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Assessing impacts of flood events in urban areas to understand the resilience of the urban system

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Abstract

The introduction of the concept of urban resilience in managing risk of natural hazards in urban areas is closely related to pointing out suitable resilience assessments. In general, resilience can be defined as the ability of a given system to face and adapt itself to unexpected events, or stressful conditions. However, resilience can assume several meanings and it can also be applied to various different field of analysis. The technical literatures, indeed, offers a large set of definitions of resilience and many approaches have been developed so far to study this property. Topical relevance of resilience, especially in reference to natural hazards, is then combined with a broad scientific debate.

In this general background, the thesis analyses urban resilience to flood risk through spatial analyses. Developing a conceptual definition of urban resilience, a methodological approach is presented to assess urban resilience of settlements located next to rivers. Assuming the configurational theory of Space Syntax to investigate the spatial layout, urban areas are analysed, in reference both to their spatial and functional features. Space Syntax is based on connections between the geometrical pattern of urban spaces (as well as spatial and visual relationships between the latter) and urban phenomena occurring within the said spaces. These connections are basically described by measures of topological centrality. Therefore, presence of flooded areas is examined according to its ability to affect spatial accessibility, consequently influencing the use of urban space. Applying the configurational approach, effects of flooded zones on spatial perception and human navigation are examined, towards evaluating consequences of floods on urban dynamics. All these aspects are related to the capability of flooded urban systems to mitigate effects of flooding, adapting itself to flood-induced consequences and preserving urban functions. This ability actually corresponds to the resilience of the considered urban systems.

The proposed methodology consists of different stages of analysis. Syntactic features and urban morphology are considered, applying configurational techniques and statistical method to process syntactic data. As a result, a set of objective and quantitative measures are achieved, able to describe the degree of resilience of urban areas located on river banks, or rather, exposed to flood risk.

Keywords: flood risk, urban resilience, Space Syntax

Sommario

L'introduzione del concetto di resilienza urbana nella gestione dei rischi naturali in ambito urbano è strettamente connessa alla necessità di individuare appropriati metodi di valutazione della resilienza stessa. In generale, la resilienza di un sistema può definirsi come la capacità di quest'ultimo di far fronte ed adattarsi a perturbazioni e cambiamenti indotti da eventi o stress improvvisi. Tuttavia, le molte accezioni che il termine può assumere, così come i diversi campi di analisi cui tale concetto può essere applicato, sono alla base di un'ampia varietà di definizioni e studi della resilienza presenti nella letteratura tecnica. All'attualità del tema in riferimento a sistemi urbani soggetti a calamità naturali, quindi, si accompagna un ampio dibattito scientifico.

In tale contesto, questo lavoro si propone di esaminare la resilienza urbana rispetto ad eventi alluvionali adottando una prospettiva di analisi spaziale. Sviluppando una definizione concettuale della resilienza urbana, la tesi presenta un approccio metodologico volto allo studio di tale proprietà in relazione ad ambiti urbani perifluviali. L'adozione della teoria configurazionale di Space Syntax, come principale metodo di analisi delle strutture urbane, consente di esaminare il layout spaziale di queste ultime in termini funzionali. Alla base dell'approccio di Space Syntax, infatti, c'è lo stretto legame tra la forma degli spazi urbani (e le loro rispettive interconnessioni spaziali e visuali) e le dinamiche urbane che si sviluppano all' interno di detti spazi. Questo legame è operativamente descritto da misure topologiche di centralità. In tale ottica di analisi, la presenza di aree inondate è esaminata rispetto alla limitata accessibilità spaziale che esse determinano e alla loro influenza sull'uso dello spazio urbano. Pertanto, l'applicazione del metodo configurazionale consente di studiare come le zone inondate possano modificare la percezione spaziale di chi naviga lo spazio urbano, ripercuotendosi sui fenomeni urbani. Questi aspetti risultano legati alla capacità del sistema urbano di mitigare gli effetti degli eventi alluvionali cui esso è esposto e di adattarsi ai relativi cambiamenti indotti preservando le funzionalità spaziali al suo interno. Tale capacità corrisponde alla resilienza del sistema urbano.

La metodologia proposta è strutturata per fasi successive di analisi. A partire dall'esame di caratteristiche sintattiche e della morfologia urbana, attraverso metodi configurazionali e statistici di analisi dei dati, la procedura sviluppata consente di ottenere misure oggettive e quantitative sulla base delle quali è possibile descrivere il livello di resilienza di insediamenti attraversati o lambiti da corsi d'acqua ed esposti al rischio alluvionale.

Parole chiave: rischio alluvionale, resilienza urbana, Space Syntax

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Introduction

The growing number of people moving into cities has produced an increasing urban land development. Urban expansion can cause the degradation of natural resources, impacting the environment and natural ecosystems. This process also determines conditions of vulnerability to natural hazards and, in case the progressive urbanisation involves hazard-prone areas, it leads to a concentration of people, assets and activities in zones at risk. With specific reference to the expansion of urban areas near river courses, a mix of natural and human-induced factors arises. Besides the aesthetic landscape value, urban rivers create sensitive conditions: on one side, river systems can be changed in their morphology, or heavily degraded by water consumption and discharge; on the other side, watercourses can constitute a critical risk factor for nearby located settlements, being the latter potentially affected by major natural phenomena of the river ecosystem. Therefore, urban rivers represent a twofold condition, being the protection of rivers from human pressure on watercourses and riparian areas to be combined with the need of having control over risks that could derive from water presence, notably the risk of river flooding. In this general context, disaster risk in urban areas results to be a priority issue, assuming particular relevance in reference to settlements located in proximity of watercourses.

Flood events in urban areas can cause different significant damages, affecting people, structures and environment, with both short-term and long-term impacts. Assessing main factors and consequences of floods informs about magnitude of flood events. From an operational perspective, this is an important knowledge enabling to point out appropriate actions to be implemented in order to prevent, mitigate or cope with floods. Flood impacts can be understood not just as effects determined by hazardous events, but actually as factors against which an effective recover ability is required. This observation allows to consider flood impacts into the wider context of managing disaster risk through integrated measures of event prevention, response and recovery. In other terms, a clear understanding of flood causes, impacts and consequences can be assumed as a step towards the definition of how a system was, or would be, able to face and recover by a calamitous event (depending on whether a past or a probable future event is studied). Therefore, following the general definition of resilience as the ability of a system to withstand and adapt itself to an unexpected crisis, the concept of urban resilience to flood events can be deduced as the capability of a flooded settlement to prevent flooding (as far as possible) and efficiently face flood-induced effects.

Urban resilience can be interpreted in many different ways and it can be analysed from several points of view. A conceptual definition results an essential preliminary step to properly set both the specific analysis perspective and the analysis method to adopt aiming at pointing out a resilience assessment. In dealing with resilience to floods, this can be not as easy as it appears, due to the wide range of structural, social, economic elements which could be affected by a flood, and the reciprocal relationships among them. Moreover, resilience can depend on factors that are not directly measurable, both at individual or community levels, such as elements related to human well-being and social dynamics. Therefore, assessing urban resilience results to be a challenging task, especially if referred to quantitative assessment approaches. Many studies have been developed so far to evaluate resilience, most of them adopting qualitative assessment or synthetic indicators of resilience defined according to the specific purpose of study.

Among others consequences, floods modify the layout of accessible spaces within flooded settlements affecting, in turn, urban phenomena. This observation represents a fundamental assumption of this thesis: correspondence between urban layout, spatial properties and urban functions is considered as an essential point. Flood-induced effects on urban structure are analysed in reference to how they affect -during and after the event- urban activities and, therefore, the degree of urban resilience. The consideration of space ability to shape urban behavior is the basic concept of the configurational approach of Space Syntax (Hillier and Hanson, 1984, Hillier, 2007), which appears to be a valid method to investigate how cities work based on their relative spatial structures. Indeed, the said approach considers that spatial geometry influences how the space is experienced by people: according to the syntactic theory, people movement and human interactions can be basically linked to spatial properties of urban environments, such as -respectively- to linear or convex spaces, and interrelations between all urban spaces (Hillier and Vaughan, 2007).

Assuming the described configurational approach, the main purpose of this study is to examine urban resilience to flood events from a spatial perspective of analysis, aiming at individuate a suitable methodology to quantitatively assess spatial resilience of settlements at risk to be flooded. Allowing to examine the influence of urban spaces on human activities, and how it varies due to a critic event, this spatial perspective of analysis provides further elements that shall be added to all the set of usually examined flood consequences.

This brief introduction delineates the general background of the analysed topic and the main motivations of this work. Starting from a theoretical framework relative to urban resilience and disaster risks, the following sections are focused on examining the connection between urban space and flood events, both conceptually and methodologically.

In Chapter 1, the context of analysis of the research topic is described. An overview of some basic concepts of disaster risk is provided, with a specific focus on flood events and main aspects of commonly adopted flood risk assessments. A review of relevant literature is presented to outline how resilience is generally defined and how the concept of resilience can be detailed with regard to urban systems and flood events. The significant contribution of considering resilience in managing risk is examined, consequently deducing the importance of appropriate resilience assessments. The configurational theory of Space Syntax is described as a suitable approach to deeply investigate urban systems. The analysis of the conceptual consistency and the methodological relevance of applying the syntactic theory to study urban resilience is followed by a review of studies developed so far to evaluate resilience through spatial analysis.

In Chapter 2, an innovative methodological approach is presented. The proposed approach is based on the connection between disaster risk assessment and spatial network analysis. The discussion of previous works, aimed at evaluating resilience through configurational measures, highlights the need to develop a suitable analysis method to analyse spatial aspects of resilience to flooding. On this basis, a conceptual definition of urban resilience to floods is provided, setting the theoretical framework based on which a multi-stage methodology is proposed to evaluate spatial resilience to flood events. Analysis phases, as well as data processing phases and relative validation procedures, are explained in detail, pointing out methods and techniques of analysis to implement the said resilience assessment methodology. Syntactic and morphologic analyses, as well as statistical data processing are considered, achieving a set of quantitative measures which contribute to comprehensively assess urban resilience. Each stage of analysis is described also examining the relative contribution to the overall purpose of understanding urban resilience. Potential applications of the developed methodology are also described to outline how the proposed procedure can actually contribute to develop and enhance urban resilience to flooding.

In Chapter 3, an application of the developed methodology is examined. The whole proposed approach is applied to three case studies of settlements located near river courses. The selected urban areas differ from each other in many aspects, such as urban structure and morphology. This variety among examined settlements allows to apply and test the validity of the developed methodology on different urban configurations. Results are presented, discussed, and comparatively analysed.

In Chapter 4, the contents of this thesis are summarised. General outcomes and applications of the proposed methodology are outlined and discussed, along with possible further developments of the presented approach pointing out the contribution the latter can provide to build urban resilience to floods.

1

State of the art

1.1 Disaster risk and related concepts

Frequency and magnitude of natural hazards in urban areas have been progressively attracting a high degree of attention from governmental and non-governmental institutions and organisations. This circumstance is reflected in the variety of institutional assessments and regulatory measures, as well as in the wide body of technical literature focused on natural disasters and disaster risk. Although this general attention to disasters risk, natural hazards still constitute a significant issue, especially for urban areas where presence of people, infrastructures and assets can clearly exacerbate effects of major natural events. In a context of general increasing vulnerability in all countries (UNISDR, 2004; UNISDR, 2015a), with consistent losses and damages due to natural hazards, reduction of disaster risk continues to be a global challenge.

Natural dynamics include a various range of events, which in some cases become adverse and serious circumstances (e.g.: geological phenomena causing volcanic eruptions, landslides or earthquakes; extreme weather conditions giving arise to floods, tsunami or droughts). Relative consequences are related both to territorial features and human-induced factors within affected areas: morphological and environmental characteristics, along with socio-economic features, can influence the effects and -in some circumstances- even the probability of occurrence of major adverse events. These considerations remain valid, to some extent, also in reference to man-made hazardous events (e.g.: fires, industrial activities related to dangerous industrial processes).

The so-called "natural disasters" are basically circumstances related to natural events. This observation leads to a key question: what makes a natural phenomenon a "hazardous" event, determining a risk, up to generate a "disaster"? A deep focus on disaster risk and related concepts can contribute to deal with this issue.

According to United Nations International Strategy for Disaster Reduction terminology, a risk represents "*the combination of the probability of an event and its negative consequences*" (UNISDR, 2009, p.25). Common approaches usually adopt the so-called "*risk equation*", expressing total risk as the product of two main factors: hazard and vulnerability (UNISDR, 2004; Downing et al, 2005; Cardona, 2004; Cardona et al., 2012; Smith, 2013; Blaikie et al., 2014; Tingsanchali, 2012):

- *hazard* (*H*) generally represents events, conditions or activities which can potentially affect or damage elements, people or systems, inducing a crisis as an hazardous condition (Cardona et al., 2012; UNISDR, 2004, UNISDR, 2005). A classification can be achieved pointing out different categories of hazards: "*natural hazards*", or rather, hydro-meteorological, geological and biological hazards; "*technological hazards*", related to technological, industrial or infrastructure failures; "*environmental degradation*", determined by human behaviors and activities which can impact natural processes or ecosystems (UNISDR, 2004). Seismic risks, hydro-geological risk, volcanic risk, fire risk, storm surges, all constitute natural hazardous events. Human activities and their failures (e.g.: failures of technological systems, nuclear attacks, industrial activities) can represent human-induced source of calamitous events of the "*anthropogenic or man-made hazards*". In some cases, human activities can determine a misuse or a degradation of natural and environmental resources. This circumstance can affect the natural occurrence probability of natural phenomena, determining the so-called "*socio-natural hazards*" (UNISDR, 2009). This category of hazards has been recently introduced into the context of natural risks and it can clearly be related to an improper management and use of natural resources. In reference to the above said risk equation, *H* value basically represents the probability of event occurrence and it mainly depends on the specific type of event. The relationship between a hazard and its occurrence probability allows to determine the total risk (Smith, 2013). Even probably representing the main trigger factor in determining a potential dangerous event, *H* constitutes a component of the risk and it does not coincide with the risk itself (Cardona et al., 2012).

- *Vulnerability* (*V*) generally represents the likelihood a certain system will be affected by a given event or stress. Difficulties in finding a unique and globally accepted definition of this concept within the literature reveal how vulnerability is broadly discussed (Birkmann, 2006; Downing et al., 2005; Manyena, 2006; Messner and Meyer, 2006; UNU-EHS, 2006; Steinführer et al., 2009). As a widely studied and applicable issue, vulnerability needs to be defined on the basis of the specific system it is referred to, as well as the study perspective from which this property is analysed. Looking at urban systems, vulnerability to natural extreme events appears to be a multi-faceted issue, definable in relation to different aspects: environment (Cardona et al., 2012); human being and communities (Blaikie et al., 2014); society and economic or political conditions (Cannon, 1994; Cardona et al., 2012; Adger, 2006; Steinführer et al., 2009), assets and human activities.

  In some studies, the physical aspect of vulnerability is specified as "*exposure*" (*E*) (Messner and Meyer, 2006; UNISDR, 2004; Steinführer et al., 2009; Zhou et al., 2010). In this view, given a certain hazard, *V* represents the attitude of elements exposed to a certain hazard to be impacted or damaged (Cardona et al., 2012). *E* is related to the set of elements located within areas at risk and, then, potentially affected by the event. In fact, *V* and *E* are not only referred to physical aspects of the urban environment, but they should also consider social features of threaten communities (Holling, 1973). More generally, vulnerability and exposure can be evaluated in reference to physical, social, economic, human and environmental factors. Therefore, depending on the specific hazard and system at risk, different aspects of vulnerability and exposure can be examined (e.g.: buildings and infrastructure, assets and people, human activities and wellbeing at risk). Exposure and vulnerability are clearly linked each other: an exposed element can be vulnerable or not. However, it needs to be exposed to a risk in order to result vulnerable (Cardona et al., 2012).

All these considerations induce to state that natural events do not constitute a source of risk or hazards, per se (Cannon, 1994). External factors, or rather elements that could potentially be affected or damaged by the event, contribute to determine vulnerability.

Insofar as there are elements that could be affected or damaged (to which the *exposure* value is referred) within the area where the event occurs (that corresponds to the potentially damaged zone, or *area at risk*), and according to the (structural or non-structural) susceptibility of exposed elements to report damages once the event has occurred (which represents their *vulnerability*), natural events can became "*hazards*". Therefore, the potential of natural events to generate dangerous or critic circumstances, or rather impacts, is a key element whose magnitude could lead to disastrous effects. The combination of natural hazards, vulnerable elements and limited ability to cope with major events determines and characterises what can be assumed as a "disaster" (UNISDR, 2005; UNISDR, 2009); relative potential expected and probable losses and damages determine the correspondent disaster risk (UNISDR, 2004). However, the strong connection between man-made elements and natural dynamics induces to rethink the widespread use of the expression "*natural disasters*" (Cannon, 1994; Blaikie et al., 2014) as well as the human role in determining these calamitous circumstances.

Activities and structural or non-structural measures, aimed at preventing calamitous events or limiting relative harmful impacts, constitute the so-called "*disaster risk reduction*" process ("*DRR*"). The latter regards risk prevention, mitigation and preparedness. The goal of reducing disaster risk can be achieved through a participatory, inclusive and coordinate set of activities and measures. All administrative and organisational levels can contribute to better prevent risk-related issues: *i*) national governments, being mainly responsible of resource allocation, infrastructural plans and large-scale response and recovery policies and actions; *ii*) local governments, being competent authorities for management of infrastructures, land use and planning, social and cultural activities; *iii*) communities, being groups of people which own buildings and assets and have capacities and knowledge related to previous experienced calamitous events; *iv*) private sector and non-governmental organisations, being able to help in communicating and bringing into effect *DDR*. *DRR* can be integrated with disaster response, which constitutes a set of policies, measures and actions to be implemented after a major event has occurred. Extending *DRR* analyses, a wider approach is achieved representing the so called "*disaster risk management*" ("*DRM*"): *DRM* considers management of risk, or rather the conditions prior to the beginning of a crisis, as well as emergency and post-disasters stages, that happen once the event has occurred (Baas, 2008; UNISDR, 2009). Highlighting the importance of managing the risk of disaster as distinct from a simplistic disaster management, *DRM* is considered to be one of the key-concept of the Sendai Framework (UNISDR, 2015b). Disaster risk has become a focus of the international debate over time. The recent "*Sendai Framework for Disaster Risk Reduction 2015-2030*" (UNISDR, 2015b) is just one of the last documents focused on this topic. Adopted by UN Member States during the Third UN World Conference on Disaster Risk Reduction, it constitutes an important global agreement concerning disasters, both related to natural and man-made hazards. Its general expected outcome of reducing disaster risk and losses is actually a continuum of the previous "*Hyogo Framework for action 2005-2015*" (UNISDR, 2005) main goals. Together with other declarations and initiatives (UN/IDNDR 1994, UNISDR, 2004; UNISDR, 2005; UNISDR, 2015b), they are both steps of the path towards the disaster risk reduction and the definition of risk management strategies. The said documents reflect the need of understanding and communicating risks, efficiently individuating risk reduction measures, managing remaining disaster risk, also promoting partnerships between governments and stakeholders. Thanks to these developments, disaster risk has progressively evolved from a strictly technical conceived discipline, often limited to a set of measures and actions to be implemented after a disaster, to a wider important issue, in some cases addressed at different governmental and territorial scales through multi-sectorial approaches.

Event's occurrence gives a temporal scale to disaster risk management, making the latter consisting of several phases (before, during and after the event). The latter can be differentiated in their main characteristics (e.g.: analytic phases or operative phases); distinct tools and ability are respectively required across event's phases, giving arise to an extensive range of natural risk-related concepts:

- Pre-event phase: a proper knowledge of typology and characteristics of a possible calamitous event can lead to risk identification (Cardona et al., 2012) and to assess individual and social risk perception (Messner and Meyer, 2006; Cardona et al., 2012). Even if being potentially at risk is an objective circumstance determined by being exposed and vulnerable to a certain hazard, human perception of riskiness can be different within threaten communities

(Steinführer et al., 2009). This circumstance can be influenced by cultural and social factor, as well as by previously experienced calamities. Concerning conditions prior to the beginning of the event, this stage is highly related to *DRR*. It can improve the capacity to anticipate the event (Cardona et al., 2012), globally enhancing risk preparedness (UNISDR, 2004; UNISDR, 2005; Messner and Meyer, 2006; Steinführer et al., 2009; Cardona et al., 2012), communication (Norris et al, 2008; Cardona et al., 2012) and awareness among communities and decision-makers (UNISDR, 2004; UNISDR, 2005; Messner and Meyer, 2006; Steinführer et al., 2009).

- During the event: emergency management (Kapucu, 2012), resistance (De Bruijn, 2004; Norris et al., 2008; Steinführer et al., 2009), response ability (Cardona et al., 2012) and coping capacity (UNISDR, 2004; UNU-EHS, 2006; Schmidt-Thomé, 2005; Steinführer et al., 2009) are required, in order to respond and cope with disaster-induced effects and immediate relative perturbations.
- Post -event phase: The ability to combine tools, expertise and resources in order to cope with event impacts and consequences (Steinführer et al., 2009; Wamsler, 2008; Hammond et al., 2015) is clearly related to the after-disaster phase, which mainly constitutes a recovery stage (UNISDR, 2004; UNISDR, 2005; Steinführer et al., 2009) for disaster-affected systems and communities. The need to socially and structurally adapt (Adger, 2000; Cannon, 1994; Cutter et al., 2008; Hufschmidt, 2011; Norris et al., 2008; Ranjan and Abenayake, 2014) to disaster-induced perturbations makes the capacity of response to be included into this phase. However, during the post-event, response capacity becomes also related to the ability to change and rebuilt the affected system (Cardona et al., 2012).

Actions of these three stages are linked, mutually influencing each other: efficacy, level of practicability and implementation of pre-event actions provide the basis for the following two stages (during and post event phases), globally affecting the overall system ability to react, withstand and recover from a crisis.

1.2 Assessment and management of flood risk in urban areas

Floods represent one of the most common disasters in urban areas. Due to the significant percentage of occurrence of floods (47% of all weather-related disasters in the time period 1995-2015, UNISDR, 2015a), these events assume particular importance, especially with reference to flood-prone urban areas. According to the EU Directive 2007/60 (European Commission, "Directive 2007/60 of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk", 2007), a flood represents a "*temporary covering by water of land not normally covered by water*". Water can come from the sea, rivers, severe rains, or from underground water channel networks, respectively determining coastal, fluvial, "pluvial", groundwater floods and sewage overflow. These circumstances can be determined by precipitations, storms, earthquakes or dam break. Different levels of risk will be defined, depending on the speed of onset and the flood discharge, as well as on extents and level of urbanisation of flooded areas, duration and predictability of the event. A further category of flood is represented by flash floods, which correspond to events caused by rainstorms in mountainous areas. Being difficult to forecast, with high water flow velocity and debris load, flash flood events can determine significant impacts (European Commission, 2007; Klijn, 2009). As regards fluvial floods, urbanisation of territories adjacent to rivers transforms these areas, influencing both the natural equilibrium of river ecosystem and the risk of flood events. Changes in land uses of flood plains affect the main function of these areas to store and collect water during high water discharge periods. Hydrologic regime results altered, with modified values of peak discharge and increased flood risk downstream (Chin, 2006; Wheater and Evans, 2009). Sedimentologic and morphological regimes are affected too: use of bare land, increase of impervious surface, replacing vegetated soils, and channelisation, influence sediment load, runoff and fluvial flood frequency (Chin, 2006). Moreover, population growth and increasing number of buildings within flood-prone areas are clearly related to flood events, both in terms of flood occurrence and magnitude (Klijn, 2009; UNISDR, 2015). This mutual relationship between urban areas and rivers highlights the importance of a rational use of natural resources in sensitive environments like territories located next to river courses.

Urban and territorial morphology influences the likelihood to be affected by floods: proximity to water resources has been assuming notable importance in human activities and settlements location; at the same time, it can become an element of hazard. Human perception of rivers as potential elements of risk can also affect the aesthetical appreciation of watercourses (Silva et al., 2005). Nevertheless, a correct perception of risk induces awareness about potential calamitous circumstances, both at communities and governmental levels. This constitutes an important social and political background, which can become a catalyst element for flood risk management issues.

"Managing" floods seeks to mitigate relative risk, both looking at conditions that could lead to the occurrence of major events, and considering all factors or circumstances which could transform a major event into a disaster. In other terms, flood risk management concerns all the determinant elements of risk (or rather, hazard, vulnerability and exposure). Even being flood management focused on limiting flood-related impacts, flood risk reduction constitutes just a part of the event management. The relation between flood risk management and reduction can be clarified examining how flood risk has been approached over time. The concept of flood risk management has generally evolved over the years, from an engineering-focused approach -mainly aimed at preventing critic events ("*flood defense*") through structural protective measures or controlling floods ("*flood events*")- to the wider idea of "managing" a risk that cannot be completely canceled out ("*flood management*"). This more recent management-focused view gives particular attention to people and society vulnerability, highlighting the need of a suitable balance between economic, social and environmental factors of flood reduction (Klijn, 2009). Therefore, disaster risk reduction belongs to the field of the flood risk management; both of them require a proper knowledge of flood hazard and relative consequences.

Flood risk management can be described as a process made up of different phases and activities. Dealing with risk, a suitable assessment can lead to analyse elements that could generate or affect the total risk. The EU Directive 2007/60 (European Commission, "Directive 2007/60 of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk", 2007) remarks the importance of reducing and managing flood risk. The Directive requires the individuation of areas potentially at risk, through a preliminary risk assessment. Based on analysing past calamitous events that caused considerable impacts and losses, along with potential consequences of probable future events, this analysis phase is proposed to define appropriate objectives and plans to manage flood risk (European Commission, 2007). The main purpose of risk management of mitigating and limiting flood-related impacts can be translated into a wide range of possible measures and actions aimed at reducing both probability of critic events occurrence and events consequences (basically constituting risk reduction measures). In this way, flood risk assessment results to be related to flood reduction and management which, in turn, can be considered part of urban planning and decision processes, involving different actors and decision makers.

