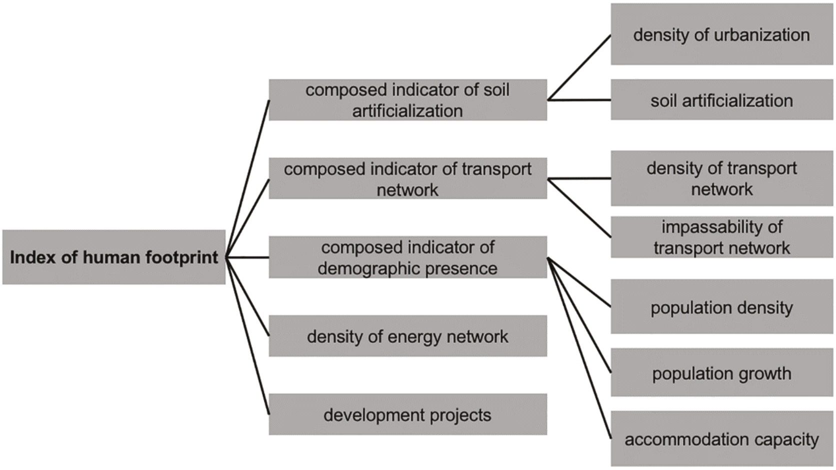

Figure 3. The index of the human footprint and its indicators.

The first indicator is a composed one which quantifies the density of urbanization and soil artificialization. The second indicator quantifies on the one hand on the density of transport network on the basis of the type of road and railway and, on the other hand, impassable obstacles (such as highways and high-speed railways) and fauna passages.

The third indicator quantifies demographic presence at a municipal level; it combines three different indicators:

- population density, based on number of inhabitants in each municipality;
- population growth in each municipality;
- accommodation capacity of each pattern.

The fourth indicator reports the presence of energy production and energy transport zones which affect ecological functionality. The last indicator takes into account the perimeters of planning and transport projects, which may impact on ecological functionality.

The two global indexes of global importance and of human footprint have been distributed in four classes using the quantile method. Their intersection allows for estimating the ecological importance of each pattern of the territory in relation to human footprint. Starting from this intersection, some relevant stakes of biodiversity preservation and ecological continuities for the development of the regional TVB can be identified. The successive intersection between indicators and the ecological structure makes the overall approach more evident, also allowing a spatialization of stakes (Figure 4).

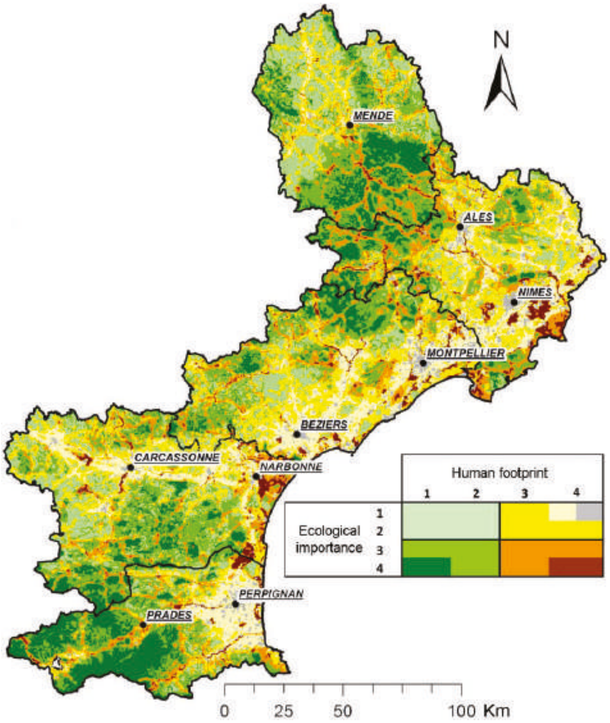

Figure 4. Map of intersection of ecological and social indicators (source: adapted from SRCE Languedoc-Roussillon).

The spatialization of indicators (Figure 4) is a combined map with different gradients. On the one hand, a gradient from pale green (low ecological importance and low human footprint) to dark green (high ecological importance and low human footprint), and on the other hand, a gradient from pale green to yellow and grey (low ecological importance and strong human footprint). A third gradient goes instead from pale green to orange and brown, thus representing a gradual increase of the spatial ecological importance but also the human footprint.

This map allows us to focus the attention on the importance of avoiding two types of transitions: the transformation of green areas into brown ones can signify an increase of vulnerability of spaces relevant for biodiversity, while the transformation from brown to yellow or grey contributes to the loss of ecological importance connected to a high human footprint.

Starting from this first work, it will be possible to identify the ecological continuities useful for the full development of the regional TVB. The intersection of these ecological continuities with protected areas allows us to identify the minimum biodiversity reserves; in the sectors of high human footprint, the map enables the visualization of existing ecological continuities and the identification of areas potentially important for their maintenance and restoration. This approach aims at identifying large areas finalized to support the functioning of biodiversity at the regional scale; these areas represent the matrix which embraces biodiversity reserves, within which it is possible to identify ecological corridors, thus emphasizing the importance of the matrix in its entirety (reserves + corridors).

5.2. The Italian Framework of Landscape and Ecological Networks

In Italy, since the National Strategy of sustainability and biodiversity preservation in 2010 [65], the realization of ecological and landscape networks has become central in the current planning debate. Nevertheless, despite this initial boost, a national organic and shared project of landscape and ecological network in Italy is still lacking. The first attempts of designing landscape and ecological networks in the Italian planning framework come from the regional level, within the context of regional landscape plans.

Italian regional landscape plans have mainly taken on a structural interpretation of landscape following a design approach; this approach assumes as the main object of preservation the ecological value and the ecosystem service value of the entire regional landscape. Within the framework of such an approach, ecological networks help to efficiently interpret this vision. In the latest years, many regions have, indeed, drafted and/or approved their landscape plan: the Regions of Piedmont (2017), Lombardy (2017), Friuli-Venezia-Giulia (2018), Tuscany (2015), Puglia (2015) and partly Sardinia (2006). Within this context, Regions have included their reasonings on landscape and ecological networks, mostly connecting them to the topic of design.

The first approved regional landscape plan which promoted this approach is the one of the Region of Puglia with the identification of an ecological network of biodiversity, in charge of identifying all the naturality elements, and a general director scheme for the multi-purpose ecological network characterized by a design approach and a strategic significance. Also, the regional landscape plan of Tuscany entrusts a leading role to the ecological network by including it as one of the four pillars on which the plan is built.

The regional landscape plan of Piedmont, the Region in which our case study is located, identifies a network of landscape connection, a multi-purpose and multifunctional system which combines ecological elements (nodes, ecological connections, and restoration areas) with historical and cultural ones. The regional landscape plan of Friuli-Venezia-Giulia considers the regional ecological network one of the networks of strategic importance, together with those of cultural heritage and slow mobility.

The Region of Lombardy has approved a regional territorial plan with a landscape value which recognize the ecological network as a priority infrastructure of this plan, and it constitutes an indicative tool for provincial and local plans.

The developed regional ecological networks are intended for delivering a territorial project [66] in its entirety; they can help to reach an economic development and a vision of long-lasting development, which is bound to landscape preservation and valorization through the development of a landscape network that can increase the benefits and services they offer. The ecological networks of these plans identify and protect the environmental value of territories in their entirety, also in urbanized areas, overcoming the confined vision of considering them only relegated to protected areas.

Ecological Networks in the Metropolitan City of Turin

The Metropolitan City of Turin (formerly the Province of Turin), selected as the Italian case study, is representative of a large and multifaceted conurbation, made up of more than 300 municipalities of different landscapes. Since the first Provincial Territorial Coordination Plan (PTCP) of 1999, the former Province of Turin has always carried out extensive territorial planning, with particular regard for the safeguarding of soils and the limitation of land take, by including their protection as a major objective together with the preservation of biodiversity.