In reference to fluvial floods, risk reduction and risk management cover a large set of structural actions and non-structural measures, to be planned and implemented both at short and long-term. Being flood hazard mainly related to the river's ability to convey high water discharge, without overflowing or bursting the bank, structural measures can be aimed at modifying the river course (e.g.: flood defence, increment of water storage capacity upstream, change in river cross section and channelisation) to increase the water discharge that can be conveyed. Even permitting to reduce probability of floods, this typology of measures can strongly affect natural river dynamics, up to influence the whole river ecosystem. Proper analyses are needed to evaluate measures effectiveness, along with environmental, economic and social factors. In fact, even reducing the probability of floods, in some cases these measures do not reduce the total value of flood risk: dams or embankment modify the risk perception, determining an increased urbanisation of nearby areas. As a result, hazard is reduced, but not exposure and vulnerability. People, assets and activities located within floodable areas constitute main elements of exposure. Innovative architectural techniques and high standards for construction of buildings and infrastructures can improve the structural capacity to cope with floods, influencing the vulnerability value. A great contribution to risk reduction can come from non-structural measures, such as urban policies, programmes and regulations, which can both influence the degree of exposure and enhance people awareness of risk. By establishing limits to urban development and land use of areas at risk, before a major event occurs, measures of urban planning constitute long-term actions and represent a significant factor in managing risk, as part of a long-term strategy of prevention and risk awareness. In this, they can be considered opposite to "*flood event management*", being the latter a set of actions to cope with an imminent flood event (Klijn, 2009). A further element to be considered is the communication of risk, as a potential factor able to mitigate flood consequences and better face major events, providing a significant contribute to the whole risk management process. Engaging people who actually may be affected by floods, risk communication plays a significant role, enhancing efficacy and effectiveness of all risk-related activities: leading to developed community skills and knowledge, people behavior results improved during and after the event. Appropriate risk preparedness can improve the ability to cope with calamities and recover by crisis, influencing event-related damages and losses.

Elements which contribute to determine flood risk are variable as related to time-varying conditions (due to both river features and the evolving urban characteristics). It follows that flood risk management needs continuous analyses to obtain updated information. In fact, beside their spatial variability, hazard and vulnerability (as well as exposure) are dynamic factors subject to change over time, depending on the variable features of the urban system they are referred to. A suitable scale of analysis and field measurements can allow to address this variability, helping in pointing out suitable decisions and actions to be implemented.

Mitigation of flood consequences through a suitable risk management needs a proper characterisation, analysis and assessment of risk factors. Focusing on flood events, different types of floods could occur, each one having its own characteristics. Therefore, the analysis of typology, probability of occurrence and main features of floods that are likely to happen in a given area informs about extent, main features and critical points of the considered events. Recalling that hazards lead to calamitous events insofar as they are able to affect vulnerable elements (among the ones located in threaten areas), vulnerability also needs to be investigated in order to completely assess flood risk. By definition, elements exposed to the risk could probably be damaged or impacted by floods, being vulnerable. Therefore, analyses of floodable areas, or rather areas at risk, provide information about vulnerability and exposure. The several perspectives from which these two latter factors can be investigated show how their assessment is clearly related to the scope and purpose of study.

Over time, usual approaches to assess flood risk have basically consisted in defining and focusing on main determinants of risk: hazard and vulnerability, or rather probability of occurrence of major events and related consequences. Assessing risk through an accurate characterisation of major events, identification of potentially affected elements and estimation of possible damages provides a large set of significant information. The latter constitutes an important background, useful to point out well-structured flood management measures, plans and policies (Hall et al., 2005; Tingsanchali, 2012), both in reference to existing flood protection systems ("*operational level*") or examining possible actions on existing systems ("*project planning level*" and "*project design level*") (Plate, 2002).

Risk assessment constitutes a fundamental part of risk reduction and, in turn, of flood risk management. It intrinsically includes a major issue, or rather the definition of how risk components can be defined and characterised. Mapping flood hazard, as required by the EU 2007/60 Directive (European Commission, "Directive 2007/60 of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk", 2007), an overview of areas at risk to be flooded can be achieved. Individuation of elements located within floodable areas informs about relative exposure. Even allowing just a qualitative exposure assessment, these risk maps give a useful contribute to risk assessment and management, providing a definition of which zones particularly need emergency measures, actions and policies for risk reduction. However, a quantitative assessment of risk assumes relevance in order to objectively estimate risk variations which may occur during time as a consequence of natural urban dynamics or implemented risk reduction measures.

In reference to fluvial floods, hazard is essentially related to river water regime and flow, even though these factors can be influenced by boundary or external conditions of the river ecosystem (e.g.: extreme or unpredicted weather conditions, natural phenomena as river bank erosion). Given a certain area, risk assessment includes the evaluation of the probability distribution of floods for that area and the magnitude of relative events, in terms of some basic event features, such as extent of flooded area, water depth, water flow. The main issue of hazard evaluation is to determine the probability that a flood water discharge, or rather a volume of water, (on the basis of relative water depth or temporal trends of flow) may stress the river system, determining an overflow of water. Therefore, quantitative measurements of hazard represent an evaluation of the probability that a certain event occurs, during a given time period. Being the occurrence of floods mainly estimated through probabilistic-based approaches -eventually supported by event modeling and simulation- availability of data results a relevant issue, both with regard to the lack of registered measures and because of the fact that some impacts and damages are not directly measurable. In general, risk analysis can be carried out on the basis of information relative to past events, in case relative database are available, or using surveys and data modeling outcomes, obtained by simulating probable calamitous conditions, in a pre-event approach of analysis (Smith, 1994). Data of past events, if available, constitute a valid knowledge base: applying statistical interpolation methods, the trend between measured water discharge (or water depth) and frequency of relative flood events can be pointed out. Statistical extrapolation can give an indication of the magnitude of possible future events (Klijn, 2009). However, further information can be necessary to properly consider any variation of flood hazard (this aspect corresponds to the temporal variation of flood risk). Therefore, computer modeling can help in simulating possible extreme weather conditions, as well as consequent probable flood events (Klijn, 2009). Hydro-geological modeling allows to define a value of flood water discharge in reference to a certain return period ("*T*"). Given a variable *X* and a certain its value *x*, the return period *T* is a statistical measure related to the probability the variable exceeds *x*. *T* represents the number of times before *X* assumes a value higher than *x* (Erto, 1999). Referring to flood events, defining *X* as the water discharge and *x* as a certain value of *X*, the return period *T(x)* is the mean number of years between two discharge values greater than *x*, or equal to *x*. In other terms, *T* constitutes a measure of the probability that water discharge exceeds a given threshold value, or rather the mean number of years between two water discharges greater or equal to a certain value assumed as maximum (Gumbel, 1941). Once known both water discharge and river features (e.g.: river cross section geometry), relative water depth and territorial morphology, the extents of flood-prone areas can be defined. In case there are protective structures, the probability that a water discharge determines a flood is obtained also considering the probability for flood defences to be overtopped or to collapse.

In reference to urban vulnerability to flood events, the wide range of vulnerability definitions provides an equally large set of relative possible measures. Whatever the adopted study perspective, assessing vulnerability is related to the difficulties in individuating and suitably evaluating representative variables of this concept.

Magnitude of floods in urban areas is intrinsically related to their consequences and impacts. Thus, impacts assessment can also contribute to an overall risk evaluation. As a consequence of the various dimensions the complex city system consist of, a wide range of flood impacts can be identified, in terms of losses and damages. In order to properly assess flood impacts, different analyses approaches can be adopted: economical, structural, social and psychological consequences of flood events are just some of all the possible effects on affected structures, human being and communities. Several methodologies of impact assessment can be found in the technical literature, considering different analysis perspectives to evaluate expected losses (if relative to pre-event analyses of potential risk) or to estimate occurred damages (if referred to past events). Usual classifications of flood impacts distinguish between "*tangible*" and "*intangible*" impacts, depending on whether they are quantifiable in monetary terms (e.g.: structural damages; losses of lives, affected mental well-being, environmental impacts); "*direct*" impacts, if they are referred to directly flooded areas, or and "*indirect*" if they are induced by direct one, and they may occur beyond spatial or temporal limits of a certain flood event (Hammond et al., 2015).

1.3 The concept of resilience

During last decades, the concept of "*resilience*" has been introduced in the wide range of risk-related terminology. As the etymological root of the term suggests (the word comes from the Latin verb "*resilire*", meaning "*to jump back*"), resilience regards the ability of a certain system to bounce back from a certain perturbation. The term is usually cited (Cutter et al., 2008; Ranjan and Abenayake, 2014) as firstly introduced by Holling (1973), in reference to ecological systems, as "*a measure of the persistence of systems and of their ability to absorb change and disturbance*" (Holling, 1973, p.14). In general, the concept is referred to a system affected by a stress or a shock, and it has been widely applied to many scientific disciplines over time: ecology (Holling, 1973, Adger, 2000), psychology (Bonanno, 2004), social and economic systems (Adger, 2000; Boon et al., 2012; Cutter et al., 2010; Norris et al., 2008; Steinführer et al., 2009), infrastructures (Hashimoto et al., 1982; De Bruijin, 2004; Cutter et al., 2010) (Ranjan and Abenayake, 2014; Zhou et al., 2010).

Focusing on natural disasters, a large number of different definitions of resilience were introduced, collected and reviewed in the literature (Manyena, 2006; Zhou et al., 2010; Reid and Courtenay Botterill, 2013; Lhomme et al., 2013). According to UNISDR, resilience is "*the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions"* (UNISDR, 2009, p.24). Further specifications about resilience can be indirectly achieved describing main characteristics of a "resilient" system. Cutter et al. (2008) described resilience as an "*inherent*" property, as it can function even during non-crisis periods; "*adaptive*", thanks to flexibility in response which characterises resilient systems during a crisis; measured with different indicators, suitable chosen in reference to the spatial and temporal scale of analysis; subject to be influenced at the community level by exogenous factors, such as policies and regulations. Based on the technical literature, ARUP and Rockefeller Foundation (2014) proposed a significant set of seven desirable features for a "resilient" urban system, the latter assumed as able to: learn from past experiences; act during crisis ("*reflectiveness*") and use available resources according to the needs, adapting its behavior ("*resourcefulness*"); ensure good governance processes to properly address needs and relative actions and measures; promote participatory decision making processes ("*inclusiveness")* bringing together different systems and institutions (*"integrated*"); face shocks and stresses, adequately designing systems and protections ("*robustness*"), holding diverse capacities to cope with major events-related demands ("*redundancy*"); adapt to emerging conditions ("*flexibility*") (ARUP and Rockefeller Foundation, 2014). Other characteristics of resilient systems can be found in Godschal (2003): "*redundant", "diverse"* and *"interdependent"*, regarding the diversity among components and how the latter work; "*efficient"*, "*autonomous"* and "*strong"*, on the basis of resources and control needed to efficiently work, "*adaptable*", learning from experience and able to change. Tyler and Moench (2012) proposed to consider main characteristics of urban resilience as related to three elements: *1)* "*systems*", meaning infrastructures and ecosystems, which should be able to work under different conditions, modifying their structure ("*flexibility*", "*diversity*"), responding to increased demand ("*redundancy*") even by replacing their components ("*modularity*") and deriving support also from other connected systems ("*safe failure*"); *2)* "*social agents*" (e.g.: individuals, households, private and public sector organisations), as important and decisive actors within urban systems which should have the capability to reorganise ("*responsiveness*"), mobilise resources ("*resourcefulness*") and improve performances, also on the basis of previous failures ("*capacity to learn*"); *3)* "*institutions"*, as rules and conventions to control interactions between systems and agents responding to stresses, to regulate access to resources and urban systems ("*rights and entitlements linked to system access*"), as well as to information on potential risk ("*information flows*"), promoting an appropriate governance ("*decision-making processes*") and dissemination of information ("*application of new knowledge*").

The property of resilience can be further investigated also on the basis of how it is placed in the domain of risk-related concepts and how it differs from other concepts. Connections between resilience and vulnerability are largely examined in the literature. Links between these concepts are characterised in several ways (even because both of them are not uniquely and precisely defined). Firstly, vulnerability and resilience can be found to be assumed as distinct concepts, opposite to each other: a low level (or a lack) of one of them determines a significant value (or an increment) of the other one, and vice versa (Manyena, 2006; Steinführer et al., 2009; Tyler and Moench, 2012). In other approaches, vulnerability and resilience are assumed as distinct properties: even influencing each other, they can independently increase or decrease (Manyena, 2006; Steinführer et al., 2009). In Cutter et al. (2008) relationships between vulnerability, resilience and adaptive capacity were analysed. A significant contribute in this distinction was provided by pointing out that if vulnerability is meant as the degree of capacity of a system, a greater connection to resilience is given. In case vulnerability is assumed as the degree of exposure or potential losses, the two concepts result to be less related each other (Manyena, 2006; Cannon and Müller-Mahn, 2010). Temporal dimension is also analysed in the relevant literature, as an element to differentiate the two concepts in regards of event stages: vulnerability is assumed as referred to all disaster phases (Steinführer et al., 2009) or just pre-event conditions (Cutter et al., 2008; Dayton-Johnson, 2004), resilience is focused on crisis and post-event phases (Dayton-Johnson, 2004; Steinführer et al., 2009; Zhou et al., 2010). According to the literature, some other concepts can be individuated as related to resilience. Assuming the latter as linked to an adaptive capacity, stability was seen as an inability to change or adapt to modified conditions (Norris et al., 2008) and resistance as aimed at preventing hazards, or rather at not allowing any change in regard to which a system could need to get adapted (or, being resilient). From a performance-based approach focused on water resource systems, Hashimoto et al. (1982) differentiated the two properties: in his work, resilience was related to the time a system needs to return to a satisfactory state after a failure, vulnerability was defined in regard to magnitude of failure consequences. This temporal characteristic of resilience can be found also in reference to hazard risks, assuming "resilient" a system, community or society able to "*resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner*" (UNISDR, 2009). Focusing on water systems, in fact, Hashimoto et al. (1982) assumed resilience as the time a water resource system needs to recover after a failure, mathematically evaluating this property as the inverse of the expected period of time the output of the system is unsatisfactory. Assuming water resource systems as infrastructures or structures of water networks (e.g.: dams, reservoirs), relative failures can cause or contribute to determine disasters. However, this direct measure of resilience descended from conceiving the concept as strictly determined by a specific system performance. At the urban scale of analysis, in the literature, resilience is often assessed through indicators that account for abilities or characteristics representative of what can be considered a "resilient" behavior, on the basis of practical experiences or general theories. However, outcomes of this inductive approach can be affected by the characteristic of the specific community in respect to which the indicators are deduced. A second approach considers to define measurements independently from the context to which they are applied (Winderl, 2015). Based on the literature, a large set of different resilience indicators can be pointed out. Resilience ability of a system is examined both through qualitative considerations and quantitative indexes (Carpenter et al, 2001; Cutter et al., 2008; ARUP and Rockefeller Foundation, 2014; Schipper et al., 2015, Winderl, 2015). As a multi-faceted concept, different quantities can be identified for each dimension of resilience. Each one of these dimensions contributes to describe and assess this property, and requires relative measurements (Cutter et al., 2008). Using indicators as proxies of resilience is quite common in the literature. Indicators provide useful contribute in analysing and simplifying the wide and complex properties of urban systems. However, subjectivity in the choice of significant variables, dependence on scale of analysis and specific hazard in respect of which they are defined, difficulties in considering at the same time different aspects of resilience, are some problems related to using resilience indicators (Cutter et al., 2008; Winderl, 2015). Schipper et al. (2015) in a recent review examined several indicators developed so far to assess resilience to climate change and natural hazards. The analysed indicators were classified according to whether the measures considered three elements, assumed as significant dimensions of resilience, or rather: *i*) level of community awareness, preparedness and ability to learn from experienced hazards ("*learning*"); *ii*) availability of alternatives to make people able to modify their behavior in order to face vulnerability ("*options*"); *iii*) ability of the affected system to cope with and recover by a crisis not completely collapsing ("*flexibility*"). The work showed that all the three dimensions were generally investigated, although to varying degrees; just in a limited number of studies "*flexibility*" was analysed, on the basis of what happens after a calamitous event. Focusing on flood risk, resilience can be also described referring to two main approaches. A first one, aimed at reducing flood probability of occurrence; flood defence and protective infrastructure will derive from this strategy. Defining resistance as "*disturbances a system can withstand without reacting*", flood resistance becomes the "*ability to let discharge waves pass without causing floods*" (De Bruijin, 2004, p. 58) as mainly aimed at preventing flood events. However, failures cannot be completely avoided: technical, economic and social issues represent limits in incrementing resistance, or decreasing vulnerability, in a way to completely prevent breakdowns. This statement permits to deduce that improving abilities to cope with flood risk can mitigate or reduce flood consequences, developing the capability of the affected systems to adapt itself to flood-related effects (or rather, their resilience). Basically admitting a certain possibility of flood occurrence, effective disaster risk strategies can be derived (both in terms of flood risk reduction and management) also linking resistance strategies and resilient-focused strategies.

1.4 Resilience assessment and the configurational approach of Space Syntax

Importance and relevance of resilience in the disaster risk arena are reflected in the several approaches developed so far to define and evaluate this property. Resilience indicators reported in the literature are mostly focused on social, environmental, economic aspects of affected human being or communities (e.g.: health, education, infrastructure, food security, access to services, among others). Several contributes attempted to define and measures resilience, revealing how topical this issue is. This is also confirmed by the increasing and considerable general attention that resilience is receiving in dealing with natural hazards in urban areas. Several partnerships, campaigns and initiatives across many countries have been introducing and developing, aiming at promoting strategies and skills to manage shocks and calamities (e.g.: The Global Facility for Disaster Reduction and Recovery (GFDRR), managed by the World Bank; the "100 Resilient Cities" campaign, promoted by the Rockefeller Foundation; the UNISDR (The United Nations Office for Disaster Risk Reduction) "Making Cities Resilient" campaign).

In its basic meaning, resilience is related to how a given system works after some variations have occurred in its structure. In reference to disasters in urban areas, settlements can be assumed as systems to be analysed in regard to their capability to continue working after a calamitous event has affected some of their parts. Considering spatial aspects, disasters create non-accessible areas within the spatial layout of affected settlements. Inability to reach or use these parts constitutes the disaster-induced perturbations, whose magnitude and typology determine how relative urban systems have to re-organise itself in order to transform post-event conditions to achieve a post-event acceptable state. The usual assumption to consider the urban structure as a physical pattern, or rather a collection of buildings, infrastructures and open spaces can be expanded taking into account that urban structures are inextricably related to urban functions and human activities within the urban environment. In this view, spatial effects of disasters are not just limited to the inability to reach some areas after a dangerous event has occurred, but disaster consequences can influence human behavior and activities too. Therefore, two main dimensions of cities appear: the physical pattern of urban spaces and the functional role that spaces assume in reference to urban phenomena. A duality seems to arise, as cities appear to be made up by two *things*: the built environment -or rather, buildings and infrastructures physically separated each other by open spaces- and a set of activities which take place within the urban environment. *"Is the city one thing or two?"* (Hillier and Vaughan, 2007, p. 205). This key question can be considered as a basic issue to address this duality and to describe the main assumptions of the configurational approach of Space Syntax, its applications and potentialities. A *"physical system"* and a *"human system"* actually coexist. Connections between these two systems stand for links between structural and functional spatial features (Hillier, 2009); or rather, the issue deals with how space and society are related each other. Aiming at developing a *one city* theory, the approach of Space Syntax assumes urban space as the "*common ground for physical and societal cities*" (Hillier and Vaughan, 2007, p. 206).

Space within which human activities happen is investigated on the basis of "*spatial configuration"*, which can be defined as a set of "*relations between all various spaces of a system*" (Hillier and Vaughan, 2007, p.206). Spatial arrangement and agglomeration of buildings shape the layout of open spaces. The latter, in turn, define the "*urban grid structure"* (Hillier et al., 1993), or rather a network of interconnected open spaces. Therefore, configurational properties concern the way all spatial units are organised to shape the whole urban layout: each element within the urban environment contributes both to create and characterise city spatial pattern. According to the so-called "*natural movement theory*" (Hillier et al., 1993) (Fig. 1.1), which constitutes the central core of the configurational approach, grid configuration can generate and affect movement rates ("*natural movement*"). In other terms, the natural movement rate is defined as generated by the spatial network itself, independently of the presence of specific activities that could act as attractors. In fact, origins and destinations of movement within urban layouts are diffused all over the grid; the role played by each space of the grid is related to its location as part of the whole grid. The link between urban configuration and movement is not dual, the latter being not able to modify spatial locations. Although the theory assumes the spatial configuration as a primary cause of movement, movement rate can be amplified by attractors, which act as movement's multipliers. Movement and attractors can mutually affect each other.

Indeed, several attractors could determine high people densities, as well as locations of attractors can take advantage of high movement rates. Grid shapes movement rates, and also land uses pattern can be affected: localisation of human activities is chosen in order to take advantage of major movement flows (e.g.: shops or retails), or to prefer low movement rates zones (e.g.: residential areas). Furthermore, the location of some activities is defined independently by the grid structure (*"non configurational activities"*). These activities can generate movement flows. Even being not influenced by movement relative to other activities, and even not being related to configurational issues, *"non configurational activities*" characterise all grids and can also act as a movement attractor. In other terms, non configurational activities are independent of spatial properties of the grid, even being able to influence attractiveness of urban zones. Attractors, movement and configuration are the key-elements of the so-called "*movement economy process*" (Hillier et al., 1993).

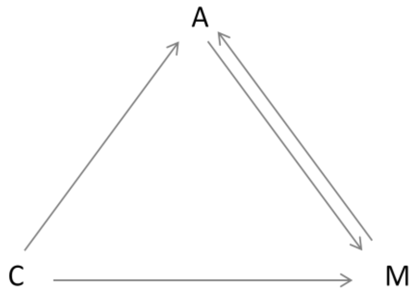

Figure 1.1: Representation of the main elements of the "movement economy process" ("*A*": Attractors; "*C*": Configuration; "*M*": Movement) (Hillier et al., 1993)

Social and cultural pattern can be included in spatial layouts; therefore, space can influence movement, generate people co-presence and possibilities of human interaction. This observation deals with the mutual influence between social phenomena and properties of spaces within which the said phenomena happen: in order to be carried out, different human activities need spaces with appropriate geometry. At the same time, certain spaces facilitate some types of activities: movement mainly happens in linear spaces (e.g.: streets), interactions are facilitated within convex areas, which allow people inside them to be reciprocally seen from each point located within these areas (e.g.: squares or public open spaces).

More complex spatial shapes ("*convex isovist*") can be obtained considering all the points visible from a given convex space (or rather, all potential people that can be visually reached from a certain convex area). Isovists stand for visual fields and they change depending on where the view point is located. This basic characterisation of space typologies explains the non-casual connection between form and function of space, highlighting that the spatial layout can influence spaces potentiality, or rather human activities that could be performed within a given space (Hillier, 2007; Hillier and Vaughan, 2007).

At a larger scale, linear movement from an origin to a destination ("*to-movement*") addresses the need of efficiently moving from a point to another one within the grid. It is related to long and mostly linear connections, mainly connecting the edge and the centre of a urban system, and intersecting each other with obtuse angles. A second type of movement regards spaces passed through going from all origins to all destinations within the study area ("*through-movement"*). This second type of movement essentially produces short lines, intersecting with quasi-right angles (Hiller, 1999). In other terms, the "*to-movement*" can be considered as referred to the selection of a destination point from an origin; the "*through-movement*" to the spaces to be passed through moving between two points of the grid.

Starting from the urban scale, up to building analysis, configurational theory of Space Syntax assumes that open spaces can be investigated through a network based approach. Spatial and functional features are evaluated through a set of centrality measures applying concepts of the graph theory. A broad academic debate has concerned the concept of "*centrality*", how the latter could be defined and properly measured (Freeman, 1978), in reference to several complex systems (e.g.: social, technologic, biologic systems). During last decades the concept has been applied also to urban systems. In general, centrality measures are based on the individuation of the shortest paths within a network, going from an origin to a destination. Therefore, centrality is generally evaluated assuming a system as a net, or rather a graph $G= (N;E)$ as a set of nodes N linked by a set of edges E. Analytical purposes and graph characteristics play a significant role in defining impedance values to evaluate minimum paths.

In the literature, three main centrality measures are defined. In more details, each elements of a given graph can be considered "central" respectively on the basis of: *i*) how many link it connects ("*degree centrality*"); *ii*) the strategic role it plays being included in several shortest paths between two other nodes of the network ("*betweenness centrality*"); *iii)* how close it is to other network nodes, in reference to the minimum length of shortest paths to other nodes ("*closeness centrality*"). Being related to network dimensions (meaning the number of nodes and edges of a graph), literature calculation methods of centrality measures define absolute and non-dimensional values to address the influence of system size on centrality values (Freeman, 1978; Hillier and Vaughan, 2007).

In the configurational approach, open spaces are represented as composed of convex spaces to define a "*convex map*" as "*the minimal set of convex spaces within the configuration*" (Turner et al., 2005, p. 427). Depending on specific operative technique, different basic elements can be assumed to analyse urban grid: "*lines*", as linear segments linking open spaces ("*Axial Analysis*", "*Angular Analysis*"); "*vertices*", as points located inside convex spaces ("*Visibility Graph Analysis*"); "*mark points*", as characteristic points or roadways ("*Mark Points Parameter Analysis*"). Although all these techniques lead to comparable outcomes, each of them is associated to a certain type of analysis (Cutini, 2010). Focusing on the axial analysis, that is usually applied at the urban scale, all spaces of a convex map are mutually linked by "*axial lines"*, defined as lines that "*join two intervisible vertices within the system*" (Turner et al, 2005, p. 429). All possible axial lines form an "*all line map*" (Turner et al., 2001). Since each axial line stands for a visual connection between two points, the "*axial map*" of an urban grid is the longest and fewest straight visual lines that pass through as to cover the whole grid (Hillier et al., 1993). The axial map can be also represented through an incidence matrix (Hillier et al., 1993) and reduced minimising the number of lines able to cover the whole urban grid, obtaining the so called "*fewest-line map*" (Turner et al., 2005). In order to apply network based measures, the axial map is converted into an "*axial graph*", respectively transforming each axial line into a node and intersections between axial lines in graph edges ("*dual approach*"). Since edges of the dual graph account for visual directions and nodes of a given graph stand for spatial connections among open spaces, dual graphs assume a topologic meaning, by definition.

Globally looking at urban systems, movement from an origin-line "*o*" to a destination-line "*d"* -within urban grid- implies to pass through some intermediate-lines (each line being a node of the relative dual graph). The latter are in a number not necessary proportional to the metric distance between "*o"* and "*d"*. Algorithmically, a "*metric distance*" can be measured from the centre of a segment to the centre of another segment of a given network. However, some works related to cognitive sciences showed that human movement is shaped not only by minimising the metric distance. In fact, visual, geometrical and topological properties can also affect the way people navigate the urban space (Hillier and Iida, 2005). Therefore, a "*topological distance*" and a "*geometric distance*" can be defined, respectively, the former as the number of directional changes, the latter as the angular changes that occur to complete a path (Hillier, 2009). According to the chosen distance, paths between points of the grid can be identified in terms of minimum metric length, fewest turns or least degree of angular changes. Aiming at pointing out shortest paths, operative techniques of Space Syntax assume as impedance the number of visual changes that occur moving from a point to another of the network (i.e. of the urban layout). The relative distance -in terms of intermediate-lines number- is called "*depth*": for each line, an "*average depth*" can be evaluated as the average number of lines to be passed through to reach all other lines of the system (Hillier, 2007). Differences among average depth values are strictly related to the whole system structure -which derives by how lines are connected each other- and are assumed to be one of the main drivers of movement. Lines with low depth value showed high movement rates, and vice versa. Derived topologic shortest paths allow to evaluate quantitative measures ("*configurational indexes"*) representative of grid's configurational properties, which actually are syntactic centrality measures. In reference to a certain line -that is, a given node of the relative dual graph- some configurational indexes can be evaluated as quantitative measure of syntactic properties (Hillier et al., 1993):

- "*connectivity index*", as a measure of degree centrality, it is defined as the number of lines directly connected to the given line. Degree measure C_D, as defined by Nieminen (1974), corresponds to the total number of adjacent nodes for a point P_i. C_D value can be obtained as the sum of all nodes directly connected to P_i:

$$C_D(P_i) = \sum_{i=1i}^{n} a(P_i, P_j)$$

being n the total number of nodes; $a(P_i, P_j) = 1$ if there is a line connecting P_i and P_j, otherwise, $a(P_i, P_j) = 0$ (Nieminen 1974; Freeman, 1978).