With the aim of preserving biodiversity and controlling the increasing process of land take, the new PTCP, approved in 2011, has reinforced the abovementioned objectives. Later, between 2014 and 2016, the ENEA (the Italian national agency for new technologies, energy and economic sustainable development) and Politecnico di Torino [67,68], have defined the guidelines for the green system (LGSV) within which a specific methodology for the definition of the provincial ecological network (LGRE) was identified. The objective of this research is the definition of a proposal for the implementation of the provincial ecological network at the local level.

The proposed methodology promotes a bioecological approach [69,70] which identifies landscape as an interconnected system of habitats by linking areas of the Natura 2000 network (core areas, corridors and buffer zones), essential for the development of ecological functionality, and sustainable use areas and potential restoration areas. In order to define an efficient process of evaluation of both ecological functionality and environmental critical issues, it has been necessary to evaluate the different land use typologies in relation to some ecological-environmental criteria: Naturality, Relevance for preservation, Fragility, Extroversion, Irreversibility (Figure 5). They do not refer to a single land use and landscape typology, as in the French case study, but they do refer to habitats and their functionality as complex and interrelated systems.

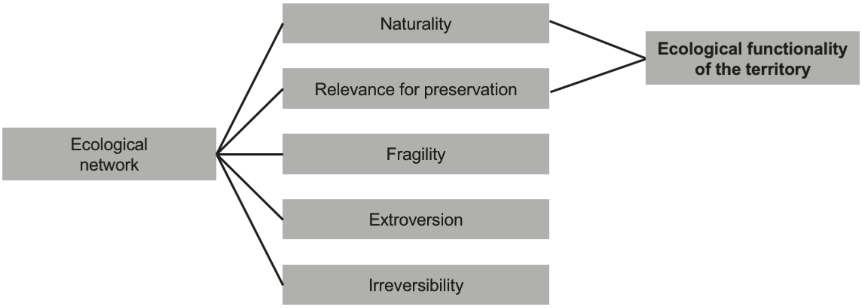

Figure 5. Indicators of the provincial ecological network of Turin.

Each ecological-environmental criterion has been attributed to each of the 97 land use typologies; the ensemble of attributed values to each land use typology characterizes them from the ecological-environmental point of view. These indicators have been further divided into different levels of specificity, varying from 5 levels (naturality and extroversion) to 3 (irreversibility).

The value of naturality, subdivided into 5 levels, is attributed to each land use typology on the basis of its proximity to the one which should be present in the absence of an anthropic disturbance (climax).

The second value, relevance for conservation, defines the level (in a scale of 4) of relevance or suitability of land uses for biodiversity preservation and considers the importance for habitat and species. It includes not only habitats of communitarian interest but also the ones whose preservation is necessary for the protection of plant and animal species of Natura 2000 network.

The classification of land uses with reference to fragility, specified on 4 levels, is carried out evaluating how much the different land use typologies are intrinsically unable of resisting to the ensemble of pressures generated by the anthropic use of the territory (such as pollution and anthropic disturbances). This indicator can be used to measure the vulnerability of a system, with reference to disaster risk, poverty, food security and climate change, within the key concepts of exposure and adaptive capacity [71]. The value of fragility principally refers to the intrinsic characteristics of a territory but, in particular for some land use typologies it is essential to evaluate the fragility which derives from the limited extension of this land use typology (for example a specific vegetal formation which characterizes a land use typology).

The level of extroversion of a land use typology depends on the intensity, probability or possibility with which that land use typology can generate pressures on neighboring areas. The value considers pressures (such as pollution, industrial production, possible diffusion of exotic species) in an integrated perspective. It is subdivided into 5 levels, ranging from the first which includes land use typologies that coincide with areas mostly occupied by human settlements to the fifth which refers to areas containing more natural typologies of land use.

The last criterion is irreversibility, which defines the level (in a scale of 3) of improbability of irreversibility in land use change which could lead to a higher degree of naturality. The first level corresponds to the most irreversible areas, as it includes sealed land use typologies (urban settlements, commercial and industrial areas).