- "*control index*", as representative of the degree to which a line controls the access to and from its neighbors. Assuming a given space and its *m* neighbours, the said space gives to each relative neighbour *1/n* control. The sum of these control values for all immediate neighbours gives the total value of control index.
- "*choice index*", as a measure of betweenness centrality, it represents how often a lines belongs to the shortest path between each pair of line of a map (i.e. all origin and destinations of a system). According to Freeman (1978), betweenness measure C_B for a point P_i is obtained comparing the number of geodesics $g_{jk}(P_i)$ between P_j and P_k containing P_i ($i \neq k \neq k; j < k$) with the total number of geodesics g_{jk} linking P_j and P_k (Freeman, 1978; Hillier and Iida, 2005). Defining n the total number of nodes in a graph, $C_B(P_i)$ can be obtained as follows:

  $$C_B(P_i) = \sum_{j}^{n} \sum_{k}^{n} \frac{g_{jk}(P_i)}{g_{jk}}$$

- "*integration index*", as a measure of closeness centrality, defined as the "*shortest journey routes between each link [or space] and all of the others in the network defining `shortest' in terms of fewest changes in direction*" (Hillier, 1998, p. 36). According to Sabidussi (1966) closeness measure C_C of a point P_i can be obtained considering the inverse of the total number of edges in the geodesic $d(P_i, P_k)$ between the points P_i and P_k (Freeman, 1978, Sabidussi, 1966, Hillier and Iida, 2005):

  $$C_c(P_i) = \left(\sum_k d(P_i, P_k)\right)^{-1}$$

The most representative measure of movement is the *integration value,* due to its direct connection with depth value. This statement was widely validated evaluating the statistic correlation between movement densities, and integration values (Hillier et al., 1993; Hillier, 2007).

In Space Syntax theory, integration values represent a measure of to-movement accessibility, while choice values are referred to through-movement rates, as the ability of a certain line to belong to shortest paths among all grid points (Vaughan, 2007). The pattern of most integrated lines may not match to the set of lines with highest choice value, even possibly being coincident (Vaughan, 2007).

Configurational indexes can be evaluated both at the local scale, referring to a defined number of lines surrounding a given one, or at the local scale, considering the whole system. Pedestrian movement resulted to be suitably predicted by local integration value while, at wider scales of analysis, journeys reflect global integration values (Hillier, 2007). Moreover, as reported in the technical literature, integration pattern at city scale showed a generally valid structure, similar to a "*deformed wheel*" shape: well-integrated lines are generally located in a way to form a ring near the centre and link this ring to the edges (Hillier and Vaughan, 2007). This wheel represents highly integrated areas from a functional perspective, e.g. corresponding to the largest shops location. This type of spatial structure was found as a common element for settlements that apparently could appear significantly different one from each other. This communality is mainly due to the need of central parts to be linked to more peripheral zones in order to create a unique city-system (Vaughan, 2007). Based on configurational measures, city centre can be identified both at the functional level, as the area in which are mostly concentrated human activities, and at spatial level, depending on its position within the whole area (Hillier, 1999). This strong relationship between configurational indexes and movement rate -or rather, urban main functionalities- makes the syntactic approach adapt to many applications aimed at investigate use and perception of urban spaces. In the literature some statistical correlations between indexes are described to deeply investigate configurational properties of urban grids: "*intelligibility*", defined as the correlation between integration and connectivity (Hillier, 1989; Hillier, 2007); "*synergy*", which represents the correlation between global and local integration (Dalton, 2007). Both these two quantities allow to overall analyse the urban network, linking global and local syntactic properties. The first one is defined as *"the degree to which what we can see from the spaces that make up a system is a good guide to what we cannot see, that is the integration of each space in the system as a whole"*

(Hillier, 2007, p. 94). The second one examines the consistency of global and local centralities and their relationship.

Assuming integration index as a sort of spatial accessibility measure (meaning how a place is considered to be near to others), integration value resulted significantly related to several phenomena: pedestrian and vehicular flows (Hillier et al., 1993; Penn et al., 1998), human wayfinding, retails and shop location, crime vulnerability, atmospheric pollution (Croxford et al, 1996; Penn and Turner, 2003; Hillier and Iida, 2005; Emo et al. 2012; Fakhrurrazi and Van Nes, 2012). Shops, retails and movement resulted to be mostly concentrated along well-integrated lines (Hillier et al., 1993). This observation reflects the principle of the natural movement: space location within the grids determines integration pattern. Being not able to modify the grid structure, human activities are located so as to take advantage of most integrated areas. Based on the possibility provided by applying Space Syntax to investigate settlement's functionality starting from analysing relative spatial layout, in the technical literature there are many studies focused on examining the influence of urban layout and spatial structures on human behavior, social, economic and environmental phenomena.

Some applications of the configurational approach attempted to evaluate effects of spatial changes in structures, in respect to space use and perception. In Koch and Miranda Carranza (2013), Space Syntax was applied to assess resilience, referring to the architectural scale of analysis. In reference to wayfinding processes, spatial layouts of buildings were examined on the basis of their capacity to not determine limitations or stress for space users after some changes in the spatial internal structure. Two measures were introduced to evaluate variations of configurational properties. Spatial changes were operatively analysed by modeling "*blocks*" placed within buildings to represent interruptions or losses of connections between spaces. In this way, two spatial configurations were obtained for each building, corresponding to spatial layouts, respectively, before and after the changes. The relative two sets of integration values were examined on the basis of their statistical correlation ("*sameness*"), assumed representative of induced impacts, both on the overall spatial layout and focusing on their local effect. Further information were achieved comparing integration values before and after the changes ("*similarity*") (more specifically, comparing minimum, mean and maximum integration values before and after the considered spatial variations). Indexes were compared each other and in reference to mean values, as well as examining their distribution, to point out how similarly the building was used in spite of changes in its structure.

At the urban scale, in Gil and Steinbach (2008) a flood scenario for the city of London was analysed. In order to estimate impacts induced by the considered event, pre and post-event configurations were compared according to their geometrical and configurational features. Distribution and values of syntactic indexes (i.e. integration index and choice index) were evaluated before and after the perturbation, as a preliminary stage to estimate the relative statistical correlation between these indexes and relative differences. Both correlation and numerical differences were assumed as representative of impacts within the system.

In Cutini (2013a; 2013b) urban resilience were analysed, introducing resilience indicators. The latter, based on configurational indexes, were deduced from some characteristics indicated as to be significant for resilient urban systems. More in details, three measures of resilience were defined: *i*) the mean connectivity value, to represent the redundancy of connections within the grid; *ii*) the ratio between the highest choice value and the total number of possible paths within a grid, to evaluate whether a line belongs to a large number of paths; *iii*) the statistical correlation between local and global integration indexes values, to define the connection between local and global urban structure. A considerable number of connections, as potential alternative paths, along with an appropriate distribution of shortest paths making the latter not highly dependent on a certain line, and a good correlation between local and global properties was assumed as representative of a good degree of urban resilience. The described indicators were also implemented to some urban structures, particularly focusing on the application of the above mentioned indicators to evaluate urban resilience to seismic events, resulting to be able to properly describe variations of the analysed property.

Lastly, in Carpenter (2012) resilience of zones affected by Katrina hurricane was examined, attempting to relate configurational indexes to social and demographic characteristics of the analysed areas. Regression models were considered to analytically relate syntactic measures to demographic statistics (e.g.: population trends, as changes in population registered after the event, variations of number of businesses and social activities). A general correspondence was shown between urban centralities and aspects assumed to be descriptive of a resilient disaster recovery (e.g.: people returning to affected zones, presence of commercial activities after the event). However, some limitations of the models were pointed out, mainly related to a limited availability of data and low correlation values of some derived regression models.

2
Methodology

2.1 The application of the configurational theory to urban resilience to flood events

The concept of urban resilience to hazards reflects a progressive shift from a mainly preventive risk management, focused on structural measures to avoid major events, to a different perspective on risk management: an effective risk management can be achieved not just avoiding major events, but also being able to face consequences of calamities, efficiently establishing acceptable conditions after calamities occurrence. Resilience is actually considered a key issue in the transition towards a risk management focused on improving system performances, instead of being just aimed at limiting losses and damages (ARUP and Rockefeller Foundation, 2014). Acknowledging that the reduction of risk cannot completely stop or avoid the risk of natural hazards, resilience leads to consider risk, getting prepared to cope with it and efficiently recover from undesired conditions.

In general, physical and structural effects of disasters or calamitous events in urban areas can compromise infrastructures and buildings, determining loss of human life in the most serious cases. Each urban system is a complex mix of physical, social, economic and environmental elements. As a consequence, disaster-related effects in urban areas have large implications and their impacts require to be examined from different viewpoints through appropriate analysis approaches. As regards the spatial aspects, major events can modify the pattern of spatial accessibility of settlements, consequently compromising the general use of urban space. This is clearly the case of urban floods, whether they are related to overflow in rivers and natural channels, or failures of urban drainage systems: flooded areas constitute physical and structural perturbations of affected urban grids. Structural approaches to analyse flood risk are usually referred to buildings and infrastructures potentially affected or damaged by a flood event. However, at a wider scale, urban layouts of settlements at risk to be flooded can also influence consequences of floods. In more details, extents and location of flooded areas within the urban systems create non-accessible zones, whose dimensions vary depending on territorial morphology and river basin hydraulic features. Flooded areas can "break" the urban grid, which -due to the event- can become smaller or divided into different parts constituting urban subsystems. As a consequence, after the event urban spatial layout changes and spatial accessibility can result modified too. Movement flows and human presence result also compromised or changed. Floods represent a spatial perturbation for the whole affected urban system. Therefore, urban structures of settlements crossed by rivers and exposed to flood risk become elements to be investigated to evaluate spatial effects of flood events. Urban structure of settlements at risk constitutes itself a further element to consider aiming at assessing disaster risk. Moreover, modifying accessibility of urban space, spatial analysis of flood effects allows to evaluate how the event affects or modifies settlements' spatial properties. Considering the latter as intrinsically linked to human-related phenomena and activities, the configurational theory results appropriate to evaluate structural changes of the urban layout with reference to how they impact use and human perception of urban space.

According to the configurational theory of Space Syntax (Hillier and Hanson, 1984, Hillier, 2007), the spatial layout is strictly linked to human activities and urban phenomena. As it can be deduced from the basic assumptions of the theory, Space Syntax allows to analyse urban settlements at the urban scale, assuming their spatial layout as composed by a set of interconnected spaces creating a network. ach element of that network -that is, each space within a given urban layout- contributes to determine the configurational properties of the whole urban system. Spatial connections make each one of the spatial elements able to affect the properties of the whole grid, reflecting the key concept of "*urban configuration*". Therefore, adopting this approach significantly contributes to achieve a proper assessment of flood effects, allowing to assess flood resilience considering the connection between spatial and functional urban properties. The possibility the approach gives to investigate use and role of urban space through configurational indexes, which basically constitute a set of quantitative values, represents a valid element aiming at individuating a quantitative analysis of urban resilience. Being the configurational properties based on topologic measures of centrality related to human perception of urban spaces, Space Syntax indexes allow to examine urban layouts based on quantitative values. A configurationally-based methodology to study urban resilience permits to assess this property taking in consideration event physical effects on the way people navigate and experience urban space, as well as flood-induced changes of urban dynamics. Along with enabling to introduce quantitative measures in characterising urban resilience, this potentiality of the syntactic method actually constitutes a significant element, permitting to include in the resilience assessment a set of cognitive and people-related flood effects, which are usually hard to be directly and synthetically measurable.

As previously described, some studies (Koch and Miranda Carranza, 2013; Gil and Steinbach, 2008; Cutini, 2013a; Cutini, 2013b; Carpenter, 2012) attempted to individuate suitable ways to describe resilience of spatial structures analysing values and distributions of configurational indexes. Although considering different scales and purposes of analysis, a common element among these approaches is the comparison between different configurations, the latter defined so as to respectively model conditions of spatial layouts before and after a considered perturbation. This comparative analysis appears to be valid also with respect to perturbations induced by flood events in urban areas: pre and post-flood event configurations can be deduced on the basis of actual urban layouts and modeled relative possible floodplains extents. Despite its conceptual validity, the said comparison appears not to be operatively achievable in reference to floods through direct measures, such as differences or statistical correlation between pre and post event syntactic measures, as considered in the relevant literature. From an analytical point of view, comparison methods adopted so far need an exact correspondence between confronted datasets, in terms of data dimensions (i.e. a same number of configurational measures relative to the two compared configurations). This circumstance mainly depends on how the two configurations (i.e. pre and post perturbation) are defined or, more specifically, on the method adopted to define the lines constituting the spatial network the indexes are referred to. In case networks are determined as a set of lines representative of visual connections between all spaces of a given grid (as required by main techniques of Space Syntax), number, position and dimension of lines vary for different configurations (namely, pre and post event configurations). In fact, presence of flooded areas can determine configurations considerably different from the correspondent actual urban status. Differences can be related to variations in grid dimensions, layout and structure. This observation highlights that, as regards flood-related assessments, appropriate procedures are required to properly evaluate resilience on the basis of flood-induced changes of urban network.

A specific focus is needed to examine the validity of resilience indicators described in Cutini (2013a; 2013b), to assess whether they can suitably describe resilience to flood risk. As previously mentioned, the said resilience measures were implemented to analyse resilience both referring to schematic spatial structures (e.g.: maze-like or star-shaped spatial structures) and urban configurations representative of real urban structures. Among all these applications, the case of perturbation induced by a seismic event was also considered. The latter may appear similar to floods: both events determine non-accessible areas and distinct configurations are deduced, which basically are to be compared. The described indicators represent global measures, not affected by dimension and structure of the specific grid they are referred to. Moreover, according to their meaning, they account for valuable characteristics of urban systems, useful both considering seismic or possible flood events. Although all these aspects corroborate the validity of the said measures to estimate resilience to floods, their application to flood events did not provide a consistent evaluation of urban resilience (Esposito and Di Pinto, 2015)[1]. This shows that further considerations are needed to assess resilience with specific reference to flood-induced perturbations at the urban scale. Non-validity of the said global resilience measures suggests that local features along with other urban characteristics could contribute to investigate this urban property, leading to articulate a more comprehensive methodology.

In fact, independently of the typology of urban flood, pattern of open public spaces changes after the event. In a broad view, flooded areas can affect the whole urban configuration, which is related to movement rates and human activities or rather, to how people navigate urban environment. Spatial functions and distribution of urban centralities, the latter being represented by highest values of main configurational indexes, can vary too.

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[1] A further application of the said resilience indicators was carried out in the context of this work, examining the river-city systems described in Chap. 3, Par. 3.1. Similar results were obtained, showing that indicators described in Cutini (2013a; 2013b) did not provide a coherent definition of resilience to flood events.

2.2 A methodology to understand urban resilience to flood risk

The multiple meanings the concept of resilience can assume determine the necessity of comprehensively define and estimate this property. Although acknowledging that an all-encompassing definition of resilience is not achievable, an integrated approach can help in addressing the issue of properly assess urban resilience, leading to well-developed flood management strategies.

An approach can be derived basically considering two aspects of urban resilience. Firstly, various urban elements and characteristics concur to develop the capacity of the whole urban system of being resilient to floods and, in general, to disasters. Secondly, the concept of resilience itself is closely related to other concepts (e.g.: resistance, vulnerability, recovery ability), all representative of the ability to deal with calamities and relative effects. Therefore, complexity both of the concept itself, and of the system to which resilience is applied, can be considered to individuate an appropriate definition of the term. The preliminary definition of resilience is assumed as necessary to set the conceptual basis to develop an assessment methodology. Based on the several ways through which urban resilience can be characterised, some generally valid key-points can be highlighted. Although there are specific different meanings, being resilient intrinsically needs an occurred or a potential change, as a shock, a stress or a crisis, to which get adapted in order to reach a (new) acceptable status. Moreover, the concept can be analysed through a system-based approach, pointing out an internal and an external dimensions. Internally, each system can be represented as made up of different components. In order to get a resilient functioning, the way all system components can co-ordinately work, replacing each other if necessary, plays a decisive role. Adopting a wider analysis scale, each system results included in a network made up by all links and connections with other distinct systems. Efficient interconnections with the outside permit to improve the overall system performance, especially during and after critic circumstances. These considerations result especially valid in reference to urban settlements: cities can be assumed as "*systems of systems*" (ARUP and Rockefeller Foundation, 2014), being then valid a system analysis approach to urban systems. As a result, urban resilience assumes different dimensions and characteristics: physical, ecological, social, economic, institutional, infrastructural, community and individual competence, local understanding of risk (Cutter et al., 2008; Norris et al., 2008). On this basis, whatever the specific objectives of analysis, defining urban resilience firstly needs to set a system of analysis subject to variations in its state variables or structure, once a certain change or perturbation has occurred. Aiming at examining fluvial floods in urban areas, "*river-cities*" are assumed as systems to be studied. Rather than just considering their physical aspects, as assets and infrastructures located nearby a watercourse, "*river-cities*" are conceived as a set of structural elements and social phenomena that take place within the urban environment.

Considering flood occurrence and all the concepts differently related to resilience, a conceptual definition of urban resilience to floods can be deduced (Fig. 2.1). The issues underlying the need of develop resilient urban systems are hazards in urban areas, as well as the circumstances that determine or increase the probability of occurrence of calamities. In particular, river floods occur when an high water discharge level exceeds the maximum water transport capacity of river channels. If dimensions and structural features of a river allow to convey a major discharge, the system can be considered resistant: it results able to "resist" not being subject to stress or crisis and, more importantly, without causing floods (De Bruijin, 2004). Therefore, resistance of river system constitutes the basic characteristic to be considered in determining resilience of river-cities. Flood defence systems, barriers or alleviation schemes allow to improve this type of resistance, contributing to hazard reduction in terms of lower failure probability, or rather flood occurrence. In case resistance level is exceeded, water overflows river banks determining a river flood; flood plain and zones next to the river constitute areas directly affected by flooding. It follows that the failure of river system ability to convey a certain discharge can determine calamitous conditions for flooded areas and, more generally, for the nearby located urban system.

Depending on flood magnitude and extent of flooded zones, flooding can potentially affect or damage people and assets located within flooded areas, which constitute elements exposed to the risk and potentially vulnerable. In fact, floods can be schematised as "external" element in respect of urban structures. However, considering floods ability to modify urban spatial layout, syntactic functions and, in turn, urban phenomena, they can induce internal changes in the urban behavior. If water overflow does not involve people, human activities or structures, no impacts are determined and, consequently, occurred flood represents just a major event. However, in reference to urban rivers this second case is quite unusual: although flood can affect small areas or, also, affected urban elements can show an adequate level of resistance, it is unlike that no (structural or non-structural) impacts are registered. Analysis of elements located within areas at risk to be flooded provides an assessment of vulnerability (and exposure). Urban planning and appropriate use of natural resource, as well as design and engineering solutions, can lead to reduce assets and people at risk, the latter constituting vulnerable (and exposed) elements. Once vulnerable elements are affected by the event, the significance of flood impacts can be deduced analysing impacted settlements, as representative of post-event system and its relative features. Impacts and changes determined by floods induce a new urban configuration. In this post-event phase, the system ability to adapt itself to the modified conditions is tested, as well as the system capability to recover in a way to ensure its basic functions. Time required to recover from an undesirable condition can be considered in defining global resilience (Hashimoto, 1982), but the concept of urban resilience to flood events cannot be related just to the recovery speed of urban system after a major flood. Once the event has occurred and the urban system has implemented its adaptive capacity (compatibly with its degree of adaptability), a new status is achieved. Comparison between the latter and the pre-event urban functioning can inform about flood-induced impacts and ability of the urban system to adaptively recover by flood consequences. This knowledge could suggest appropriate post-event measures, to be implemented after flood occurrence: in this way, a further system status is obtained, which will -in the future- cope with possible hazardous circumstances.

It follows that urban resilience is defined as a dynamic process, resistance, vulnerability and adaptation being its main elements. In the specific case of river-cities, the said process (Fig. 2.1) regards both river features and urban characteristics.

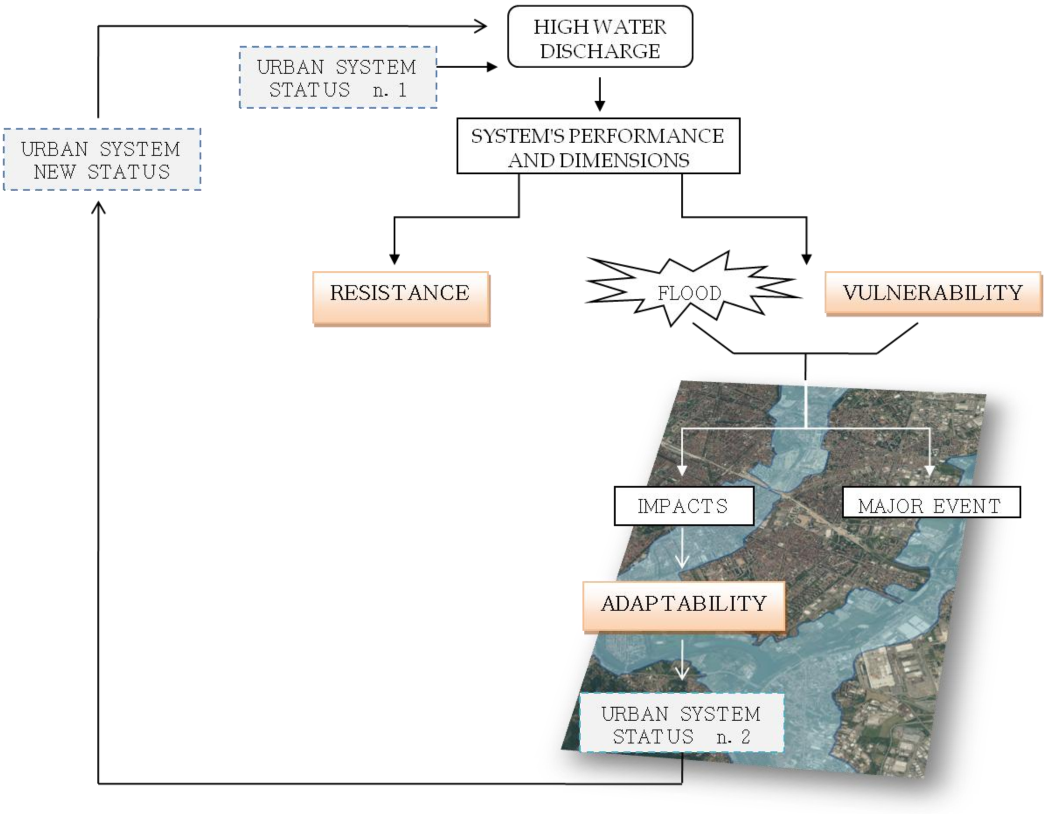

Figure 2.1: The concept of resilience represented as a cyclic process

Elements at risk, as well as the degree to which they might be affected by a major event, induce potential threats for the urban environment (that is the risk, indeed). The need to cope with hazards and to recover from them, highlights the necessity to be prepared to face potential flood-induced perturbations. In fact, the resilience-process results articulated throughout all flood phases (i.e.: before, during and after the event) and continuously evolving over time thanks to feedbacks between event phases: risk preparedness, reduction, response and adaptation to consequences are all able to determine and influence resilience ability. This observation permits to notice that resilience needs vulnerable elements to arise; however, it does not need event occurrence to be "built" and structured. Considering that floods can affect wider areas than just the directly flooded ones, up to impact the whole urban structure, the spatial dimension of urban resilience goes beyond the extent of areas directly at risk, involving larger parts of the urban system. Therefore, resilience assessment requires a suitably defined study area.

On the basis of this conceptual definition, some considerations can be outlined as follows:

- Spaces in urban environment constitute places where people move and interact. Natural disasters -and floods, among them- determine limitations in the pattern and extent of accessible areas. How changed accessibility due to floods can affect human dynamics? Or rather, structurally altering urban layout, how can flood events modify and impact human spatial perception?
- Depending on urban structure and features of flooded settlements, different are the spatial extent of flooded areas. The latter are also differently located within affected settlements, according to both watercourses and territory morphology. On varying of these elements and urban morphology, physical vulnerability and magnitude of impacts change. How these typologies of vulnerability and spatial impacts of urban floods can be evaluated?
- As far as impacts on urban structure change, different is the degree of adaptability that the urban system needs in order to withstand flood-induced perturbations and reach a new acceptable equilibrium after the event has occurred. It follows that risk analysis, vulnerability and impacts assessments can be assumed to understand urban resilience. Considering possible impacts as induced changes within the spatial structure of settlements located in proximity of rivers, can these factors be considered in an adaptive-post-event perspective, leading to understand urban resilience?
- Adaptability is a key element in sensitive urban environment, such as settlements located along or nearby rivers. Although these urban areas can benefit from water resources, rivers clearly also represent a potential of risk. Can a quantitative approach allow an objectively comparison between different urban structures, in order to estimate trends and variations in risk-related impacts and urban resilience, as concern the spatial aspects?
- A structured and suitable assessment of hazards, followed by the identification of main urban vulnerability elements and risk drivers, constitutes a basic focus in dealing with potential disasters and a valid support to disaster risk management. How knowledge of space-focused urban resilience can help in defining efficient and effective risk management measures?

Based on these considerations, a multi-stage methodology is proposed to assess urban resilience to floods adopting a spatial perspective of analysis. Different stages are defined to evaluate urban resilience focusing on main factors of resilience as process:

- analysis of the urban structure of settlements potentially at risk is assumed as the preliminary stage of the procedure, as the basic study to characterise the initial status of the whole analysis system;
- assuming a certain flood event, or rather considering the case of an exceeded river resistance level, a focus on areas at risk is considered to provide a framework of elements exposed to risk, as part of a vulnerability assessment.
- the subsequent analysis of a potential post-event configuration is defined to investigate the modified urban layout and outline how the urban system organises itself to respond to occurred impacts. Considering the status after a flood event, the methodology allows to examine "post-event" conditions deduced taking into account presence of flooded areas. In reference to flood occurrence, this status corresponds to the emergency phase (which, indeed, occurs *after* the flood). Although being a transition period of time, disaster emergency phase plays a fundamental role in reference to urban resilience and flood impacts: in the short-term, emergency characteristics can affect the ability to generally cope with the event; in the long-term, it can influence the following post-emergency phases (e.g.: reconstruction phase). Changes in urban dynamics are a measure of how the event impacts the system: adopting a dynamic standpoint, they inform about the ability of the system to adapt its internal and functional features as a response to the occurred changes in the pattern of accessible spaces.
- a further stage of analysis referred to the post-event phase. The common understanding of these information as impacts can be revised interpreting them as changes, or rather as effects of the adaptive capacity of the river-city system, contributing to understand resilience ability of the affected system.