The integrated combination of the first two indicators, naturality and relevance for conservation, has allowed us to define a territorial zoning process based upon its reticular value and its ecological functionality (Figure 6). Based on their ecological functionality, areas have been divided into four different classes: (1) areas with a high ecological functionality, (2) moderate functionality, (3) residual functionality and (4) null functionality. The first class, areas with a high ecological functionality, is optimal for the development of habitats and species; the second class, despite a lower functionality, gathers areas which are very important for reticularity. Areas with a residual functionality can be partially used for the expansion of the network. Areas included in the last class are considered as obstacles for the development of the network.

The application of this methodology to specific territories has allowed us to define a diffused reticularity for the territories involved and it contributed to making it more evident which parts of these territories are more sensitive to sudden changes caused by human activities. In fact, the methodology can be used to identify the natural areas of significant importance for the conservation of biodiversity. In addition, it also allows us to define possible areas for priority expansion of the ecological network.

Starting from their peculiar territorial context, this methodology has been further adopted and adapted to some local experimentations [67]: municipalities of Bruino, Ivrea with Bollengo, and Chieri. These experimentations were developed starting from analysis of the supra-municipal ecological system and with an active participatory process and public consultation to select the most suitable local connectivity paths. Indeed, the approach previously presented was reconsidered in each experimentation in order to guide and provide local bodies with specific measures to limit urbanization and enhance the ecological state of each territory. Each experimentation has therefore defined specific methodological and operative orientations which could be further implemented in urban plans. This implementation is eased through a simplified analysis of land use typologies which allow also to non-experts to create specific local ecological functionality maps.

The experimentation of the bioecological approach has led to the definition of a processual methodology which defines two types of action: the conservation of the structural elements of the network, which could consider implementing interventions of environmental improvement, and the design.

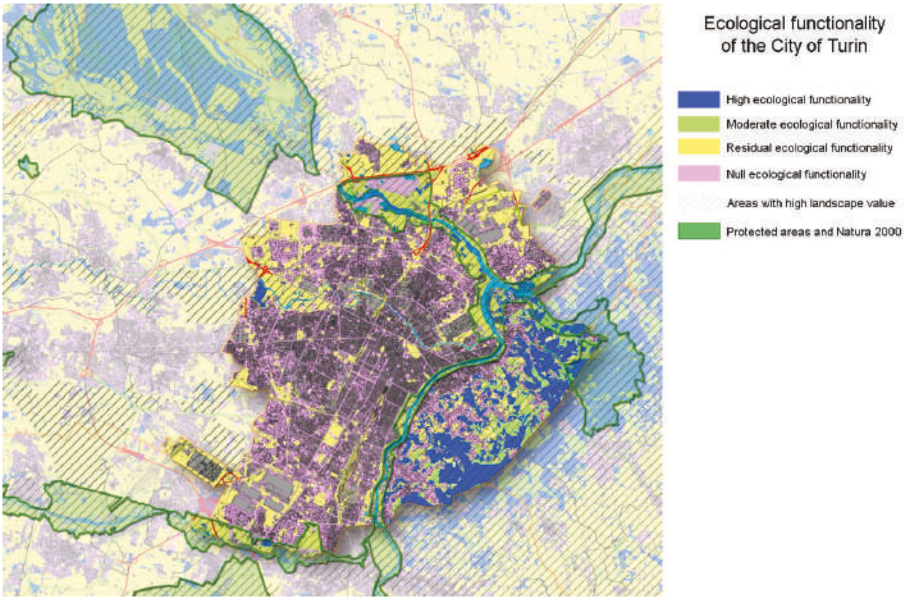

Figure 6. Ecological functionality of the city of Turin (source: adapted from PTC2 Torino).

6. Discussion

Thus far, we have shown how the concept of GI has entered both sustainability and resilience discourses; in particular, we explored some representative case studies of GI with the objective of interpreting the role of evaluation tools for the definition of territorial sustainable and resilient scenarios. This exploration has attempted to clarify and explain how some planning elements of design, implementation and management, such as GI, can help to enhance sustainability and resilience (Table 3) at different scales (from the national to the local one).