Combining the information deduced from each one of these stage of analysis, an overall understanding of the degree of urban resilience is achieved. Each part of the procedure can be suitably examined in regard of its relative contribution to defining resilience.

2.2.1 Applying Space Syntax to analyse urban structures of river-cities

The first step of the methodology is defined examining urban structure of river-cities. Rivers have always been considered a resource for human activities, over time affecting the development of nearby areas. Rivers morphology, hydraulic and ecological characteristics can affect the attitude of areas located on river banks to be transformed into built environment. Settlements arisen along watercourses constitute a representative case of the mutual continuous influence between natural and urban environment. Rivers inclusion in the urban environment can be seen as a balance between environmental and human-related needs. Specific sector-based approaches of study allow to singularly analyse, on one side, the river environment and, on the other side, the nearby located urban structures. Assuming river ecosystem and urban environment as two different layers, different quantities can be defined as representative, respectively, of the river dimensions (e.g.: length of the main branch, average width, river basin area, hydraulic regime) and the urban features (number of inhabitants, average inhabitants density, main land uses) (Silva et al, 2006). However, the said layers are inextricably linked each other: localisation, morphology and urban structure of river-cities are clearly related to urban environment; at the same time, they have been also influenced by hydro-morphological and environmental features of rivers they are crossed by, the latter being aspects related to the natural environment. Globally looking at both river and city systems, information can be reached as regards their mutual influence and how they have been mutually shaping each other. Focusing on spatial features, this equilibrium can be detected analysing the intersecting points between the two said layers: location of urbanised areas, land uses pattern with respect to the river course, position of the bridges and riverfront features are all indicators of the influence of the river on the urban morphology. In particular, number and location of river crossings can be seen as representative of the capacity of the urban system to "jump over" the river, being able to include the watercourse within the urban system. Bridges assume a strategic role, both in reference to their structural connecting function between the banks, and due to their ability of creating people visual and physical contact with the river environment. Indeed, promoting human activities and movement along and across the rivers, bridges can increase the symbolic value of the river (Manning, 1997).

Therefore, urban layout and morphology of cities crossed by rivers contribute to achieve a deep knowledge of urban-river environments. Further considerations about river-city structure can be achieved analysing relative configurational properties. Beside the availability of infrastructures, able to physically link two river banks, other factors determine spatial and functional inclusion of rivers within nearby located urban areas. In fact, the role that river crossings play, as part of a correspondent urban configuration, does not exclusively coincide with the basic ability to physically connect areas located on different sides of a watercourse. The spatial distribution of configurational indexes within a urban grid, along with the location of main syntactic centralities in respect of the river course, reveals if the river has been considered as an attractor over time, or as a separating element during the process of urban development. As a result, two distinct urban layouts can be schematically deduced: a structure gravitating towards the watercourse, or a structure organised along the river as made up by distinct areas working as isolated micro-systems in relation to the river.

A deep understanding of urban characteristics, both relative to spatial pattern and relative human perception, is a basic part of resilience assessment, allowing to properly characterise the actual urban configuration ("*Scenario 0*") as the status-quo potentially at risk to be modified by flood events.

In order to syntactically assess river-city relationship, configurational measures are evaluated at this stage through Space Syntax analyses. Syntactic indexes referred to axial maps are mainly evaluated on the basis of depth measure. However, while navigating the urban environment, human perception of visual changes varies also according to the turning angle size of directional changes (Montello, 1991; Dalton, 2003). As a consequence, selection of movement routes results affected not only by the number of changes moving within the grid, but also by the angular entity of that changes. Based on this observation, the so-called Angular Segment Analysis technique ("*ASA*") (Turner, 2000; Turner, 2001b) results to be particularly valid to analyse spatial configurations at the urban scale. More in details, *ASA* allows to take into account the incidence of intersecting angles between axial lines in defining paths of movement. Given that minimum angular paths routes correspond to minimum directional changes, angular measures are based on the concept of "*angular mean depth*" L_a^α, which is the ratio between the sum of all the shortest angular paths l_{ab} (from every axial line a to every other axial line *b* of the set *V(L)* of all axial lines) and the sum of all intersection angles between all lines of the system (Turner, 2001b):

$$L_a^{\alpha} = \frac{\sum_{b \in V(L)} l_{ab}}{\sum_{e \in E(L)} w_e}$$

Weighted angular distances are defined assuming intersection angles as a weight: the more an intersecting angle tends to be right, the higher will be its weight. In order to suitably define angular changes, lines of axial maps are segmented, or rather split into two part in correspondence of intersecting points (Turner, 2001b). Therefore, axial maps become "*angular segment map*" and *ASA* indexes consider both geometric and topological factors that affect movement patterns. Constituting an advanced measure of the standard syntactic indexes, angular indexes showed an improved correlation with movement rates than axial syntactic indexes. This statistical correlation enforces the ability of *ASA* to reproduce movement patterns (Hillier and Iida, 2005; Turner, 2000; Turner, 2001b). The higher statistical correlation between angular measures and movement flows -if compared to the same correlation referred to usual indexes- appeared to be not related to network features. It followed the algorithmic ability of *ASA* techniques to better reproduce human behavior and spatial perception (Hillier and Iida, 2005). Based on this observations, *ASA* technique constitutes an appropriate method to investigate urban configuration, providing a correspondent set of syntactic angular measures. Spatial models can be defined selecting all open and accessible spaces within relative urban settlement, both regarding to pedestrian and vehicular movements. Therefore, *ASA* outcomes can be considered valid in reference to both these type of movements. Angular analysis can be performed using the Depthmap software platform (Turner, 2001a; Varoudis, 2012). In order to deeply analyse grid features, configurational indexes can be evaluated at global and local scales, setting different metric radii to calculate syntactic measures. Two specific values of radii assume particular relevance: *i*) R = 400m can be suitably considered to reproduce pedestrian flows, at the local scale; *ii*) R = n (being *n* the total number of lines of each segment map) corresponds to the whole system and it can be referred to global measures relative to longer movements, such as vehicular flows. On the basis of *ASA* indexes values, main configurational centralities can be pointed out highlighting the set of spaces with highest configurational indexes.

A threshold value has to be set to define which segments exactly create the syntactic cores. As suggested in the technical literature (Hillier et al., 1993), a percentage equal to 10% of lines with highest values of a certain configurational index can be assumed to point out relative "cores".

Numeric values and spatial distribution of indexes within a given urban grid allow to investigate the main structure of the analysed city and further detailed considering measures of statistical correlations between indexes (e.g.: intelligibility, synergy), as described in the literature (Hillier, 1989; Hillier, 2007; Dalton, 2007).

Being the syntactic features and their spatial distribution representative of how urban spatial pattern shapes human activities, configurational properties analysed at this stage of the procedure provide a significant knowledge to properly assess the role played by watercourses in reference to urban phenomena. Configurational features deduced applying Space Syntax *ASA* technique can be examined in relation to watercourses location. This approach constitutes a specific application of the configurational theory to investigate river-cities structures based on spatial and functional connections between rivers and surrounding urbanised areas. Number of river crossings, relative location and role in reference to movement economy can be specifically assumed as indicators of the degree of connections between river banks, representing a synthetic measure of the described river-cities relationship.

2.2.2 Urban structure and vulnerability assessment

Magnitude of flood events is mainly linked to flood-induced effects and impacts, which, in turn, are related to all the elements affected by a certain flood event. On this basis, analysis of areas at risk is assumed as a second stage of the procedure. Importance of an accurate characterisation of elements at risk basically consists in the derived possibility to assess components of vulnerability. The latter contribute to outline possible event effects within the whole settlement. Urban vulnerability is a multi-faceted concept, involving considerations related to structural and non-structural elements that can be impacted by a certain event: structural elements, networks of infrastructures and technologies, economy, natural environment, social structure, human lives, people safety and wellbeing. Whatever the specific aspect a study is focused on, vulnerability is strictly related to that parts of a system which could be affected by a certain perturbation, in a direct or indirect way.

Focusing on flood-prone urban areas, elements directly exposed to risk result to be located within potentially floodable zones. Starting from characterising areas at risk ("*AAR*") to be flooded, elements within these areas are assumed as potential weaknesses of the urban system. Considering properties or urban grid of river-city systems, a physical vulnerability is investigated to point out and describe the part of urban network at risk to be flooded. Subsequently evaluating other urban characteristics, a multi-step procedure is obtained to investigate physical vulnerability of the urban grid.

Aiming at analysing elements at risk, it is indispensable to point out *AAR* to define the specific system of study ("*STEP 0"*). Given that serious damages and losses are more likely to happen next to the river, or within the flooded area, flood-prone areas can be assumed as *AAR*. Extent of *AAR* can be deduced on the basis of hydraulic modeling of hydrological processes, water distribution and value of flood discharge, fluid dynamics and evaluation of river cross sections and river basin features. These aspects are related to severity and characteristics of flood events as well as morphology of territory. Magnitude of floods is usually referred to the return period *T* of the calamitous event; on varying of *T*, distinct floods can be modeled varying, in turn, correspondent areas at risk to be flooded. In order to operatively define extents of area at risk ("*STEP 0*"), spaces at risk to be flooded can be deduced from relevant plans and documents. Specific data and maps elaborated by relative River Basin Authorities can be considered to individuate extent of flood-prone areas for given flood return period. The EU Water Framework Directive (European Commission, "Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy", or WFD, 2000) requires that each Member State defines a river basin management plan for each river basin district within relative State territory. Furthermore, the EU 2007/60 (European Commission, "Directive 2007/60 of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk", 2007) requires Member States to assess flood risk mapping flood extent, in order to point out elements at risk and define suitable risk reduction measures.

Plans and documents drawn up in accordance with all these regulatory measures and legislation provide information that allows to define and geographically locate flood prone areas.

Focusing on *AAR*, a correspondent part of the grid can be derived. Syntactic features of spaces at risk can be examined to investigate network vulnerability ("*STEP 1*"). The whole pattern of syntactic values within a grid contributes to set and identify urban features and city behavior. Integration and choice indexes can be considered representative of the two main movements within the grid (or rather, the so-called "*to-movement*" and "*through-movement*") (Hillier, 1999). Therefore, global (R= n) and local (R= 400m) integration indexes, along with global (R= n) choice index (and relative cores) can be considered to investigate main configurational features. Values of *ASA* syntactic indexes can be sorted by their values to point out relative highest values, which basically represent spaces with strategic role in respect of urban dynamics. This classification can be also graphically reported obtaining a sort of syntactic map, as a thematic representation of the urban network able to highlight the spatial distribution of indexes within the grid. More specifically, high values of indexes correspond to parts of the system which configurationally play a fundamental role in respect of urban dynamics. This point can be clarified looking at the configurational indexes and their meaning: well-integrated zones (or rather, spaces that contain segments with high integration index value) constitute areas likely to become destinations for movement paths, meaning high density of people as well as human activities; high values of choice index correspond to parts of the urban network that represent the main connection paths between different points of the grid, or rather spaces related to considerable crossing flow movement rates. Integration and choice indexes can be assumed to investigate urban dynamics; spaces with high value of these indexes (the so-called "*core*") and, at the same time, located within the potentially flooded areas (that is *AAR*) configurationally constitute key-elements at risk. The more likely are the cores to be located within flood-prone areas, the higher will be flood effects on city behavior. Depending on the specific syntactic index and relative core at risk, different will be the effects on the whole pattern of movement and urban phenomena, according to the specific connection between each index and the whole movement economy process.

At this step of the procedure, a visual analysis of main syntactic elements exposed at risk can be achieved overlapping syntactic cores and flood-prone areas. More detailed considerations can be obtained examining numerical values of each configurational index. Based on the outcomes of syntactic analysis, each line of a given spatial network is associated to a set of configurational measures, meaning all available indexes. Therefore, each configuration corresponds to a set of quantitative variables, or rather to a relative dataset of configurational measures. Indexes numerical distribution can be deeply examined on the basis of values frequency distribution, which analytically is a summary of data occurrence in different ranges of values. Frequency distribution of examined indexes (i.e. global integration (R=n), local integration (R=400m) and global choice indexes (R=n)[2]) can be useful to further analyse syntactic properties on the basis of indexes numerical distribution. Frequency of values (processed datasets, in the described context of analysis, correspond to a set of values as measures of each index for all segments of a syntactic network) can be obtained organising each dataset in reference to a certain number of intervals of values. Dividing the whole range of values (or rather, all values of a given index), in equal and non-overlapping intervals, frequency can be obtained as the number of occurrences of values within each interval. Occurrences of values in each interval allow to plot a frequency distribution curve. The actual configuration of a urban system ("*Scenario 0*") and the part of the same network located within the area at risk correspond to two different frequency distributions: the former is representative of the whole grid, the latter is relative to spaces at risk to be flooded. For each syntactic measure, two distinct frequency distribution curves can be obtained, respectively, in reference to the whole urban layout -in its pre-event configuration ("*Scenario 0*")- and specifically focusing on the set of lines which result located within *AAR*. The latter can be assumed as potentially affected by the event ("*flooded area*") according to the adopted scenario analysis approach. A first overview of how the system is vulnerable to the event can be achieved comparing these two trends based on frequency curves: the more similar are the areas under the two said frequency curves, the wider will be the part of the network exposed to flood risk.

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[2] As largely assumed in several applications of Space Syntax reported in the literature, considering the logarithmic values of choice index (and, more specifically, Log(Global choice + 1) allows to better investigate choice index, permitting to highlight the range of highest choice values.

Ratio between the area under the frequency distribution curve relative to floodable zones ("A_f") and the area under the frequency distribution curve representative of the whole grid ("$A_{tot.}$") can be defined as a "*susceptibility indicator*" ("I_s"), being a measure of how the grid is susceptible to be affected by a flood event:

$$I_s = {}^{A_f}\!/_{A_{tot.}}$$

Aiming at providing a meaningful measure, frequency distributions of values and I_s are evaluated on the basis of segments length (segments, respectively, of the whole system or included in the floodable area): accounting for the network extension, indeed, length of segments results to be more significant than the segments number. I_s can assume values between 0 and 1, increasing the level of syntactic vulnerability as I_s value becomes higher. Although examining the whole range of a certain configurational index provides useful considerations, a focus on the highest indexes values allows to point out to what extent the syntactic cores of the system will be affected by the event. Therefore, A_f and $A_{tot.}$ values can be specifically compared in reference to segments with high syntactic values (i.e. segments of each core). Depending on each configurational index, as well as on the threshold value according to which the core is defined, different values of I_s can be obtained. The set of lines with 10% of highest values of each considered index can be selected as a core, to specify I_s values in reference to each syntactic cores ("$I_{s,int(R=\ n)10\%}$"; "$I_{s,int(R=\ 400m)10\%}$"; "$I_{s,choice(R=\ n)10\%}$"). The wider range of 30% of highest values can be also considered to complete this specific part. Further measures can be obtained ("$I_{s,int(R=\ n)30\%}$"; "$I_{s,int(R=\ 400m)30\%}$"; "$I_{s,choice(R=\ n)30\%}$") completing the quantitative estimation of network at risk, with specific reference to the most strategic part of the grid according to movement economy. This detailed analysis is particularly significant given that severe impacts are more likely to derive from a large core at risk: highly contributing to increase the total configurational vulnerability, cores at risk deserve a special attention as they constitute a relevant indication of how the system would be affected in its main parts.

On the basis of these outcomes, a further step of analysis can be defined to investigate how areas at risk are related to the whole system (or rather, flooded and non-flooded zones constituting the study area in its actual configuration).

Relating syntactic features to other urban aspects, a broad vulnerability assessment can be achieved ("*STEP 2*").

Although in different ways, accordingly to urban structure and flood characteristics, consequences of a major event affect the whole urban system, not just flooded parts. Therefore, in the view of a detailed assessment of urban vulnerability, the procedure integrates different dimensions which jointly contribute to a comprehensive approach:

- the definition of flood-prone areas provides the main area at risk, based on *hydraulic and morphological characteristics*;
- starting from urban layout, c*onfigurational features* allow to analyse the use of space and the influence of spatial pattern on human activities. These aspects can be quantitatively and synthetically represented through the spatial distribution and values of syntactic indexes.
- land uses pattern defines the *urban morphology* which, in case of settlements next to rivers, is linked to the presence of watercourses and it can contribute to describe flood consequences, in terms of elements at risk and potential damages.

Including all these urban features in a multi-layer analysis approach, all the described aspects can be considered to point out main characteristics and elements of urban vulnerability. The highest contribute to urban vulnerability can be identified referring to the case of a syntactic core at risk (or rather, a core located within *AAR*) and, at the same time, located within urbanised areas. Assuming integration and choice indexes as representative of syntactic properties, analyses at this stage can be focused on global integration index, global choice index and local integration index. These three measures, indeed, provide a suitable overview of main movement flows, exploring both global and local dynamics.

Network at risk can be firstly described as the percentage of segments at risk, or rather segments located within *AAR*. This value can be obtained as the ratio between the total length of segments at risk and the total length of the whole network.

Segments constituting each considered syntactic core (global (R= n) integration core; local (R= 400m) integration core, global (R= n) choice core) and -at the same time-located within area at risk, constitute the percentage of core at risk. This value corresponds to the ratio between the total length of segments within a core at risk and the total length of the whole network. Cores at risk can be further classified according to land use of the area they belong to. Length of segments of cores at risk for each land use area can be divided by the total length of the whole network, obtaining percentages of core at risk for each land use. According to all steps of this scheme, each percentage represents a specification of the relative previous one. Relative measures of core at risk can be also evaluated, comparing the length of segments of each core within *AAR* and the total length of all segments of the same core. Similarly, a relative percentage of core at risk in reference to each land use can be obtained, as the ratio between the length of core segments located within a certain land use area and the total length of all segments of the core. A special attention is needed for continuous or discontinuous urban fabric at risk[3]. These land uses represent sensitive parts in reference to urban vulnerability, accounting for highly populated hazard-prone areas, or rather significant concentration of human activities.

A "*network-based vulnerability*" ("V_{ntw}") can be introduced and defined as the sum of the total percentage length of all cores at risk (i.e.: global integration core, global choice core and local integration core within *AAR*) with respect to the total length of the segment map ("$L_{TOT.}$"):

$$\boldsymbol{V_{ntw,1} = \frac{\sum_i L_i}{L_{TOT.}} \quad (i \in Int.Core_{R=n})}$$

$$\boldsymbol{V_{ntw,2} = \frac{\sum_j L_j}{L_{TOT.}} \quad (j \in Int.Core_{R=400m})}$$

$$V_{ntw,3} = \frac{\sum_k L_k}{L_{TOT.}} \quad (k \in Choice\ Core_{R=n})$$

$$V_{ntw} = V_{ntw,1} + V_{ntw,2} + V_{ntw,3}$$

These percentage values are -also in this case- referred to the length of segments, which results to be representative of network extents. Being a percentage, V_{ntw} value constitutes a quantitative and objective measure of grid vulnerability.

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[3] According to CORINE -Co-ORdinated INformation on the Environment land cover classification (www.eea.europa.eu), "*continuous urban fabric*" can be defined as mainly constituted by buildings, roads and artificial surfaces, up to cover more than 80% of the total area; "*discontinuous urban fabric*" is referred to areas with buildings and artificially covered surfaces, covering just a percentage between 30% and 80% of the total area due to the presence of discontinuous vegetated zones (Bossard et al., 2000)

Based on how V_{ntw} is defined, its value results also able to summarise physical, syntactic and morphological features of areas at risk (Fig.2.2).

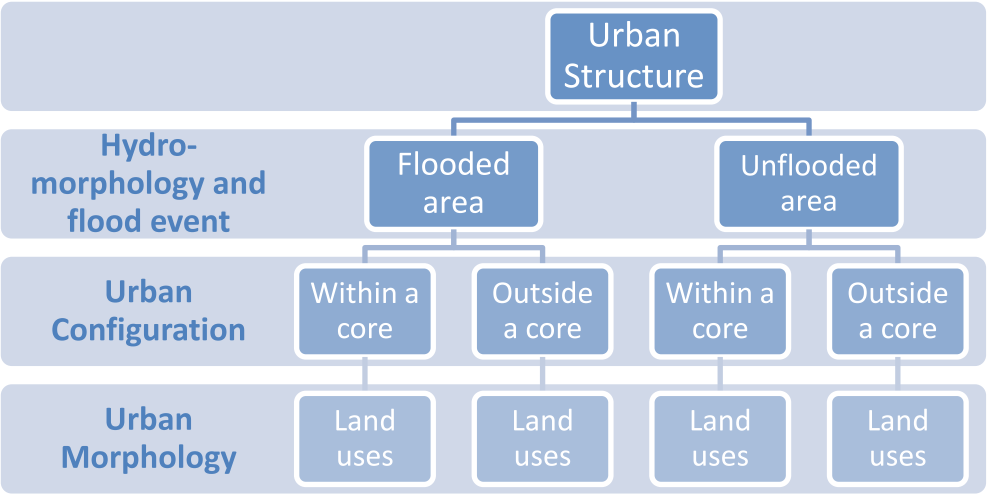

Figure 2.2: Schematic representation of the multi-step procedure proposed to evaluate urban vulnerability as a component of urban resilience

The said approach can be implemented overlapping areas at risk, syntactic cores and land use patterns. As an outcome, areas at risk can be characterised in reference to the percentage of each core at risk and relative land uses.

Outcomes deduced from all the steps allow to describe and characterise urban vulnerability to flood risk in reference to urban structure and layout. Further information can be achieved relating these results to other characteristics of urban areas. In fact, demography, number of people and inhabitants density within AAR constitute significant elements to be taken into account to assess vulnerability, being the percentage of people potentially exposed to a certain event one of the main concerns of vulnerability to natural risk. Value of "*population at risk*" can be evaluated as the percentage of people within *AAR* in reference to the total number of inhabitants of the whole study area. Combining population at risk with the defined "*network-based vulnerability*", level of vulnerability is further investigated ("*STEP 3*"). Being both non-dimensional numbers and being also independent of the size of the system they are derived by, these measures permit to compare level of vulnerability of different urban systems, or several configurations of a given urban structure.

2.2.3 Assessment of flood-induced configurational changes

The main innovation of introducing the concept of resilience in dealing with disaster risk comes from interpreting consequences of stresses or crises not just simply as to be avoided, but rather as induced changes to which the affected urban system should adapt itself in order to better face them. Being prepared to cope with disaster consequences supposes the disaster effects and consequences to be adequately known before event occurrence. Although this could appear an obvious point, it is not an easy issue in relation to expected impacts of natural phenomena. In some cases natural events are unforeseeable, both considering their occurrence and extent (or rather, elements they will potentially affect or damage). In other cases, likelihood of occurrence and events characteristics can be assessed, leading to point out elements at risk. As concerns flood events, they can be defined in time and space, although with a degree of uncertainty related to events magnitude and frequency. Extent of food plains can be known, constituting areas directly at risk to be flooded. Moreover, real-time data of rainfall and water levels, along with event modeling and historical data of past events, lead to flood forecasting. The latter constitutes a significant part of disaster risk management and it differs from flood warning, which specifically refers to events that are about to happen (WMO, 2011). Considering this spatio-temporal floods characterisation, the analysis of how the affected system would be after a flood can contribute to flood management. The possibility to model flood events enables to examine post-event phase, also under different conditions on varying of type or magnitude of examined flood. If post-event conditions (meaning the emergency phase) can be modeled, as is the case of floods, they can result to be considerably different from relative pre-event ones. Urban structures can be modified both in terms of layout and dimensions of accessible parts. In fact, flooded areas can induce substantial spatial changes within affected urban systems, being the inability of people or vehicles to move within flooded areas one of the most evident effects. However, the event indirectly affects the whole urban system, modifying the overall pattern of spatial accessibility. Broken connections between flooded areas and other parts of the settlement can create isolated zones, physically separated from the rest of the city to vary degrees, such as: areas hard to be reached, or zones reachable from system outside through a unique connection, as "*peninsulas*", up to create areas completely inaccessible, as "*islands*". In some cases, connections which still continue to be functional (if there are any) despite occurrence of a major event, can give more relevance to some areas. This circumstance occurs when certain locations after the event result easier to be reached than others, owning a higher level of accessibility than others, or also being more accessible if compared to the relative pre-event condition. In reference to the movement economy, this last category of spaces can assume a more central spatial role than remaining zones, as well as in respect of the role they had before the event (Gil and Steinbach, 2008).

Focusing on floods in urban areas, the possibility to define affected zones is the underlying element to model a possible structure of the urban layout after a certain hazardous event. Knowledge of areas at risk and their extent allows to apply a scenario analysis. More specifically, the actual configuration of a river-city can be assumed as a pre-event scenario ("*Scenario 0*"). Being known flood-prone areas, which constitute *AAR*, a second configuration of the same system can be obtained overlapping *AAR* and the before-event grid. The non-flooded areas of *Scenario0*-configuration provide a post-event scenario ("*Scenario 1*"). Examining the latter and comparing its syntactic features to the relative pre-event configuration, significant information are achieved about how the system would be altered by a flood event. This approach actually stands for individuating impacts on the said system. In this sense, impact assessment is a significant part of the risk management process and resilience-focused disaster risk management: knowledge of post-event conditions -even with a certain degree of uncertainty, as above mentioned- provides a clear and effective frame of how, where and what the urban adaptive capacity is needed.

Even if extent of affected areas can appear spatially limited, flooded spaces affects urban behavior at a wider territorial scale. This consideration is consistent with the basic principles of the configurational approach: each space -according to its location within the grid and its spatial connections to the other parts of the system- contributes to define the whole spatial configuration. In this way, consequences determined by a space that becomes flooded (or rather inaccessible) are not just related to its area extension. Induced effects can also depend on how that space is linked to the system and which functional role it assumes within the said urban system.