The analyzed methods for biodiversity evaluation surely contribute to improving the ecological quality of a system, its resilience, and its adaptivity, but they also necessitate further development of specific indicators for a more precise analysis of vulnerability and of the equilibrium states of the system. We emphasize how these methods measure ecological functionality on the basis of the capacity of each habitat and buffer zones to resist and react to pressures or shocks maintaining their functions within a long period perspective.

In both cases (Table 3), indicators of ecological functionality appear to be highly relevant for reading the quality of the system. All the indicators can be associated with sustainability while not all of them can be considered as suitable indicators for measuring resilience. In order to qualitatively measure resilience, in particular social-ecological resilience, it is indeed necessary to consider more specific aspects which allow for reading the persistence of social-ecological elements of the system and its biological diversity.

Table 3. French and Italian indicators and their relationships with sustainability and resilience.

			Resilience	**Sustainability**
French indicators	**Index of ecological importance**	ecological functionality of natural milieu	x	x
		density of remarkable landscapes	x	x
		patrimonial responsibility		x
		ecological functionality of agricultural practices	x	x
		ecological functionality supplied by water milieu	x	x
	Index of human footprint	composed indicator of soil artificialization	x	x
		composed indicator of transport network		x
		composed indicator of demographic presence	partially	x
		density of energy network		x
		development projects		x
Italian indicators		naturality	x	x
		relevance for preservation	x	x
		fragility	x	x
		extroversion		x
		irreversibility		x

Framing our analysis within the social-ecological perspective of resilience, which is about "people and nature as interdependent systems" [72], we can delineate some main differences between the two approaches led by the French case study and the Italian one. Under the GI definition, the Italian methodology has opted to develop a strictly ecological approach, with few indicators. They do not explicitly refer to a specific milieu, as occurs in the French case study, but they tend to analyze habitat functionality in a more aggregate and integrated way, as a complex system. On the other hand, the French methodology appears to be more complex as it operates in a wider spectrum, combining ecological indicators with social ones and showing itself to be capable of evaluating the impacts of human activities on the environment. Despite the apparent complexity of these indices, the French methodology allows us not only to assess the sustainability of a social-ecological system but also its resilience. Instead, the Italian methodology, since its apparent simplification in indicators and operationalization, seems to mainly address sustainability, as if it is an aggregated component of the habitat quality.

The two cases analyze two uneven territorial systems: on the one hand, the French case study considers a regional scale which must refer to a national framework of biodiversity valorization; on the other hand, the Italian case study refers to a provincial network. Despite the differences of territorial scale, an element common to the two approaches is the necessity of reaching the network project after a debate between the spatialization of the evaluation of biodiversity gradients and territorial stakeholders. In both cases, the selection of the most relevant connectivity paths for the construction of the ecological network is the result of an inclusive process in which stakeholders identify the most relevant landscape for integrity, quality and identity of each social-ecological system. Participation, in the Italian case study, is actively proposed in order to develop a sustainable approach for GI quality; in fact, GI design is the result of shared visions for the future and for the management of the territory (building consensus, promoting participation and trying to integrate self-organization initiatives for environment management and top-down approaches). Another difference lies in the fact that, as is demonstrated by the recently approved regional landscape plans, Italian networks act as multifunctional networks in support of ecological and recreational landscapes. In contrast, in France there is a relationship with the fruition and the social use of these spaces but the projects of TVB aim mainly at improving habitat quality.

7. Conclusions

Each experience has shown how a GI approach can contribute towards implementing the social-ecological quality of a territory and delivering value to sustainability and resilience. In particular, starting from the measurement of social-ecological quality of territories they are significant as they allow us to identify territorial and local stakes and delineate strategic and transversal design actions. It is difficult to decide which experience provides greater assistance towards achieving the objectives of sustainability and resilience; indeed, the choice of a proper method depends on different factors, such as data availability and precision, territorial features, and scale of analysis.