A first analysis of the affected settlement can be aimed at investigating the post-event configuration and its syntactic properties. The main way to understand and evaluate syntactic properties is to examine relative configurational indexes, in terms of their values and their geographical distribution within the grid. Applying Space Syntax analysis to post-event configurations means to examine each non-flooded part of the system, whether if flooded areas make the river-city system just smaller, but still compact, or they split the grid in several isolated subsystems. In order to assess flood impacts, *Scenario1*-configuration is investigated at this analysis stage. On varying of flooded part, *Scenario1*-configuration may just consist of a limited part of the relative *Scenario0*-configuration, or of several small areas of the original *Scenario0*-configuration. These two circumstances correspond, respectively, to the case flooded areas are confined to a certain zone or diffusely distributed in the study area. Therefore, *Scenario1*-configuration can be assumed as made up by subsystems; applying Angular Segment Analysis to each one of them, the latter are singularly examined, one at time. Relative spatial distribution of configurational centralities can be obtained too. Being the configurational measures proxies of human activities and dynamics, a pattern of urban centralities permits to individuate areas that would be more likely to assume a strategic role as regards people presence and movement. Adopting this procedure of analysis, connections between studied urban systems and outside, at regional or national scales, are not considered. In this way, the most severe condition the urban system could cope with is examined. Focusing on *Scenario1*-configuration, highest values of analysed configurational values within each subsystem (global (R= n) and local (R= 400m) integration indexes, global choice (R= n) values) provide a pattern of spatial distribution of main cores during the emergency phase.

In order to assess flood consequences, it appears necessary to compare the affected structure and its relative pre-event conditions. A comparative analysis can be defined, graphically matching pre and post-event configurations, and correspondent urban centralities, to notice if the said centralities are preserved, changed in their extent, shifted in their location or deleted, as a consequence of a flood event. However, a more structured comparison is needed, based on objective comparison methods to obtain results not affected by the dimension of the system they are referred. This constitutes an important issue in dealing with disaster-induced changes of urban layout. As it can be evident in the case of floods, pre and post-event urban layout differ each other from many point of views, the most evident differences are the system dimension and layout. The more the comparison criteria are able to objectively include different characteristics of the analysed systems, the wider will be the confrontation and the range of achieved information. Configurational indexes represent the key elements to be investigated. Values of indexes values can change on varying of dimensions of the system they are referred to, or rather the number of lines of the relative syntactic map. In order to address this problem, normalised measures of the main configurational indexes (respectively, normalised integration and choice indexes) can be calculated as proposed in the literature (Hillier et al., 2012). In reference to a given radius R, normalised integration ($NaCh_R$) and normalised choice indexes ($NaCh_R$) can be obtained from measures of angular choice (Ch_R), angular total depth (TD_R) and the node count[4] (NC_R):

$$NaCh_R = \frac{\log{(Ch_R + 1)}}{\log{(TD_R + 3)}}$$

$$NaCh_R = \frac{(NC_R + 2)^{1.2}}{TD_R}$$

Normalised values mathematically avoid the dependence of indexes from the size of the system they are referred to, even preserving the ability of normalised syntactic measures to reproduce movement rates. Normalised values of global integration and global choice can be examined on the basis of their relative frequency distributions. This comparative analysis between pre and post-event scenarios allows to point out how the event can transform the system. Moreover, outcomes of this part of the procedure permit to evaluate if the set of spaces which assume new functional roles, constituting post-event cores, owns suitable characteristics to coherently play their new central role in reference to human co-presence, flows and urban phenomena.

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[4] Space Syntax theory considers spaces to be analysed through network-based methods, representing urban spaces as nodes linked by lines, the latter accounting for spatial connections between the said spaces. Given a certain segment, the node count represents how many nodes, i.e. spaces, are located within the area defined by the assumed radii of analysis ("R"). If globally evaluated (R= n), the whole system dimension would be considered and the node count would be a constant value for every space within the system (as all the spaces of the grid are considered).

A more structured comparison between the said *Scenarios* can be achieved starting from analysing the analytical properties of measures related to each segment map. From an analytical point of view, configurational indexes constitute a set of quantitative measures. They can be represented as a numerical database of values associated to a given urban configuration: each line or segment owns a number of measures equal to the number of evaluated syntactic indexes. Dimensions of this database can be very large, depending on the extent of the map (or rather, the number of network segments) and the number of considered indexes. Syntactic indexes are correlated each other, as the statistical correlation among their values can show. This observation suggests that a proper combination of them could be found to preserve the information they provide, avoiding redundancy represented by their mutual statistical correlation. The multivariate statistics can be applied, permitting to examine multiple variables and their mutual relationships. Among multivariate statistical techniques, the principal component analysis ("*PCA*") allows an exploratory data analysis aimed at reducing the number of observed statistically correlated variables by pointing out a smaller number of new uncorrelated variables ("*principal components*") (Hotelling, 1933). The latter are individuated as able to account for a large amount of variance of the original observed variables (Wold et al, 1987; Zani and Cerioli, 2007; O'Rourke et al., 2013).

Description of *PCA* basic concepts and potentialities allows to notice *PCA* validity to compare different urban configurations. Large datasets, made up by several variables referred to many units, can be difficult to be examined. Although large amounts of data can lead to several analysis and represent a valid set of information, their own numerosity can constitute an obstacle in overall examining features and phenomena they account for. *PCA* represents a methodology to explore data aiming at finding relationships between variables of examined datasets. *PCA* procedure permits to properly reduce dimensionality of dataset on the basis of how all variables are mutually correlated, taking into account a large part of their variations (Wold et al., 1987). Decreased amount of data, obtained applying *PCA*, derives not from analysing a limited number of variables or elements at a time, but from the possibility to interpret the original dataset through a lower number of new variables. As a result, *PCA* outcomes represent fewer values to be managed and interpreted than original data. It follows an easier data interpretation and a simplified way to emphasize data main features, commonalities and characteristics.

In more details, a given dataset can be organised as a matrix ***X*** (*n x p*), having *n* rows, as the number *n* of examined elements or objects, and *p* columns, as the number *p* of quantitative measured and correlated variables. Based on *ASA* measures, a set of eight variables can be assumed as to completely represent main characteristics of the grid at the urban scale. Segment length, global (R= n) and local (R= 400m) choice index, global (R= n) and local (R= 400m) integration index, local (R= 400m) node count, total (R= n) and local (R= 400m) depth provide a description of the network structure and main centrality measures of a given grid. All these indexes constitute a set of *p* (*p*=8) variables to be processed through *PCA*. While *p* is a fixed value once defined the number of examined configurational indexes, the segment map dimension *n*, defined as the number of elements of a given segment map, depends on network size. Therefore, ***X*** (*n x p*) data matrix can assume different dimensions, to be specifically defined in each case.

Considering different urban grids, the statistical relationships between some configurational indexes referred to different segment maps (Fig.2.3) show that, even changing the numerical value of the each correlation coefficient, the relationships result to be similar in all cases (meaning high or low, direct or indirect correlation). This circumstance can be explained noticing that the correlation between variables depends on how they are defined and not on the specific dataset they are referred to.

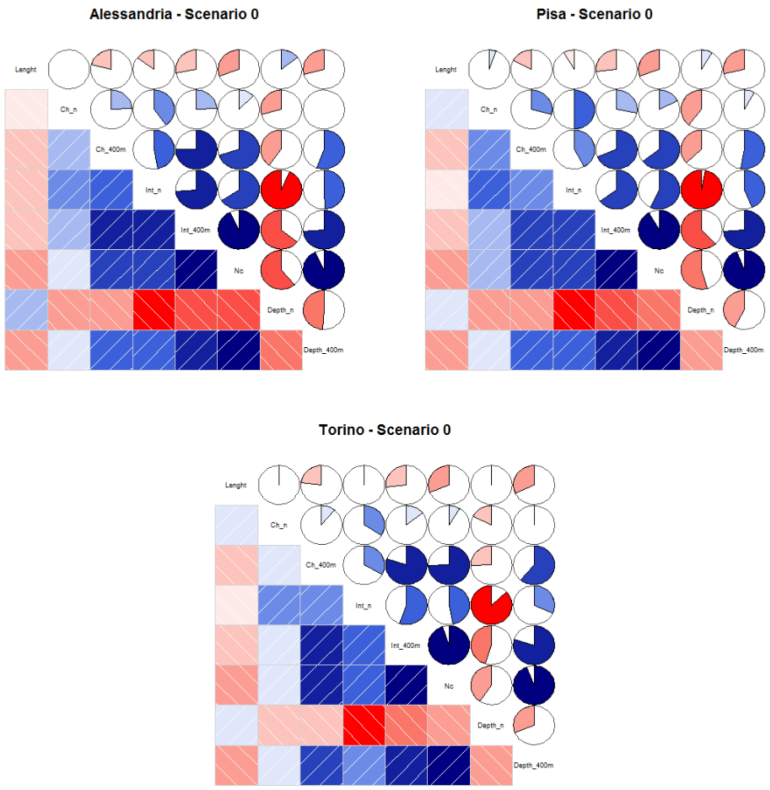

Figure 2.3: Representation of correlation matrices (the so-called "*correlograms*"). Correlations are evaluated considering a set of eight configurational measures: segment length ("*lenght*"), global choice (R= n, "*Ch_n*"), local choice (R= 400m, "*Ch_400m*"), global integration (R= n, "*Int_n*"), local integration (R= 400m, "*Int_400m*"), node count ("*Nc*"), total depth (R= n, "*Depth_n*"), local depth (R= 400m, "*Depth_400m*"). (Pie charts: magnitude of the correlation. Blue color ramp: increasing direct correlation; Red color ramp: increasing inverse correlation).Indexes measures are derived applying Angular Segment Analysis to three different urban structures (for a detailed description of these urban layouts, see Chap.3, Par. 3.1)

Applying *PCA*, $\boldsymbol{X}$ values are usually represented as deviation from correspondent average value of each variable. The basic consideration of *PCA* approach is that, if p results a large value, it can be useful to organise variables in a way to reduce their number, not undermining the overall informational content and the statistical variance of the original data. On the basis of the statistical correlation among p variables, a set of new variables PC_i ($i = 1...p$) ("*principal components*") is defined from $\boldsymbol{X}$ ($n \times p$) matrix, obtaining as many component as many original p variables. Components PC_i ($i = 1...p$) are obtained as linear combinations of the original p variables; PC_i ($i = 1...p$) are uncorrelated and listed by their variance in descending order. In order to find coefficients of these linear combinations, able to maximising the variance each PC_i ($i = 1...p$) can represent, a maximum problem is derived. The latter requires to be solved by introducing Lagrange multipliers λ. In fact, being every PC_i ($i = 1...p$) a linear transformation of all p variables, the variance of each principal component can be expressed through the covariance matrix $\boldsymbol{S}$ ($p \times p$) of the initial dataset. $\boldsymbol{S}$-eigenvectors $\boldsymbol{a_i}$ ($i= 1...p$) contain coefficients of relative p linear combination PC_i ($i = 1...p$). Variance of each principal component PC_i ($i = 1...p$) is represented by relative **S**-eigenvalue $\lambda_i (\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_p)$ (listed to follow the decreasing variance criteria). **S**-eigenvalues are commonly displayed with correspondent number label i of the relative component, obtaining a line segment plot ("*screeplot*"). In case p variables differ from each other in their order of magnitude, they need to be analysed in terms of normalised deviation from average (or rather, considering the correlation matrix $\boldsymbol{R}$ instead of $\boldsymbol{S}$). This is actually the case of the examined syntactic dataset whose variables differ in their numerical values and order of magnitude.

In order to achieve the main goal of variable reduction, the number p of components is reduced to a smaller value k ($k<<p$). The number k of meaningful principal components PC_i ($i = 1...k$) basically depends on the amount of original variance explained by each PC_i ($i = 1...k$). The selection of k value is carried out selecting PC_i ($i = 1...k$) able to represent a reasonable percentage variance of the original $\boldsymbol{X}$ ($n \times p$) database. According to the relevant literature, this selection can be done on the basis of distinct criteria (O'Rourke, 2013; Zani and Cerioli, 2007): *i)* the cumulative variance explained by all selected PC_i ($i= 1...k$) represents at least a percentage of 70-75% of the total variance of the original database; *ii)* the set of PC_i ($i= 1...k$) accounts for at least 95% of variance of each initial p variable; *iii)* in reference to the case of p standardised variables, the set of PC_i ($i= 1...k$) can be assumed as corresponding to the principal components whose λ_i ($i= 1...k$) eigenvalues values are greater than one. This criterion is based on considering just components able to reproduce a variance higher than the variance of each single original variable (the latter having variance equal to one as standardised variable); *iv)* based on the scree plot, k can be defined equal to the component number at which the line graph shows a significant change in slope, which is representative of a low variance explained by the following PC_i ($i= k+1...p$) principal components (Zani and Cerioli, 2007).

As an outcome of this selection of components, a new k-dimensional space is obtained: the set of n original elements can be represented with new k coordinates called "*scores*". On the basis of k value, the original (n x p) dataset can be graphically displayed in the PC_i (i= *1...k*) space. The representation of score values in the new k-dimensional space of principal component is called "*score plot*". Axes of this graph have no physical meaning, but they represent the selected components PC_i (i= *1...k*). The latter constitute the directions along which the maximum variation of data values is registered. Therefore, besides reducing dataset dimensions by defining and selecting significant new variables, *PCA* also allows to graphically represent complex and large dataset in a new variable space, the latter having a limited number of dimensions.

Both numerical and graphical results of the whole procedure have to be interpreted to deduce information about the studied variables and the phenomena they account for. Firstly, the meaning of principal components can be defined according to their relationship with each one of the initial variables they are deduced from. Considering the m-th principal component $PC_{i=m}$ (m= *1... k*) and the relative $\boldsymbol{a_m}$ eigenvector, the correlation coefficients r_{ml}between $PC_{i=m}$ and each l-th variable X_l the can be evaluated:

$$r(PC_{i=m};\, X_l) = \; a_{ml}\sqrt{\lambda_m}$$

This coefficient points out to what extent each p variable contributes to define the said $PC_{i=m}$. Outcomes are usually displayed in a graph ("*component plot*"). In case k= 2, the latter become a 2-dimensional plot, whose horizontal x-axis and vertical y-axis respectively represent the selected components (PC_1, PC_2). Coordinates of each point within this graph correspond to the statistical correlation between the variable that point represents and the k principal component the axis stands for. The graph shows as many points as the p original variables are processed. Correlation coefficients can vary from -1.0 to +1.0, by definition. A one-radius circumference can also be represented ("*correlation circle*"): the more a point (i.e. a variable) is close to the circle, the better that variable is properly modeled through the selected PC_i (i= *1...k*). Moreover, linking each point to the axis origin, $\mathbf{h_i}$ (i= *1...p*) vectors can be obtained. Given a certain $\mathbf{h_i}$ (i= *1...p*), the greater is its projection on a axis, the more the correspondent variable contributes to define the component that the considered axis represents.

Direction of $\mathbf{h_i}$ ($i = 1...p$) vectors accounts for direct or inverse correlation between relative variables and components. In this way, the relationship between the principal components and original variables is deduced (Zani and Cerioli, 2007).

As regards the interpretation of *PCA* results, significant information can be obtained relating the score-plot and the component plot: points located near the axis origin in the score plot own values of all p variables similar to relative variable averages; points with an high value of a certain score -or rather, an high coordinate value in the score plot- account for elements with an high value of that relative component (or rather, higher than average value of the original variables that component represents); points along the direction of a given $\mathbf{h_i}$ ($i = 1...p$) vector correspond to elements with higher than average values of the variables referred to the said $\mathbf{h_i}$ ($i = 1...p$) vector.

In order to describe how *PCA* can be applied for the purpose of deeply analyse different urban configurations, some considerations are needed to highlight the analytical structure of configurational measures. Following the general overview, indexes referred to each urban grid can be organised to obtain an $\boldsymbol{X}$ ($n \times p$) matrix having n rows, as the number of lines of each map, and p columns, as the number of measured configurational indexes. Depending on map extent and number of indexes, n and p values can considerably vary. However, being a matrix of numerical and statistical related values, $\boldsymbol{X}$ ($n \times p$) can be processed through *PCA* aiming at reducing its dimensionality and highlighting indexes features. As a result *PCA* allows to examine the available indexes together, globally interpreting them all at once. It follows a facilitated overall analysis of each map, providing a global framework of grid main features. This method to summarise and interpret urban features through a comprehensive approach becomes even more useful when applied to different datasets. Since *PCA* outcomes are not influenced by the dimension of the processed dataset, they can be compared for distinct datasets to obtain a valid comparative analysis. Therefore, applying the *PCA* method to urban configurations, relative results enable to make a comparison between different urban grids. Provided outcomes are independent of the specific structure and size of the map they are referred to. This allows to conclude that comparison between *PCA* outcomes, deduced processing data referred to different maps addresses the need for a global and objective match between different configurations determined by flood event occurrence.

The described statistical approach to better understand urban features can be further developed providing an easier interpretation of *PCA* outcomes. Score plots, indeed, constitute a representation of a large dataset in the sub-space of *k* selected significant components. Coordinates of each point of the score plot represent the value of relative principal component. The interpretation of score plots can be facilitated by grouping points of the graph on the basis of similarities among the latter. In this way, the advantage of *PCA* of summarising large sets of variables in a lower number of components can be combined with the possibility to individuate characteristic groups of elements. This further data processing permits to easily point out dataset characteristics, or rather spaces property that each value represents. Reminding that coordinates of each point are representative of PC_i (i= 1...k) (which, in turn, stand for a wider set of configurational measured variables), proximity between points in the score plot means similarity in the relative score values. Based on the meaning of each point in reference to configurational measures, this circumstance is representative of commonalities between urban characteristics that scores and components represent. The definition of clusters of points, as a further processing phase of *PCA* outcomes, allows both to summarise the property represented by the processed variables and to individuate meaningful groups of elements. Therefore, scores results to be analysed and suitable criteria to define points proximity in the graph stand for appropriate method to point out spaces which share similar syntactic features.

As an exploratory technique, cluster analysis ("*CA*") aims exactly at this goal (Tryon, 1939): given a certain dataset of elements, *CA* method permits to merge elements in groups. Each cluster contains elements similar among each other, and sufficiently different from elements of other groups. *CA* procedure can be outlined starting from describing some preliminary choices needed to operatively set the method. As a basic step, variables to be processed have to be selected, according to the specific field and purpose of the analysis. Grouping elements requires to evaluate distances between units, the latter considered in pairs. Distances between all pairs of elements can be collected in a distance matrix $\boldsymbol{D}$ (n x n). Once distances are known, groups can be defined through different iterative procedures: *i*) a top-down approach, if the whole original set of elements is divided into a number of *g* groups, being *g* fixed a priori ("*non-hierarchical analysis*", "*NHCA*"); *ii*) a bottom-up approach, in case -at the first step of the method- as many groups as the number of analysed elements are assumed, progressively merging the latter -during the following steps- up to include all them in a single group ("*hierarchical analysis*", "*HCA*"). Non-hierarchical analysis is mainly based on iterative algorithms to satisfy a given objective function, so as to achieve a suitable internal cohesion of each group (e.g.: minimising the deviance between groups or minimising the distance between each point and the centroid of the group that point belongs to) (Hizir, 2003; Zani and Cerioli, 2007). Focusing on hierarchical agglomerative methods, the number of groups is not known. There are various criteria in the literature to define distance between groups to be progressively combined as to complete the clustering procedure (Zani and Cerioli, 2007; Everitt, 2011; O'Rourke, 2013). Defining x and y two elements included in two different groups, respectively named C_1 and C_2 (containing n_1 and n_2 elements), main linkage methods define distance between groups on the basis of distinct specific values:

- Single Linkage (or "*nearest-neighbor technique*"):

$$d(C_1;\ C_2) = \min\ d(x,y) \quad (x \in C_{1;}\, y \in C_2)$$

- Complete Linkage (or "*furthest-neighbor technique*"):

$$d(C_1;\ C_2) = \max\ d(x,y) \quad (x \in C_{1;}\, y \in C_2)$$

- Average Linkage:

$$d(C_1;\ C_2) = \frac{1}{n_1 n_2}\sum_x \sum_y d(x,y) \quad (x \in C_{1;}\, y \in C_2)$$

- Centroid Linkage (or "*unweighted pair-group method using the centroid approach*", UPGMC), the distance between two groups C_1 and C_2 is assumed equal to the distance between relative centroids $\overline{\boldsymbol{x_1}}$ and $\overline{\boldsymbol{x_2}}$**:**

$$d(C_1;\ C_2) = d(\overline{\boldsymbol{x_1}}, \overline{\boldsymbol{x_2}}) \quad \overline{\boldsymbol{x_1}} \in C_{1;}\, \overline{\boldsymbol{x_2}} \in C_2$$

- Median Linkage (or "*weighted pair-group method using the centroid approach*", *WPGMC*), the distance between two groups C_1 and C_2 is considered as the distance between relative groups centroids. Unlike the centroid linkage, according to median linkage method centroids of merged groups are weighted to deduce the centroid of the resulting cluster.

- Method of Ward, based on merging clusters by minimising the total variance within the clusters. It is operatively applied evaluating the euclidean distance between centroids of each pair of groups:

$$d(C_1;\ C_2) = \frac{n_1\, n_2}{n_1 + n_2} \|\overline{\boldsymbol{x_1}} - \overline{\boldsymbol{x_2}}\|^2 \quad \overline{\boldsymbol{x_1}} \in C_{1;}\, \overline{\boldsymbol{x_2}} \in C_2$$

According to the how distance between clusters is defined, relative closest groups are progressively merged following the agglomerative algorithm. Each linkage distance determines different groupings, and each linkage method has its own limitation in detecting groups (Hizir, 2003; Zani and Cerioli, 2007; Everitt, 2011; O'Rourke, 2013). Whatever type of distance is assumed, outcomes of the iterative process of hierarchical classification can be represented using a tree diagram ("*dendrogram*"). The horizontal *x*-axis of this graph usually displays labels of single units; the vertical *y*-axis represents the distance at which units are merged to create groups and, in turn, groups are progressively merged according to the agglomerative approach. Dendrograms allow to visualize the entire process reporting groupings step-by-step: each vertical line of the diagram stands for a cluster, each horizontal line corresponds to the distance at which clusters are merged. Interpretation of the dendrogram can be used to define the number of significant clusters: different "*cutting point*" will provide different partitions. A criterion to properly define the cut-level can be based on avoiding to separate elements similar to each other, or rather, cutting the tree plot in correspondence of a small *y*-distance among groups. Clustering stability can be investigated to assess the robustness of the grouping solution mainly through measures representative of comparisons between different possible clusterings (Fowlkes and Mallows, 1983; Zani and Cerioli, 2007).

Implementing hierarchical cluster analysis as a further processing phase of *PCA* outcomes, each point of a given score plot is included in a suitably defined group, according to similarities between units of the processed dataset. Once set the method of aggregation and the criterion to individuate the appropriate number of partitions, two more measures can be considered to assess and validate the consistency of obtained clustering solutions: the silhouette value (Rousseeuw, 1987) and the cophenetic correlation coefficient (Sokal and Rohlf, 1962).

The minimum average dissimilarity *b(i)* between each element *i* of a given cluster *A* and all elements of any other cluster *C* (*C≠A*) can be compared to the dissimilarity *a(i)* from *i* to all other units of the same group *A*. Dissimilarities correspond to the distance between any pair of elements, such as Euclidean distance. Silhouette value *s(i)* can be obtained comparing how far is *i* from all elements of its cluster to how far is the nearest (distinct) group:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i); b(i)\}}$$

This measure can vary between -1 and +1 (the more the value is close to 1, the more properly the elements are grouped) and it is representative of how properly a point is included in the cluster it belongs to (Rousseeuw, 1987; R Core Team, 2014). An overall weighted silhouette value can be also obtained, assuming the number of elements of each group as a weight. Silhouette value just depends on the partition and not on the specific applied clustering algorithm the groups were deduced from.

The cophenetic correlation coefficient ("*CCC*") (Sokal and Rohlf, 1962; Saraçli et al., 2013; R Core Team, 2014) is a measure of how well a dendrogram $\{T_i\}$ represents the distances between pairs of elements of the original dataset $\{X_i\}$. Considering two elements *i* and *j* of a set of values $\{X_i\}$, the Euclidean distance $x(i,j) = \left|X_i - X_j\right|$ can be compared to the dendrogrammatic distance $t(i,j)$ between two model points T_i and T_j. The height of the dendrogram node at which T_i and T_j are first joined together graphically represents $t(i,j)$. Defining $\bar{x}$ the average value of the $x(i,j)$ and $\bar{t}$ the average value of the $t(i,j)$, *CCC* constitutes the linear correlation coefficient between original distances between data elements and distances between units after the partitions (i.e. each unit being included in a group):

$$CCC = \frac{\sum_{i<j}[x(i,j) - \bar{x}]\,[t(i,j) - \bar{t}]}{\sqrt{\left\{\sum_{i<j}[x(i,j) - \bar{x}]^2\right\}\left\{\sum_{i<j}[t(i,j) - \bar{t}]^2\right\}}}$$

As a correlation coefficient, *CCC* value can vary between -1 and +1; *CCC* values close to 1 account for an accurate hierarchical clustering solution of observed data.

Reminding that each element of a cluster is deduced from a set of *ASA* measures, partitions of each score plot can be also interpreted according to the spatial meaning of the points, analysing the spatial distribution of obtained clusters within relative segment maps.

Robustness of *HCA/CA* outcomes can be further analysed also with regard to the chosen linkage method. All linkage methods are based on properly merging single elements to create partitions. However, they consider different distances between groups to merge. Therefore, the choice of linkage influences the clustering process and the resulting classification. A comparison between groupings obtained from diverse linkage distances can lead to evaluate the influence of the clustering algorithm on the definition of groups. Given n values and two different hierarchical clusterings A_1 and $\boldsymbol{A_2}$, for each number k ($k= 2,\ldots, n-1$) of clusters the matching matrix $M= [m_{ij}]$ includes the number of common objects between the cluster i ($i= 1\ldots k$) of A_1 and the cluster j ($j= 1\ldots k$) of A_2. The similarity measure B_k proposed by Fowlkes and Mallows (1983) constitutes a numerical value representative of the degree of similarity between two hierarchical clusterings:

$$B_k = \frac{T_k}{\sqrt{P_k Q_k}}$$

$$T_k = \sum_{i=1}^{k} \sum_{j=1}^{k} m_{ij}^2 - n$$

$$P_k = \sum_{i=1}^{k} m_{i\cdot}^2 - n$$

$$Q_k = \sum_{i=1}^{k} m_{\cdot}^2 - n$$

$$m_{i\cdot} = \sum_{j=1}^{k} m_{ij}$$

$$m_{\cdot j} = \sum_{i=1}^{k} m_{ij}$$

Matching common units between clusters of different partitions, the higher is the number of pairs of elements included in the same cluster both in A_1 and in A_2, the more B_k value is close to 1. If $B_k = 1$, there is a complete correspondence between the said clusters. Alternatively, B_k is zero if all elements belong to diverse clusters of the two considered partitions A_1 and A_2. Hierarchical clusterings to be compared can derive from data referred to diverse data sources, from different algorithms or distinct linkage methods. Each B_k value can be further detailed in regard of the relative confidence interval ("*CI*"). The latter represents an estimated range of values which is likely to contain (with a defined probability) the true value of a parameter (Erto, 2008), (or rather B_k in this specific data processing). Even if B_k values can be obtained for each dataset (i.e. each distance matrix relative to each one of the considered linkage methods) and for a relative defined number k of meaningful clusters, B_k probability distribution is not known. The bootstrapping procedure (Efron, 1979) can address the individuation of B_k probability distribution. Given a variable $\boldsymbol{X}$ and l independent observations ($x_1, x_2, ..., x_l$), the bootstrap algorithm constitutes a statistical method to estimate the unknown probability distribution F of an estimator θ. By generating N samples, the bootstrapping allows to obtain the probability distribution of the unknown parameter θ. More in detail, a number N of l-dimensional samples ("*bootstrap samples*") are generated by randomly re-sampling with replacement from the original ($x_1, x_2, ..., x_l$) observations. For each bootstrap sample, a correspondent value $\hat{\theta}$ can be calculated. The whole set of estimated $\hat{\theta}_i$ ($i = 1...N$) values provides an empirical distribution of θ ("*bootstrap distribution*") which, in case N is a very large value, can be assumed as a good approximation of the sampling distribution. On this basis, the similarity measure B_k can be considered as an estimator whose probability distribution has to be evaluated. Given k clusters, each comparison between linkage methods provides a value of B_k. Re-sampling from the original sample to which B_k is referred, performing a bootstrap method ($B_{k1}, B_{k2}, ..., B_{kN}$) values are obtained deriving the probability distribution of B_k. This allows to evaluate main summary statistics and, notably, confidence intervals. Therefore, B_k values permit to match linkage methods to assess similarity between them in order to evaluate the influence of the adopted methodological decision of the clustering algorithm on the general results. Subsequently implementing a bootstrapping algorithm, the numerical stability of B_k values is further examined.

Once the *PCA* and *HAC* are carried out, the processed dataset results as a set of similar groups of elements, each one owning distinctive features. In reference to configurational measures, each cluster represents a certain class of urban spaces characterised by specific similar features. This outcome is particularly relevant observing that *HAC* outcomes are deduced from *PCA*. Therefore, clusters are representative of spatial similarities outlined globally considering *all* available syntactic indexes, in respect of the whole urban grid. On the basis of *PCA* and *HAC* results, comparison among clusters permits a synoptic frame of clusters similarities and differences between different maps.

In case the latter are referred to distinct urban configurations related to a flood event impacting the grid, the entire statistical *PCA/ HAC* procedure permits to compare pre and post event scenarios or, also, different river-cities amongst them. Correspondence between elements of processed datasets and segments of relative syntactic maps allows to spatially represent the results of *PCA* and *HCA*. This matching between analytical and spatial elements permits to interpret the whole statistical-based processing phase in reference to spatial features (represented by the original *p* variables), in order to individuate occurred changes and variations after event occurrence. It follows a comprehensive and objective overview of grid's variations and changes determined, in the specific case, by the flood.

2.3 Urban resilience, flood risk and urban planning

The conceptual and operative definitions of urban resilience can be further completed outlining possible applications of the proposed assessment methodology.

Assuming the configurational theory to perform spatial analysis, relationships between urban spaces are a key-element to evaluate syntactic centralities and related urban phenomena. Therefore, the configurational approach allows to investigate physical perturbations determined by floods in reference to their impact on urban functions. Configurational properties, mainly described by syntactic indexes, basically constitute the input data to apply the proposed resilience multi-stage assessment methodology.

Each structural or non-structural action (or rather, respectively, actions which directly modify urban spatial layout, or modify urban characteristics even not affecting the spatial pattern of open spaces) can modify accessibility pattern and syntactic properties; as a consequence, main components of urban resilience can be affected too. Therefore, an appropriate analysis of urban development measures is essential to understand how the said measures can potentially impact resilience components in terms of settlements response to flood emergencies, recovery and ability to adapt itself to flood-induced perturbations.

Being resilience also related to river features (in terms of river resistance), actions on the river system can affect resilience too. Flood protection measures or defence measures (e.g.: dikes, defence walls, detention basins) are aimed at reducing or limiting flood risk in a given area (i.e. reducing the hazard, as the probability of occurrence of flood events). Actually, these measures can modify the pattern of accessible areas and relative location, as well as extent and location of areas at risk. The new induced spatial distribution of configurational centralities can be examined in reference to the configurational-based resilience of the system changes.

Moreover, the connection between resilience and urban layout represents an opportunity to develop resilience itself. According to the configurational approach, indeed, affected urban structures are globally examined, as a whole. In fact, this aspect coherently reflects the fact that urban settlements experience calamitous events in their entire scheme, not just limited to directly affected zones. The relationship between grid properties and urban resilience provides the possibility to consider modifications of urban layout -in its entire layout- as part of a resilience-focused disaster management. Modifying urban grid, spatial pattern of centralities consequently changes; as a result, elements of resilience process can vary too. Therefore, urban design measures can be aimed at improving resilience, even if they regard non floodable zones (e.g. aiming at reducing network vulnerability, or facilitating an appropriate development of new centralities during the post-event phase).

The scenario approach based on which the methodology is structured permits to analyse different urban configurations in reference to flood occurrence, namely pre and post-flooding configurations. Real or designed conditions (i.e.: actual urban structure, as well as a past or a future urban conditions) can be considered as starting status of the procedure. In fact, each one of the described variations on urban grids can be assumed as corresponding to a new modified urban configuration. The latter can be considered as new "*starting-scenarios*" in respect of a flood event: implementing the methodology, the correspondent vulnerability to floods and new correspondent post-event conditions are obtained. Further scenarios can be defined assuming various potential calamitous conditions (e.g.: varying event magnitude, probability of occurrence of hazards or the return period of flood discharge). Implementing the scenario approach, relative outcomes outline overall changes of urban resilience. A significant understanding of resilience ability is deduced for each examined action on the grid.

Considering urban morphology, land uses, localisation of main urban functions, level of urbanisation and demographic features, together with syntactic features, resilience is analysed both based on grid properties and taking into account further urban characteristics. The former are intrinsically related to the urban network; the latter contribute to reinforce and complete information deduced from syntactic analysis.

Therefore, the methodology represents a tool to evaluate the general level of urban resilience on varying of elements within the urban system. The possibility to model future urban conditions, analysing relative resilience degree, considerably contributes to apply resilience in urban planning process. Once defined actions aimed at achieving a better system reaction in case of hazard, they can be examined to evaluate relative consequences on urban resilience degree. Outcomes of the procedure can also suggest appropriate interventions, to ensure an adequate overall ability to resiliently cope with flood event. Information about the location of configurational centralities in the post-event configuration, indeed, can be critically interpreted, examining how new core areas can suitably assume their new functional role. In the context of urban planning, the new pattern of centralities can be interpreted as a basis to individuate which areas need interventions, in order to appropriately accommodate new movement rates. A better adaptability is then derived, improving resilience. In a view of resilience-oriented flood management, these information can be useful to enhance the system reaction, given that the derived knowledge can help in defining risk management measures and evaluating relative efficacy. Therefore, the procedure allows to define *-before* flood events occurrence- actions to "*built*" resilience.

Actually urban areas mainly imply to adopt a strategic thinking of city systems as evolving entities. In fact, urban systems are continuously evolving both in their physical and socio-demographic structures, under social, economic and political pressures. Therefore resilience thinking fits governance of urban environments, in the wide context of urban planning, other than disaster risk management strategies. This dynamism gives to risk management strategies a degree of uncertainty, as they could consider and be referred to conditions already changed. A proper monitoring phase can address this circumstance in order to make the flood management process able to respond to urban development. Again, the scenario approach and the mutual connections between components of urban resilience permit to match scenarios representative of different moment in time, providing a temporal trend of resilience. In this view, the analytical potential of the methodology to compare different structures can be exploited as a possibility to achieve updated information about resilience, as well as its diachronic evolution as a result of urban development.

Syntactic meaning of configurational indexes basically relates to human perception of space and human movement. Therefore, knowledge of syntactic centralities after a flood, or rather during the emergency phase, allows the further possibility of suitably define facilities locations based on how people perceive and navigate urban spaces.

Importance of relating water management, disaster risk and urban planning can be easily deduced in the general context of finding a balance between a responsible use of natural resources and increasing urbanisation. Integrating these fields becomes even more significant for urban environments located next to rivers, both to assess actual conditions and to consider evolving conditions related to urban development or planning measures.

3
Application of the methodology

3.1 Implementation of the methodology to case studies

The proposed methodology to assess urban resilience to floods adopts a system approach to analyse urban structures through different stages of analysis. Syntactic and morphological urban features, as well as configurational and statistical analysis methods and tools, contribute to implement the described assessment approach.

According to the methodology, a first preliminary analysis of urban structures of settlements located next to rivers permits to characterise urban systems as potentially at risk. Outcomes of this phase provide an overview of the several aspects that can be assumed representative of the influence of rivers on the urban environment. Being this stage of analysis representative of pre-event conditions, the whole urban layout is examined in its actual configuration ("*Scenario 0*"). Examining *ASA* configurational features in reference to watercourses location, this stage constitutes a specific application of the configurational theory to investigate river-cities structures.

A second stage of the methodology is focused on analysing areas at risk to be flooded ("*AAR*") to evaluate vulnerability of the urban network to flood events. Quantitative measures of vulnerability are obtained progressively examining morphological, syntactic and demographic features through a multi-step procedure (*STEP 0*, *STEP 1; STEP 2; STEP 3*). As an outcome of this stage, the "*network-based vulnerability*" ("V_{ntw}") is obtained. Network at risk is characterised both in regard to land use pattern and percentage of people directly at risk to be affected by a flood event.

The third phase of analysis aims at describing the urban configuration once the event has occurred, and how the city structure changes in respect of its relative normal configuration. Analysis of post-event configuration and a suitable comparison with the pre-event conditions permits to investigate how the event affects the system, or rather how the latter adapt itself to flood-induced variations. Perturbations induced by major events -either they are intended as impacts or change- imply to examine the threaten system in terms of the structure it assumes once the event has occurred. In reference to floods, once known the type of flood and the main characteristics of the event, the definition of a certain occurrence probability permits to define areas potentially affected. Superimposing flood plain areas on the actual urban configuration, areas at risk are delimited. At the same time, remaining parts of the urban system can be assumed as representative of that part of the system which is not directly affected by the event. Post-event configuration ("*Scenario 1*"), consisting of non flooded zones, constitutes the analysis system at this stage of the proposed procedure. Comparison between *Scenario0* and *Scenario1* is carried out through statistical-based analyses.

Following the outlined stages, an application of the methodology is described in this section, in reference to three river-cities chosen as representative case studies: Alessandria (IT); Pisa (IT); Torino (IT) (Fig. 3.1 - Fig. 3.3). Even being all located nearby rivers, or crossed by watercourses, these case studies constitute an adequately internally diversified set of river-cities: historical evolution of settlements, location of urbanised areas, built form layout, pattern of land uses, number and location of river crossings, are just some of the aspects they differ by. On this basis, their selection allows to apply the methodology to investigate different urban structures, also testing the validity of the procedure in reference to different urban layouts. Each study area is chosen so as to entirely include the whole relative metropolitan zone (not just assuming administrative boundaries). In order to suitably investigate each single urban structure, all the study systems are delimited according to the extent of the built environment as well as physical and morphological boundaries. Starting from the derived spatial models, obtained selecting all open and accessible spaces within each study area, Angular Segment Analysis is applied. Angular configurational indexes of integration and choice are evaluated for different radii (R= 400m, R= 800m, R= 1200m, R= 1600m, R= 2000m) for all case studies (see APPENDIX A). Subsequently, the multi-step methodology is carried out to investigate level of resilience to flood events. Some operative aspects are assumed for all case studies: *i*) syntactic cores are defined as 10% of highest values of each considered index; *ii*) frequency distributions are defined assuming 100 intervals for all examined parameters and measures; *iii*) all information related to land use are deduced from CORINE (Coordination of Information on the

Environment) land cover database of the European Environment Agency (latest 2012 update "CORINE2012", www.eea.europa.eu); *iv*) all available linkage methods are implemented (see APPENDIX B); however, the average linkage is assumed to define solution partitions and relative *HCA* clusters; *v*) *PCA/HAC* outcomes are validated considering the silhouette value, the cophenetic correlation coefficient and the similarity measure between partitions B_k. In the following sections, the description of each analysed configuration is completed correspondent values of B_k referred to comparison between partitions respectively obtained with the average linkage and with other available linkage methods. Partitions are mutually compared through relative B_k values (see APPENDIX C). *vi*) 95% confidence intervals ("$CI_{95\%}$") are provided for all B_k values (see APPENDIX C); $CI_{95\%}$ values are derived applying the bootstrap method to all B_k setting in all cases 1000 bootstrap samples.

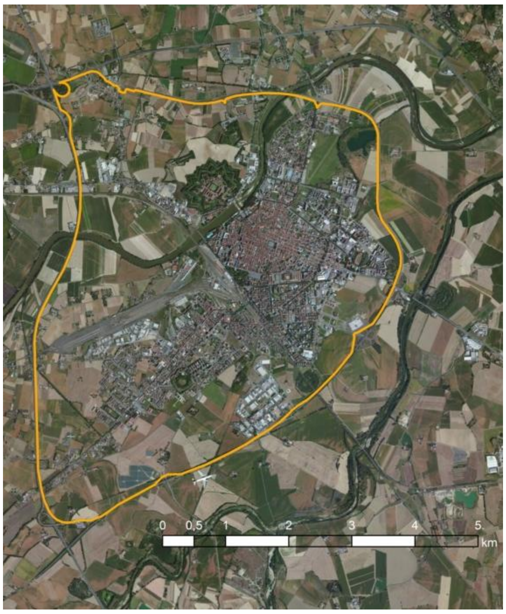

Figure 3.1: Alessandria - Study area boundary

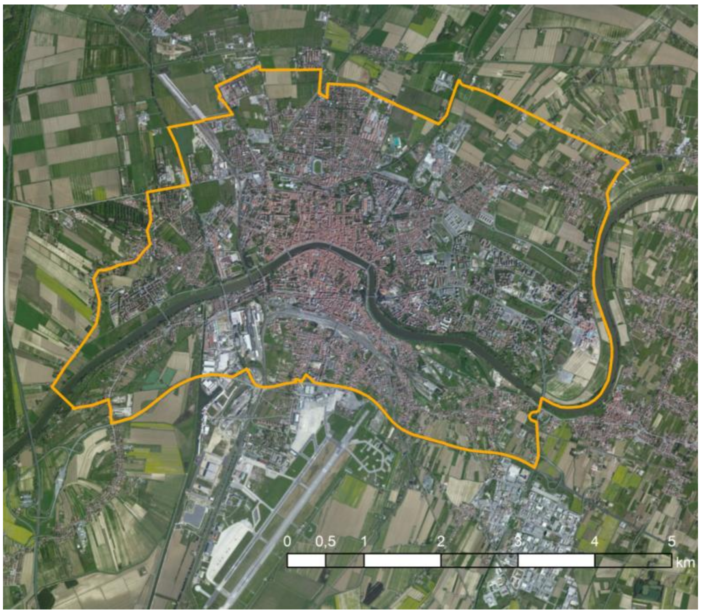

Figure 3.2: Pisa - Study area boundary

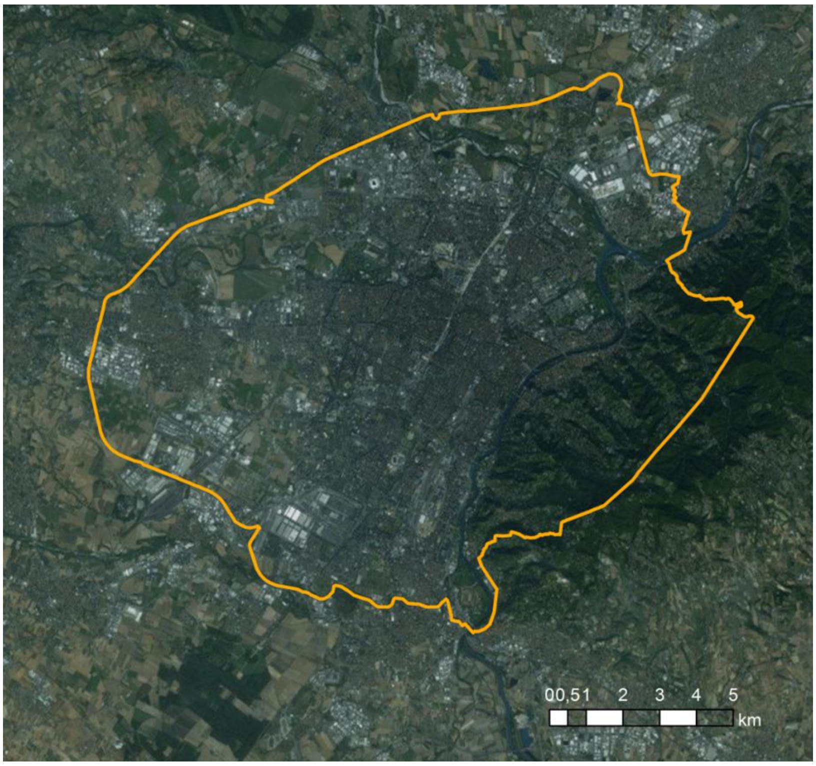

Figure 3.3: Torino - Study area boundary

❖ Alessandria

The study area is located in the north-west part of Italy. It covers about 29.0 km^2 with a mixed land uses pattern. The area is crossed by Tanaro river, whose total basin extent reaches around 8080 km^2 (Autorità di Bacino del fiume Po, 2006). The river divides the study area in two sub-areas (Fig. 3.4) differing from each other with reference to their extents as well as land uses. The first one ("A_1") is located in the southern part of the system, with a total area of about 21.6 km^2 almost equally composed of artificial surfaces (53.8% of A_1) and agricultural areas (46.2% of A_1). Territory of the second subsystem ("A_2") is significantly smaller than A_1, having a total area ("A_2") of about 6.6 km^2 largely covered by agricultural zones (72.8% of A_2)[5]. Looking at land uses pattern, it can be clearly deduced that urban areas are mostly concentrated in the southern river bank.

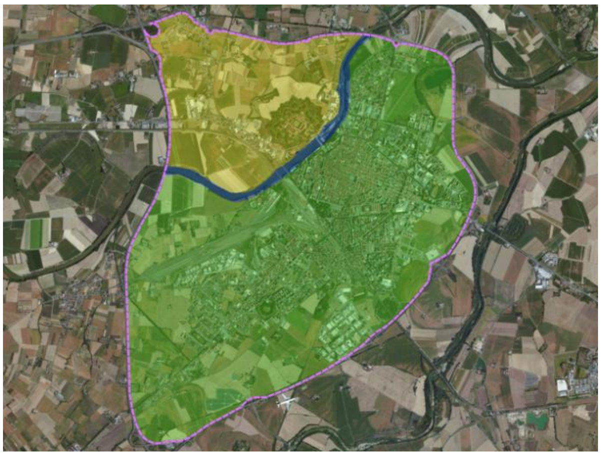

Figure 3.4: Alessandria - Study area boundary and subsystems (green area: A_1; yellow: A_2, blue: river)

In the same part of the study system, the urban grid presents a structured orthogonal layout, which almost completely contains both global (R= n) and local (R= 400m) integration cores (Fig. 3.5, Fig.3.6). Global choice core is spatially distributed within the grid, reflecting the connections between points of the grid that choice index represents (Fig. 3.7). The only bridge that connects the two river banks is included into the global choice core, as an important link to overcome the river unifying the urban system.

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[5] All percentages of land uses are obtained from the latest 2012 update "*CORINE2012*"of CORINE land cover inventory.

Figure 3.5: Alessandria - Global integration core (R = n) (black: segment map, red: 10% highest values)

Figure 3.6: Alessandria - Local integration core (R = 400m) (black: segment map, red: 10% highest values)

Figure 3.7: Alessandria - Global Choice core (R = n) (black: segment map, red: 10% highest values)

Synergy measure ("*S*"), or rather the statistical correlation between global and local integration, results to be not particularly strong (*S*= 0.54). However, this outcome allows to retain that there is a certain connection between global and local configurational structure, even not being noticeably high.

Considering a 500-years flood event, areas at risk to be flooded ("*AAR*") largely covers the northern part of the study system (Fig. 3.8) (Autorità di Bacino fiume Po, 1999) ("*STEP 0*"). Extent of *AAR* constitutes a percentage of 43.7% of the total study area extent.

Figure 3.8: Alessandria - Area at risk
(yellow: 500-year floodplain; orange: open spaces constituting the urban grid)

Segments of network within *AAR* constitute a percentage of 35.2% of the total length of the whole segment map. Superimposing main syntactic cores on *AAR*, areas of cores at risk to be flooded can be deduced, to be analysed both graphically and numerically ("*STEP 1*"). Even being the cores mostly located outside *AAR*, thematic maps of cores at risk (Fig. 3.9 - Fig. 3.11) still show a significant part of cores at risk.

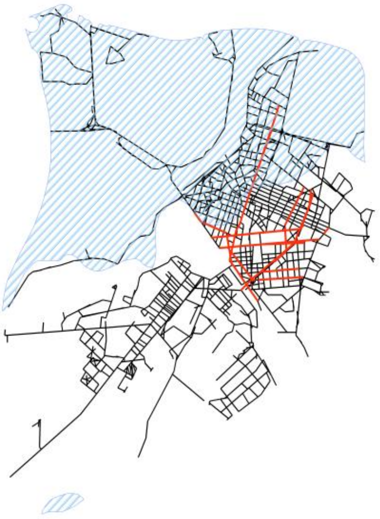

Figure 3.9: Alessandria - Global integration core at risk (black: segment map, red: global integration core (R= n), blue: area at risk)

Figure 3.10: Alessandria - Local integration core at risk (black: segment map, red: local integration core (R= 400m), blue: area at risk)

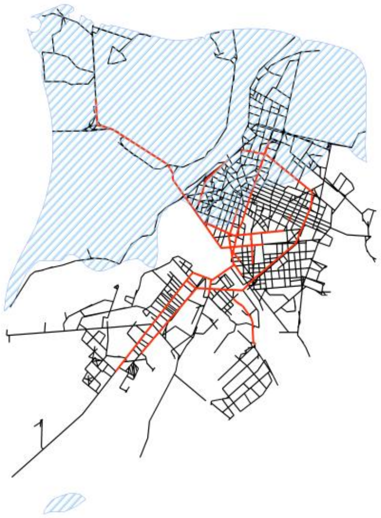

Figure 3.11: Alessandria - Global choice core at risk
(black: segment map, red: global integration core (R= n), blue: area at risk)

Frequency distributions of analysed indexes can be deduced for the whole system and the floodable parts. In reference to global integration and choice indexes, correspondent frequency curves of areas exposed to risk basically reflect the trends of relative frequency curve of the whole system (Fig. 3.12 - Fig. 3.14).

This outcome shows that elements exposed to risk are distributed within the whole range of values of each index, globally affecting all system configurational functions.

Focusing on syntactic cores (or rather, 10% of highest values of each index), susceptibility indicators can be obtained. Choice core results the most "susceptible" being exposed to the considered flood event. Lower -but still significant- values are obtained for global and local integration core at risk ($I_{s,\ int.\ (R=\ n),\ 10\%}$ = 0.17; $I_{s,\ int\ (R=\ 400m),\ 10\%}$ = 0.23; $I_{s,\ choice\ (R=\ n),\ 10\%}$ = 0.30). In reference to the wider range of 30% of highest indexes values, global integration susceptibility indicator does not vary ($I_{s,\ int.\ (R=\ n),\ 30\%}$ = 0.17). Choice core at risk increases ($I_{s,\ choice\ (R=\ n),\ 30\%}$ = 0.37) and local integration core sharply increases up to nearly double the correspondent 10%-range value ($I_{s,\ int.\ (R=\ 400m),\ 10\%}$ = 0.37).