The activity of measuring ecological quality and the resilience of a system is a requirement for the construction and the selection of territories on which to attribute a transformative scenario in an integrated, reticular green system, that is a GI. GI is indeed a system which can guarantee multiple equilibria and the stability of a social-ecological system by increasing and maintaining ecosystem services. GI is also a fundamental tool for orienting towards an adaptive transformation through the selection of those territories which better fit as places of connectivity; this selection is made upon participatory processes, in both case studies, which give priority to the creation of biodiversity scenarios for the construction of a shared and desirable future. In this context, a GI project first has to be evaluative but as a second step it must be designed together with different territorial stakeholders; this approach could strongly contribute to the construction of a new, adaptive and less vulnerable cycle for territories.

With this in mind, it is important to underline how cities are increasingly giving higher importance to the role that society has to play; in particular, they are engaging on people empowerment and on the improvement of decision-making processes through the active participation of citizens in developing GI [73]. In resilience discussion, GI appears to be not just a design of systems or structures, but it is also a co-created and integrated process within complex social-ecological systems. With regard to sustainability, GI surely conveys an idea of the future based on a different ecological quality of a territory to which a dynamic fruition of the landscape has to be associated; the combined outputs can result in a weighted multi-scalar territorial choice highly anchored to the desiderata of territorial actors. Despite literature on the resilience of GI agrees that, if poorly planned, it can lead to decrease social inclusiveness [74], in our view it is fundamental to expand GI in planning mainly for their multifunctionality, for promoting diversity and for managing connectivity. It is furthermore essential to guarantee that the localization of connectivity systems is chosen through the measurement of ecological quality and functionality but also through social awareness of all possible networks, including the ones supporting the fruition of GI.

In conclusion, a sustainability and resilience strategy based on GI appears to be more adaptable not only to new and evolving territorial and societal challenges, but, as it can also be tailored to each local context, it can also provide multidimensional solutions to multidimensional challenges in cities. Additionally, we have noticed how literature on resilience is rapidly growing while there are still few studies on the linkages between urban project, urban form and resilience. In this context, a further step of the research is the shift from the measurement to the proposal of proper design and technological nature-based solutions at different scales, from the vast-scale to the lot one. These design and technological solutions can help to overcome different territorial vulnerabilities and shocks in the face of adaptation to climate change and quality of life.

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Erratum

Erratum: Urso, G., et al. Resilience and Sectoral Composition Change of Italian Inner Areas in Response to the Great Recession. *Sustainability* 2019, *11*, 2679

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The authors would like to make the following corrections to the published paper [1]. The changes are as follows:

(1) Replacing the descriptions:

Figure 2, presented above, can help us distinguish areas as pro-trend vs anti-trend in this way:

1. If a municipality grows more than the nation in growing sectors at the national level (Area EC_i^+), and declines in declining sectors at the national level (Area $EC_i^{-\prime}$) then it is "pro-trend".
2. Oppositely, if most of the excess of change lines are in the Areas $EC_i^{+\prime}$ and EC_i^-, municipalities are defined as "anti-trend".

with

Figure 2, presented above, can help us distinguish areas as pro-trend vs anti-trend in this way:

- If a municipality grows more than the nation in growing sectors at the national level (Area EC_i^+), and declines in declining sectors at the national level (Area $EC_i^{-\prime}$) then it is "pro-trend".
- Oppositely, if most of the excess of change lines are in the Areas $EC_i^{+\prime}$ and EC_i^-, municipalities are defined as "anti-trend".

The authors and the Editorial Office would like to apologize for any inconvenience caused to the readers by these changes. The changes do not affect the scientific results. The manuscript will be updated and the original will remain online on the article webpage.

Reference

1. Urso, G.; Modica, M.; Faggian, A. Resilience and Sectoral Composition Change of Italian Inner Areas in Response to the Great Recession. *Sustainability* **2019**, *11*, 2679. [CrossRef]

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