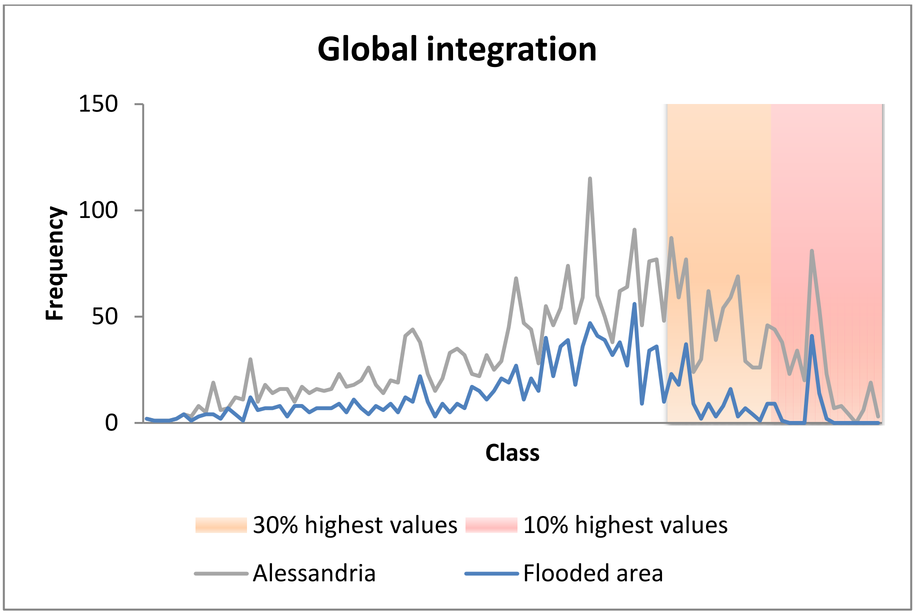

Figure 3.12: Alessandria - Frequency distribution curve of global integration index values (R= n)

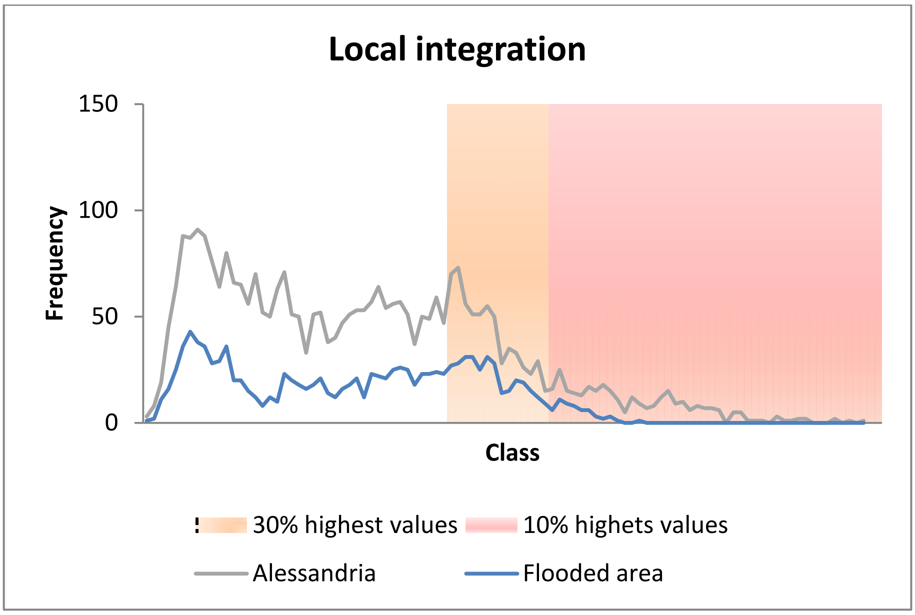

Figure 3.13: Alessandria - Frequency distribution curve of local integration index values (R= 400m)

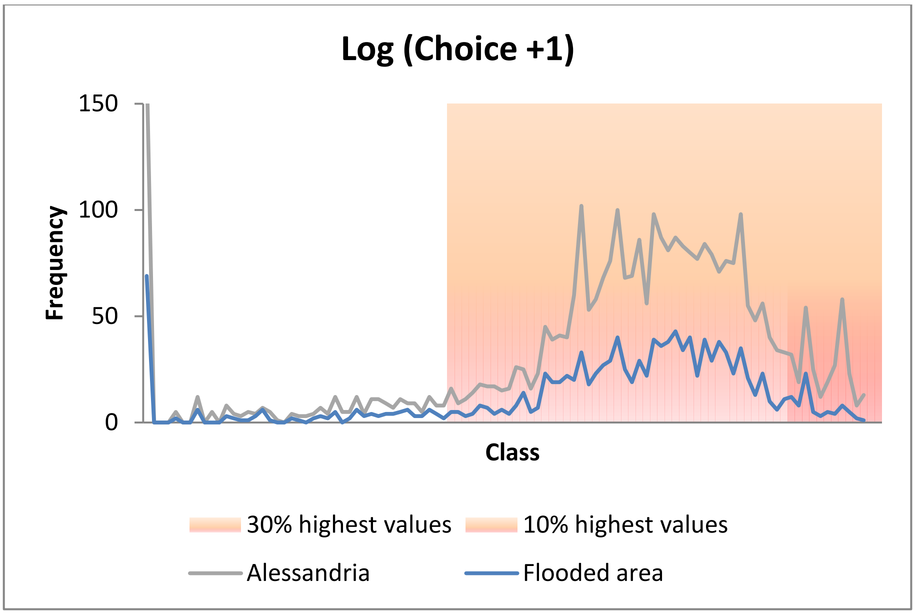

Figure 3.14: Alessandria - Frequency distribution curve of global choice index values (R= n)

Overlapping areas at risk, main syntactic cores and land use pattern (based on CORINE2012 land cover inventory), a detailed specification of elements of vulnerability is provided ("*STEP 2*"). Nine different land use types are individuated. Main cores at risk (V_{ntw1} = 1.3%; V_{ntw2} = 1.4%; V_{ntw3} = 2.8%) are mostly located within urbanised areas and commercial zones (Fig. 3.15 - Fig. 3.19, Table 3.1). The relevant percentage of integration core at risk correspond to urbanised areas; the high relative percentage of choice core at risk is coherent with high susceptibility indicators for choice index. This outcome allows to point out that flood consequences could be potentially severe, being cores at risk mainly located within continuous and discontinuous urban fabric, as well as industrial districts. In the context of physical vulnerability assessment, these three land use categories can be assumed as the most vulnerable elements. The latter are likely to constitute the most urbanised areas, increasing the vulnerability level as regard people at risk to be affected by the event. Elaborating ISTAT data (ISTAT, 2015), inhabitants at risk constitute 26.3% of total population and, together with the total value of all cores at risk (V_{ntw} = 5.5%), completes the vulnerability assessment ("*STEP 3*"). Outcomes show a significant level of urban vulnerability, both based on grid features and potential damages, and human risk (Fig. 3.20).

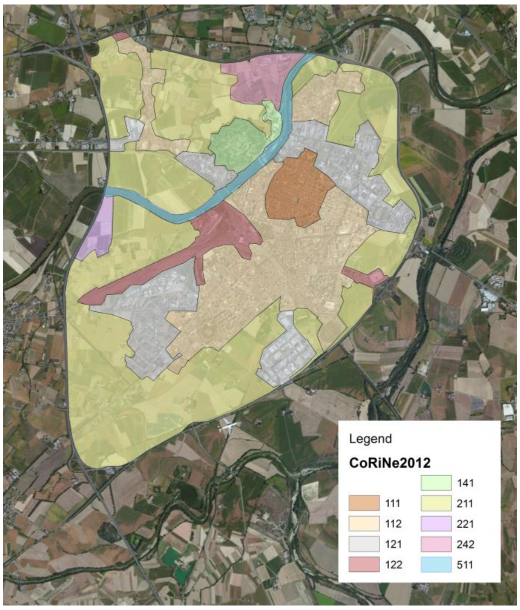

Figure 3.15: Alessandria - Land use (111: Continuous urban fabric; 112: Discontinuous urban fabric; 121: Industrial or commercial units; 122: Road and rail networks and associated land; 141: Green urban areas; 211: Non-irrigated arable land; 221: Vineyards; 242: Complex cultivation; 511: Water courses) (CORINE2012)

Segments at risk	35,2%			
Global integration core at risk	17,3% *(1,3% of tot.)*	49,2%	*(0.6% of tot.)*	Continuous urban fabric
		4,7%	*(0.1% of tot.)*	Discontinuous urban fabric
		46,1%	*(0.6% of tot.)*	Industrial or commercial units
		0,0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0,0%	*(0.0% of tot.)*	Green urban areas
		0,0%	*(0.0% of tot.)*	Non-irrigated arable land
		0,0%	*(0.0% of tot.)*	Vineyards
		0,0%	*(0.0% of tot.)*	Complex cultivation
		0,0%	*(0.0% of tot.)*	Water courses
Local integration core at risk	23,1% *(1,4% of tot.)*	77,1%	*(1.1% of tot.)*	Continuous urban fabric
		10,0%	*(0.1% of tot.)*	Discontinuous urban fabric
		13,0%	*(0.2% of tot.)*	Industrial or commercial units
		0,0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0,0%	*(0.0% of tot.)*	Green urban areas
		0,0%	*(0.0% of tot.)*	Non-irrigated arable land
		0,0%	*(0.0% of tot.)*	Vineyards
		0,0%	*(0.0% of tot.)*	Complex cultivation
		0,0%	*(0.0% of tot.)*	Water courses
Global choice core at risk	30,3% *(2,8% of tot.)*	39,4%	*(1.1% of tot.)*	Continuous urban fabric
		38,5%	*(1.1% of tot.)*	Discontinuous urban fabric
		19,4%	*(0.6% of tot.)*	Industrial or commercial units
		0,0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0,0%	*(0.0% of tot.)*	Green urban areas
		0,0%	*(0.0% of tot.)*	Non-irrigated arable land
		0,0%	*(0.0% of tot.)*	Vineyards
		0,0%	*(0.0% of tot.)*	Complex cultivation
		2,7%	*(0.1% of tot.)*	Water courses

Table 3.1: Alessandria - Percentages of network and syntactic cores at risk for each land use

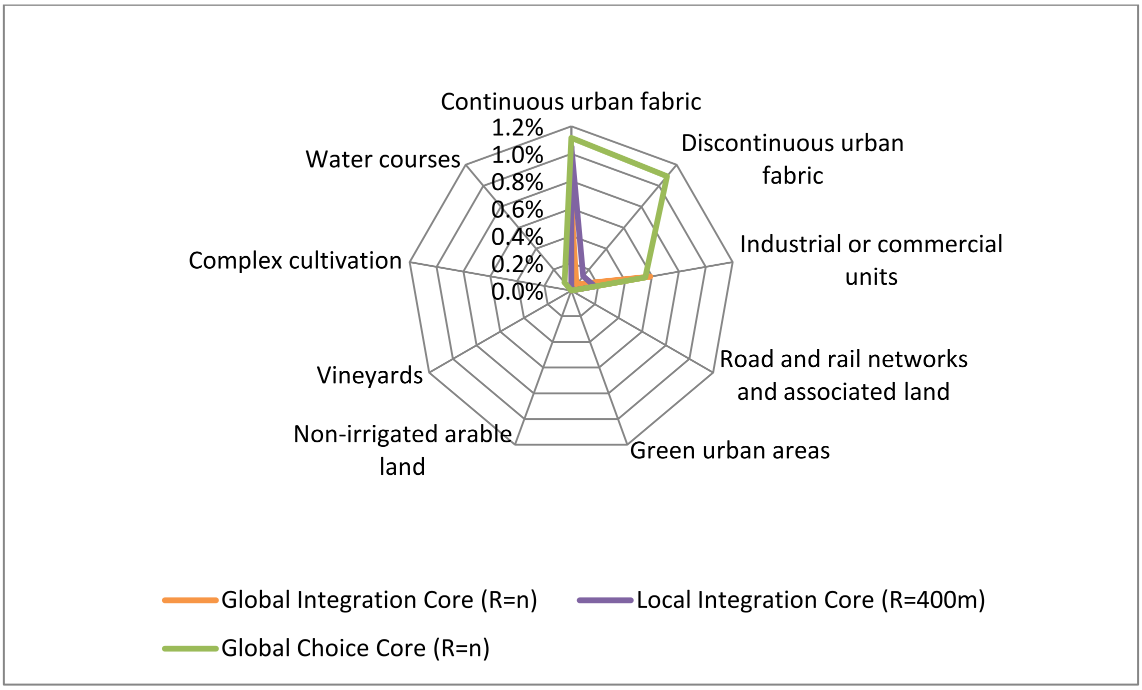

Figure 3.16: Alessandria - Percentages of syntactic cores at risk for each land use

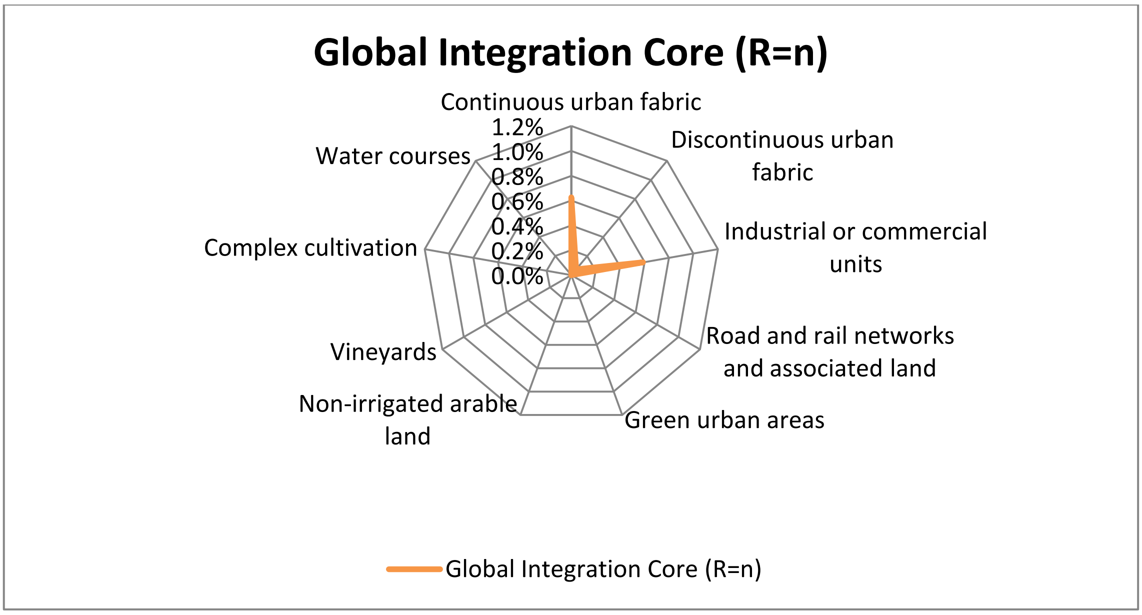

Figure 3.17: Alessandria - Percentages of global integration core at risk (R= n) for each land use

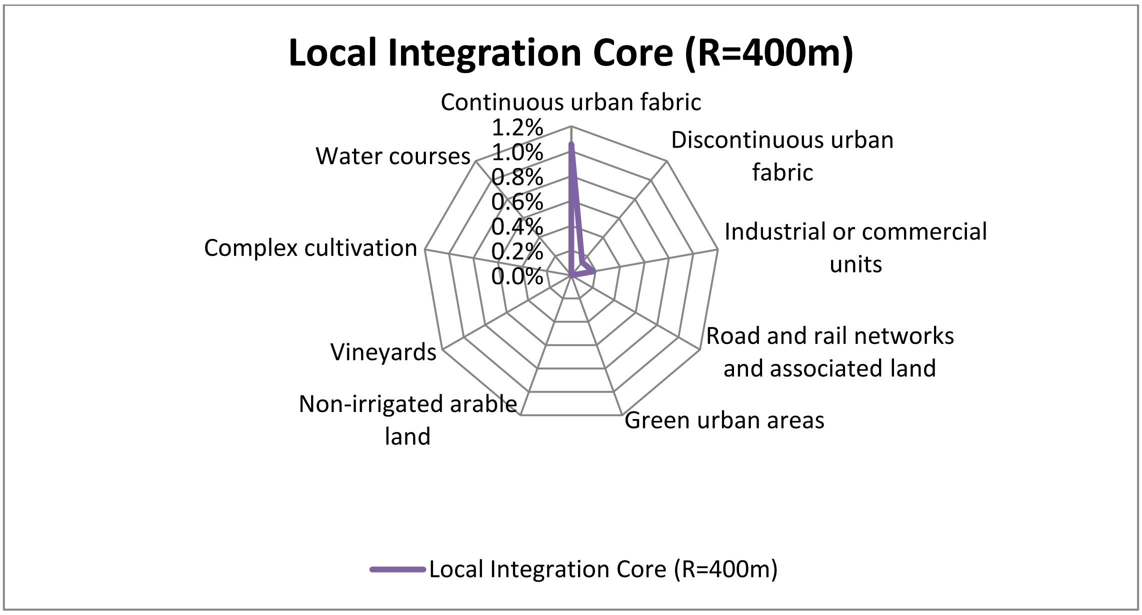

Figure 3.18: Alessandria - Percentages of local integration core at risk (R= 400m) for each land use

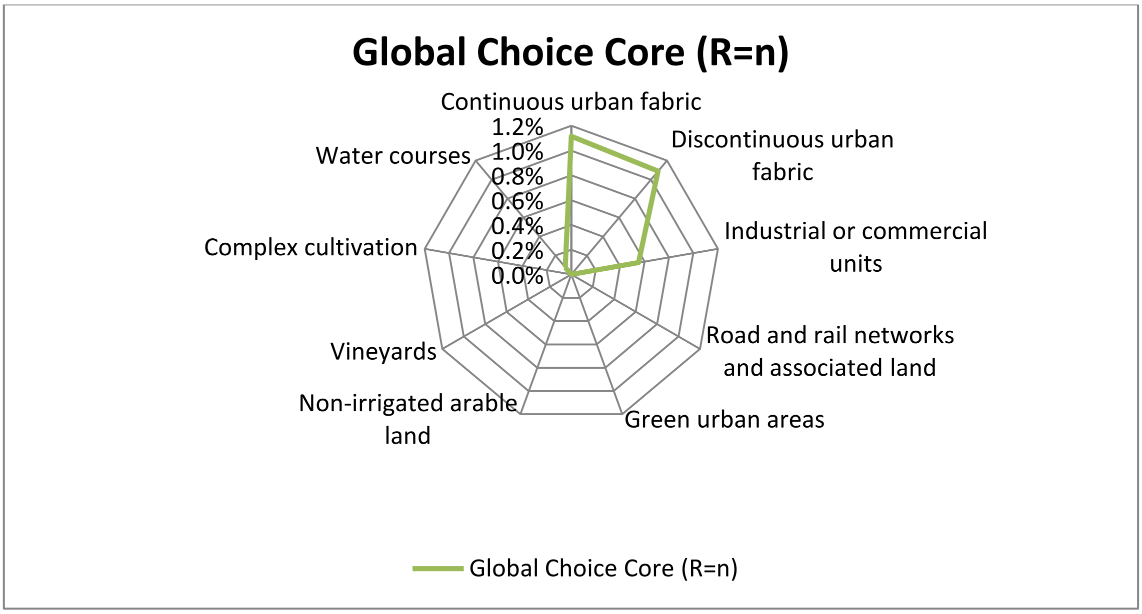

Figure 3.19: Alessandria - Percentages of global choice core at risk (R= n) for each land use

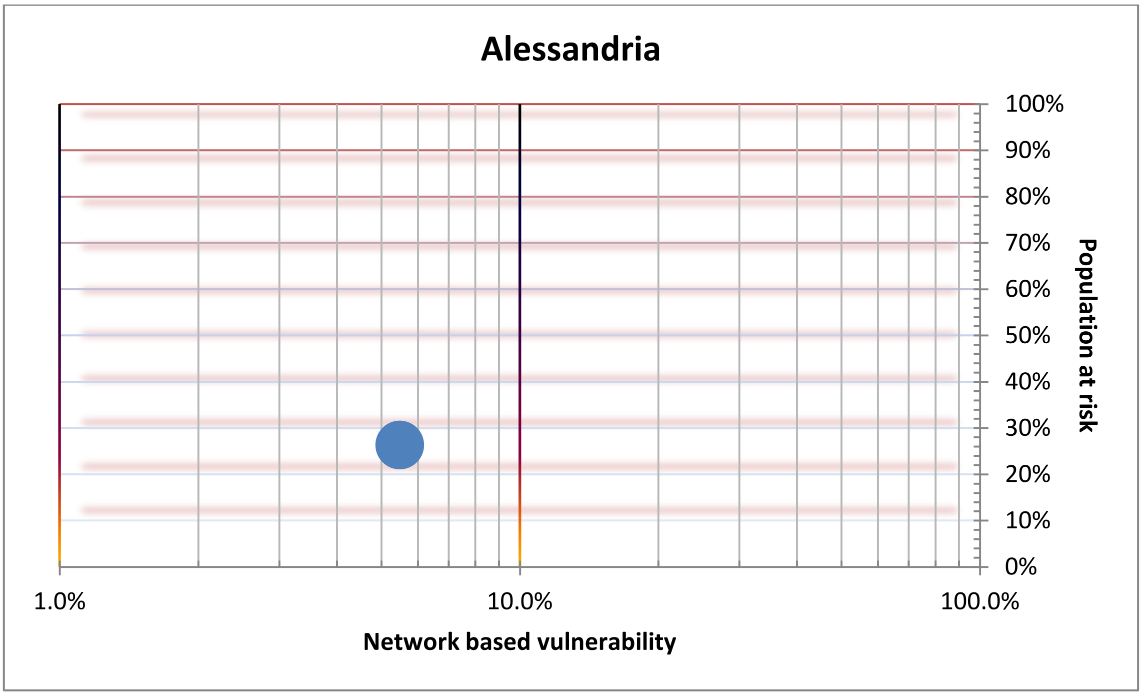

Figure 3.20: Alessandria - Representation of vulnerability elements

The 500-years flood-prone areas cover a large part of the study area. The southern part results to be not at risk to be flooded, constituting the *Scenario1*-configuration. Applying *ASA* to this non-flooded subsystem, the post-event configuration is examined (Fig. 3.21, Fig. 3.23, Fig. 3.25). Outcomes show the presence of structured global and local cores, even being these new cores smaller if compared to relative *Scenario0*-configuration cores (Fig. 3.22, Fig. 3.24, Fig. 3.26). All examined indexes are changed in their values and spatial distribution: in reference to global integration, new areas assume a central role becoming part of the relative post-event global integration core; local integration core and global choice core result modified due to the lack of same parts if compared to *Scenario0* correspondent cores.

Figure 3.21: Alessandria - *Scenario 1*, global integration core (R= n) (black: segment map; red: global integration core (R= n); grey: segments within flooded areas)

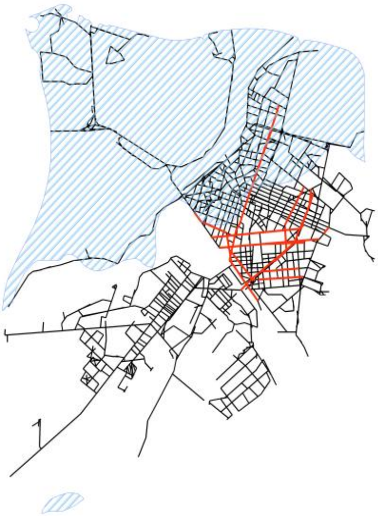

Figure 3.22: Alessandria - *Scenario 0* (black: segment map; red: global integration core (R= n); blue: area at risk)

Figure 3.23: Alessandria - *Scenario 1*, local integration core (R= 400m) (black: segment map; red: local integration (R= 400m); grey: segments within flooded areas)

Figure 3.24: Alessandria - *Scenario 0* (black: segment map; red: local integration core (R= 400), blue: area at risk)

Figure 3.25: Alessandria - *Scenario 1*, global choice core (R= n) (black: segment map, red: global choice (R= n); grey: segments within flooded areas)

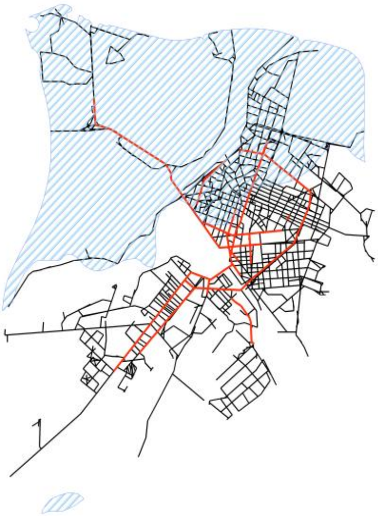

Figure 3.26: Alessandria - *Scenario 0* (black: segment map, blue: area at risk; red: global choice core (R= n)

Analysing normalised global (R= n) integration for the two *Scenarios*, relative frequency distributions show two almost overlapping curves, meaning an overall similar pattern of integration. Normalised global integration and choice (R= n) present a decrease in *Scenario1*, if compared to correspondent frequency distribution of *Scenario0*. However, the two frequency distribution curves show a similar distribution of values across all the considered 100 intervals (Fig. 3.27, Fig. 3.28).

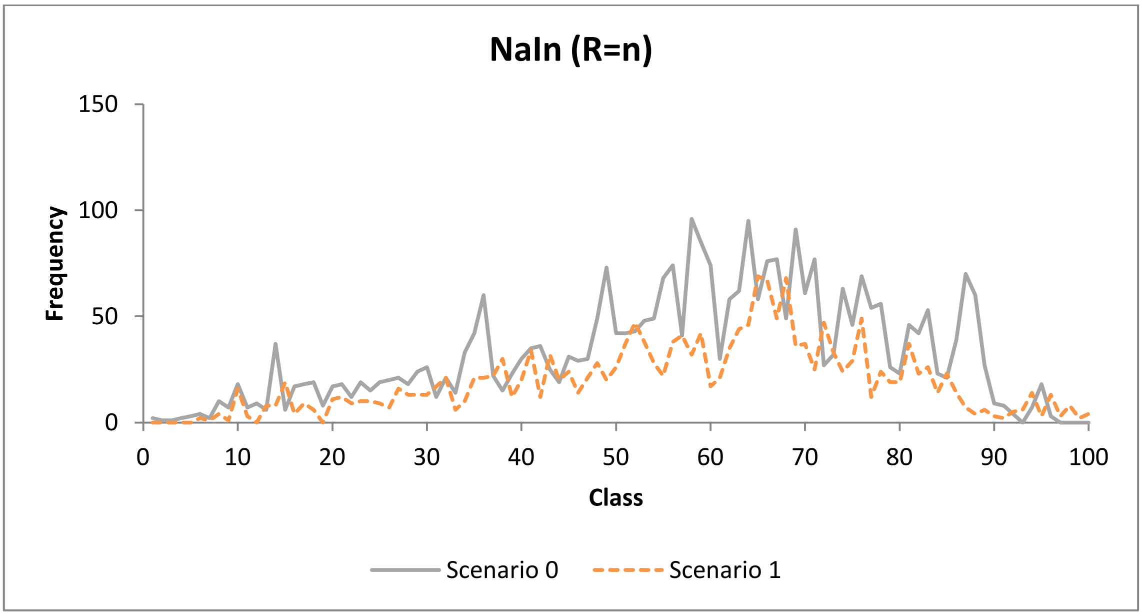

Figure 3.27: Alessandria - Comparison between *Scenario 0* and *Scenario 1* frequency distribution curve of normalised global integration values

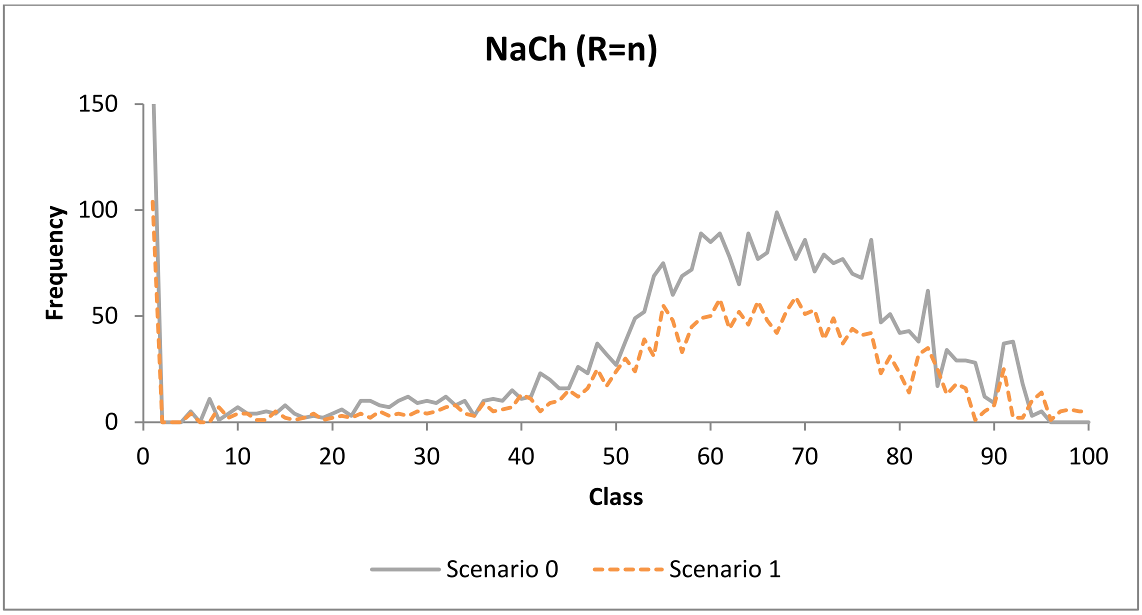

Figure 3.28: Alessandria - Comparison between *Scenario 0* and *Scenario 1* frequency distribution curve of normalised global integration value

In order to achieve a global comparison between *Scenario0* and *Scenario1*, the correspondent two configurations are analysed on the basis of *PCA* outcomes. Processing syntactic dataset respectively for *Scenario0* and *Scenario1*, in both cases two principal component are selected (PC_1, PC_2) as able to accurately reproduce the original dataset, according to all criteria of selection of meaningful components (see Chap.2, Par. 2.2.3):

- ***Scenario 0*** - Three groups can be pointed out to highlight main features of the grid (Fig. 3.30). A first large set of elements with value similar to mean values of all variables can be pointed out (Fig. 3.30, black points; Fig. 3.31, black segments). In addition, a significant group of points is defined with distinctive values both of global integration and global choice (Fig. 3.30, orange points; Fig. 3.31, orange segments). It has to be noticed that, even not constituting a proper separated group, the group of points of this second cluster having high values of both x and y coordinates (or rather, PC_1 and PC_2) are also characterised by high value of local indexes (Fig. 3.29). The second cluster highlights the skeleton of the syntactic structure, assuming a significant role for the movement economy. Indeed, correspondent segments that cluster accounts for are located within the most urbanised zone. A further cluster is made up just of two elements (Fig. 3.30, blue points; Fig. 3.31, blue segments): similarly to the previous group, these units represent spaces with high values of global choice, but they are separately grouped having also a significant segment length. In fact, these two elements constitute some of the main connections between the two river banks on which the urban system is structured.

(*Silhouette* = 0.361; *CCC*= 0.694;
B_k *[Avg.-Single*] = 0.916; B_k *[Avg.-Complete]*=0.710; B_k *[Avg.-Median]*=0.748; B_k *[Avg.-Centroid]*= 0.916; B_k *[Avg.-Ward]*=0.640).

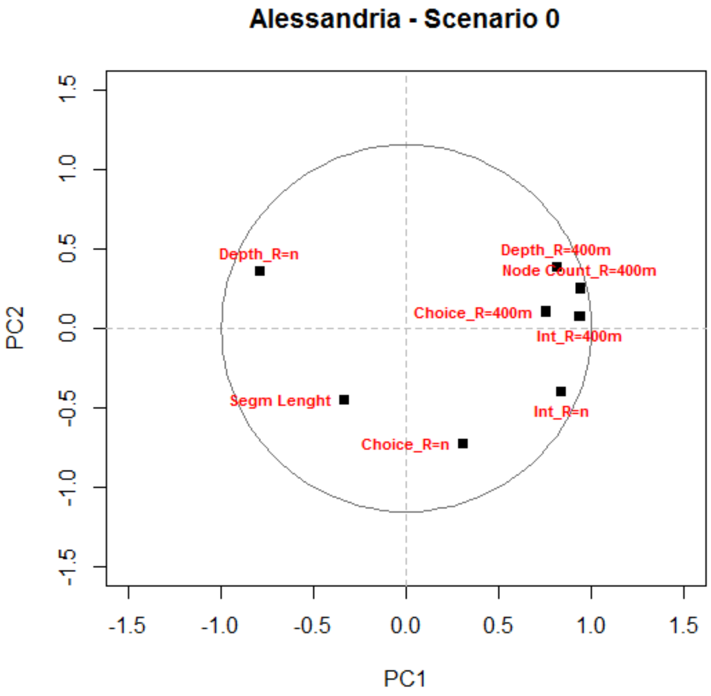

**Figure 3.29: Alessandria - *Scenario 0*,
correlation circle**

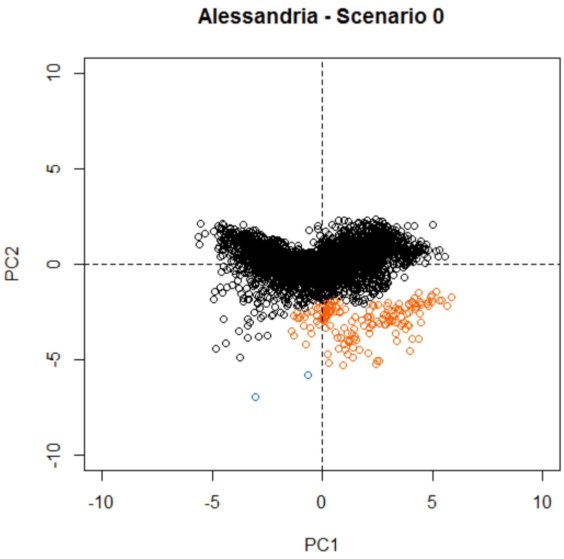

Figure 3.30: Alessandria - *Scenario 0*, score plot

Figure 3.31: Alessandria - *Scenario 0*, outcomes *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.30)

- ***Scenario 1*** - Four clusters that can be individuated from the dataset of syntactic measures (Fig. 3.33). A large group of segments with average values of all considered *p* variables (Fig. 3.33, black points; Fig. 3.34, black segments). A group of elements owns particularly significant values of local indexes (Fig. 3.33, green points; Fig. 3.34, green segments). This strategic role is limited to the local scale, having this cluster low values both of global integration and global choice. A meaningful second set of elements represents segments with distinguishing values of global (both integration and choice) and local indexes (Fig. 3.33, orange points; Fig. 3.34, orange segments). Correspondently, location of relative segments within the grid shows a set of spaces where local and global dynamics are overlapped. Few elements constitute a further group, representative of high choice long segments, not well integrated (Fig. 3.33, blue points, Fig. 3.34: blue segments).
  (*Silhouette* =0.327; *CCC*=0.719;
  B_k *[Avg.-Single*]= 0.819; B_k *[Avg.-Complete]=* 0.680; B_k *[Avg.-Median]=* 0.710; B_k *[Avg.-Centroid]* 0.833; B_k *[Avg.-Ward]=* 0.631).

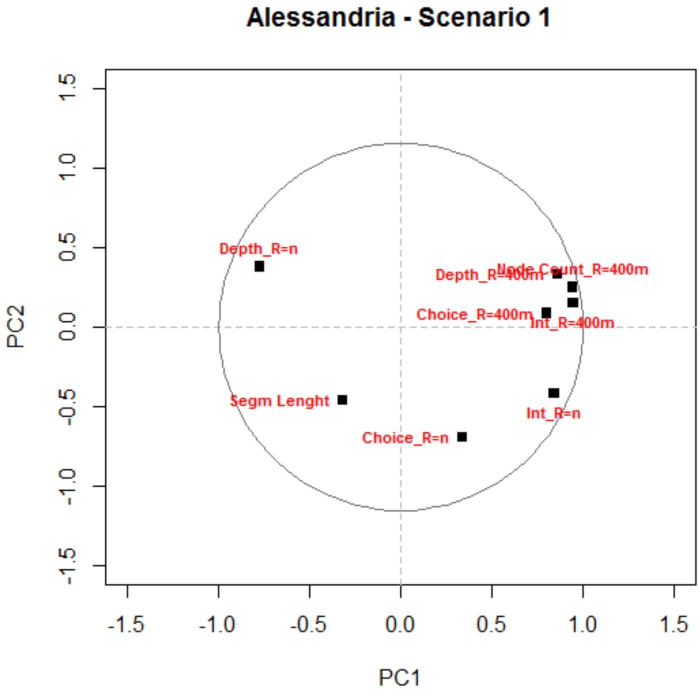

Figure 3.32: Alessandria - *Scenario* 1, correlation circle

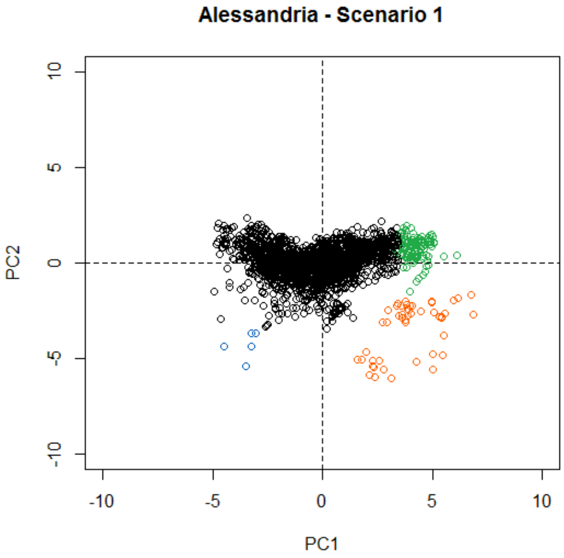

Figure 3.33: Alessandria - *Scenario 1*, score plot

Figure 3.34: Alessandria - *Scenario 1*, outcomes *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.33)

Based on the comparison between outcomes of this stage, it follows that basically local centralities emerge after the event. These post-event local cores are more clearly defined than in the actual configuration. Spaces with strategic global role can still be pointed out after flooding, even constituting a more restricted area of the grid than in *Scenario0*. As a result, the event gives a more specific function to some spaces, limiting their role at the local scale and sharpening the difference between local and global roles.

❖ Pisa

The study area is located in the central-west part of Italy, covering about 24.9 km^2 of mostly urbanised territory. The area is almost centrally crossed by Arno river, one of the major Italian rivers, having a total basin of 9116 km^2 (http://www.adbarno.it). The river course divides the system in two sub-areas, respectively having -the first one ("A_1")- a total area of 17.0 km^2 and -the second one ("A_2")- a total area of 7.0 km^2 (Fig. 3.35). Both these subsystems show a similar land uses distribution (based on CORINE2012 land use inventory data): a large part of artificial uses (66.6% of A_1; 72.7% of A_2) mixed with a smaller percentage of naturally covered lands (33.4% of A_1; 27.3% of A_2 area).

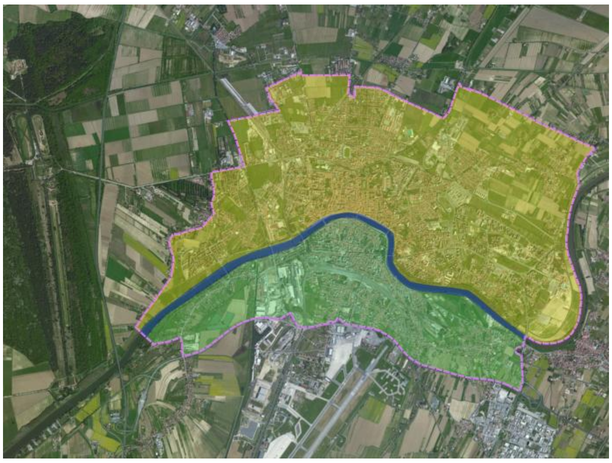

Figure 3.35: Pisa - Study area boundary and subsystems (green area: A_1; yellow: A_2, blue: river)

Syntactic cores of the system -both at global and local scale- are located along or next to the river (Fig. 3.36 - Fig. 3.38), reflecting the importance of the water course in structuring the grid and influencing activities located on river banks. In particular, local centralities strongly converge next to the river. The choice core highlights a more diffused structure connecting different points of the network.

Lastly, according to synergy value, local and global structure do not show a mutual high level of connection (*S* = 0.42). Given the particular physical and syntactic structure of this river-city, all cores (both at global and local scale) include bridges. Some river crosses belong to more than one core at the same time, playing a particularly relevant role in regard of the movement economy process. The linking function of bridges, indeed, can be assumed representative of the ability of the urban system to include the river in itself. According to the meaning of syntactic cores, in the case of the said river crossings, this function is also combined with their influence as destinations (as well as connection paths) within the system.

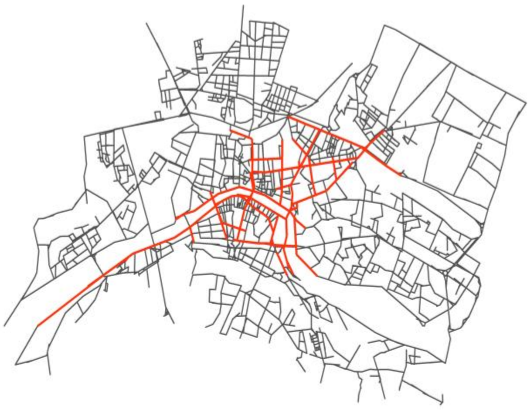

Figure 3.36: Pisa - Global integration core (R= n) (black: segment map; red: 10% highest values)

Figure 3.37: Pisa -Local integration core (R = 400m) (black: segment map; red: 10% highest values)

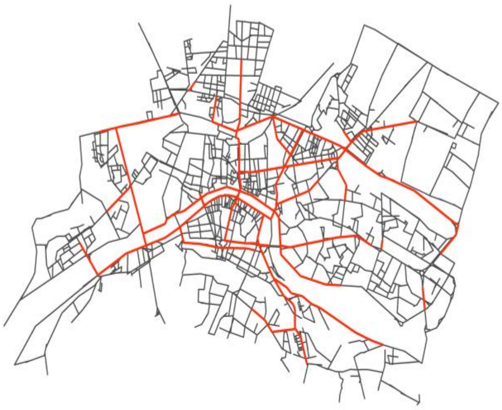

Figure 3.38: Pisa - Global choice core (R = n)
(black: segment map; red: 10% highest values)

In order to evaluate network vulnerability, *AAR* ("*STEP 0*") is defined considering a 100-years return period event (Fig. 3.39) (according to the criteria adopted by Arno River Basin Authority (2002), *AAR* constitute areas at risk to be flooded in case *T*≤ 100 years and water level higher than 0.30m) (Autorità di Bacino del fiume Arno, 2002). Arno river crosses almost centrally the study area. However, territorial morphology and presence of a smaller water course next to the upper-west border of the study area determine large (and scattered) zones at risk to be flooded within the analysed system. Extent of *AAR* constitutes 38.4% of the total study area.

Figure 3.39: Pisa- Area at risk
(yellow: 100-year floodplain; orange: open spaces constituting the urban grid)

Shape and extent of flood prone areas, as well as the cores mostly located along and across the river, make the system highly exposed to floods. A general overview of areas at risk (Fig. 3.40 - Fig. 3.42) allows to deduce that large parts of all cores result to be at risk to be flooded ("*STEP 1*").

Figure 3.40: Pisa - Global integration core at risk (black: segment map; red: global integration core (R= n); blue: area at risk)

Figure 3.41: Pisa - Local integration core at risk (black: segment map; red: global integration core (R= 400M); blue: area at risk)

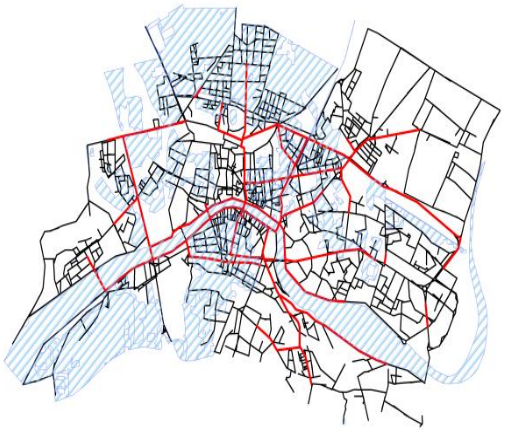

Figure 3.42: Pisa. Global choice core at risk
(black: segment map; red: global integration core (R= n); blue: area at risk)

All segments at risk constitute the 33.1% of the total network length. Focusing on the most strategic spaces of the grid, or rather spaces that contain segments of cores, the susceptibility indicator shows that the local integration core is the most likely to be affected by the event ($I_{s,\ \text{int.}\ (R=\ 400m),\ 10\%} = 0.67$). Slightly lower values are obtained for global integration ($I_{s,\ \text{int.}\ (R=\ n),\ 10\%} = 0.46$) and global choice ($I_{s,\ \text{choice}\ (R=\ n),\ 10\%} = 0.33$). In reference to global integration core, similar results are achieved both examining 30% of highest values ($I_{s,\ \text{int.}\ (R=\ n),\ 30\%} = 0.43$), confirming that most integrated areas are near the river, even assuming a wider range of values. Graphically comparing frequency distribution curves (Fig. 3.43 - Fig. 3.45) of total and floodable areas within 10% highest values ranges, their trends show that a large part of the system is exposed to risk, especially for global and local integration. Small differences in respect of relative 10% values can be noticed for local choice and global choice ($I_{s,\ \text{int.}\ (R=\ 400m),\ 30\%} = 0.56$; $I_{s,\ \text{choice}\ (R=\ n),\ 30\%} = 0.31$). These results reveal a highly vulnerable local structure, confirming and substantiating considerations deduced from thematic maps of cores at risk.

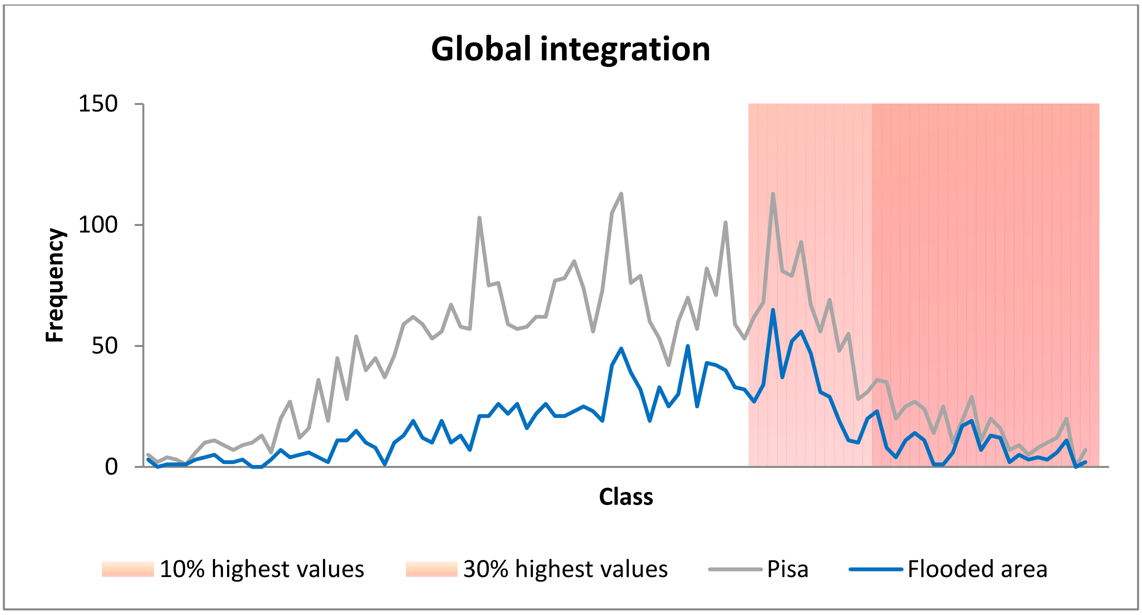

Figure 3.43: Pisa - Frequency distribution curve of global integration index values (R= n)

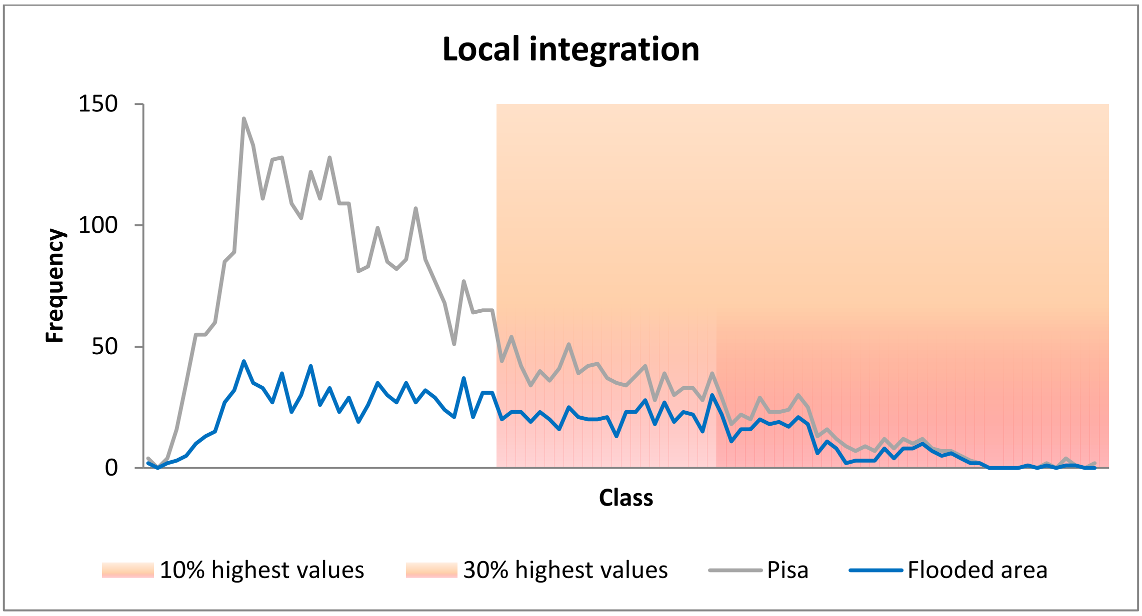

Figure 3.44: Pisa - Frequency distribution curve of local integration index values (R= 400m)

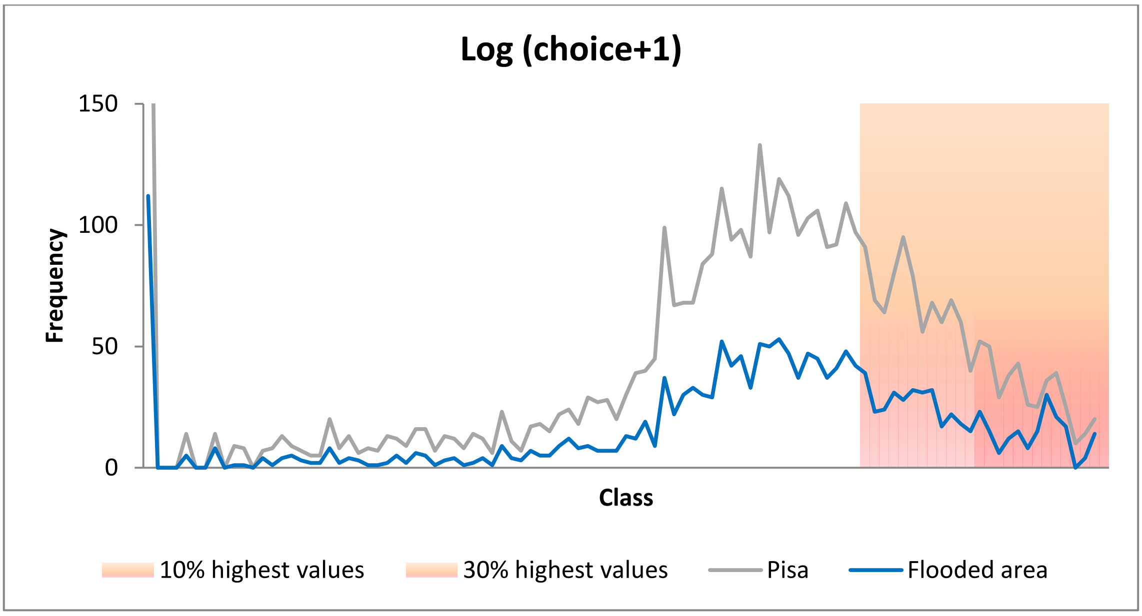

Figure 3.45: Pisa - Frequency distribution curve of global choice index values (R= n)

Large parts of all cores are located within *AAR*. Nine types of land uses can be individuated within the study area (CORINE2012) (Fig. 3.46). However, all cores at risk are almost concentrated within urban fabric and industrial and commercial areas (Table 3.2, Fig. 3.47 - Fig. 3.50). In particular, local integration core within continuous urban fabric is a strong element of vulnerability, representing in large part pedestrian movement and local activities that can be affected by the event, in addition to the historical and artistic value of the areas that core belongs to. Similar trends are shown by global integration core and choice core. Examining land use pattern of areas at risk, it follows that most of these cores at risk are also located in the most urbanised and densely inhabited part, which at the same time mostly constitutes the historical centre of the city ("*STEP 2*"). The event affects all examined cores, particularly impacting the local movement and dynamics, being at risk more than half of the local integration core (67.4% of the core is at risk). Percentages of cores overlapping watercourses stand for river crossings at risk. All these observations allows to conclude that, as concerns configurational and morphological issues, a flood event can seriously affect Pisa urban structure, especially regarding both the integration cores (i.e. at global and local scale).

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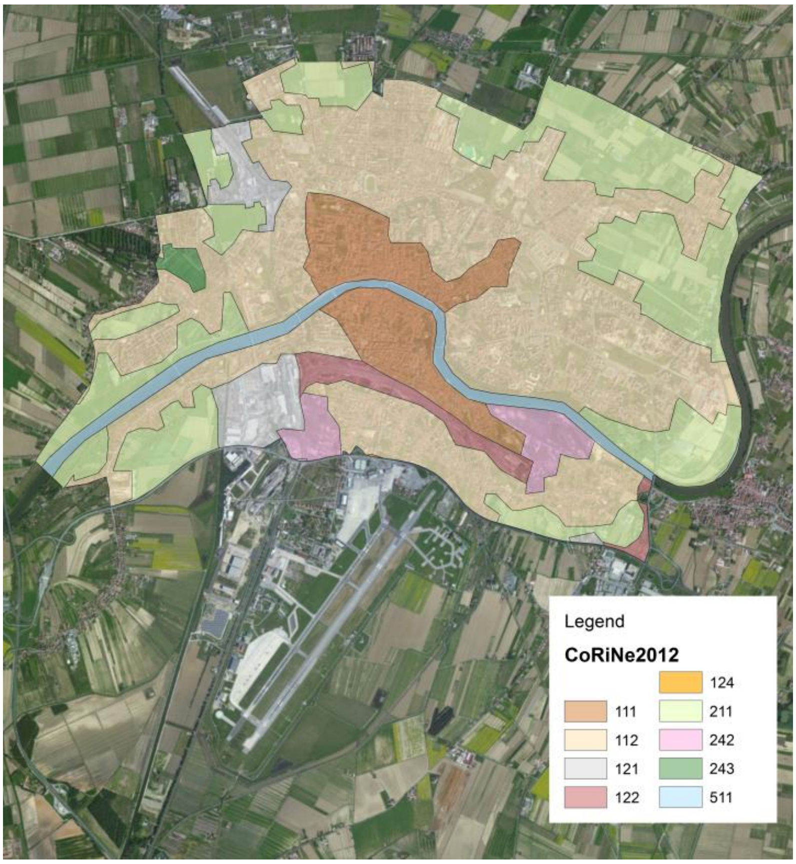

Figure 3.46: Pisa - Land use (111: Continuous urban fabric; 112: Discontinuous urban fabric; 121: Industrial or commercial units; 122: Road and rail networks and associated land; 124: Airports; 211: Vineyards; 242: Complex cultivation; 243: Land principally occupied by agriculture, with significant areas of natural vegetation; 511: Water courses) (CORINE2012)

Segments at risk	33.1%			
Global integration core at risk	45.6% *(4,3% of tot.)*	51.6%	*(2.2% of tot.)*	Continuous urban fabric
		42.7%	*(1.8% of tot.)*	Discontinuous urban fabric
		0.0%	*(0.0% of tot.)*	Industrial or commercial units
		0.0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Green urban areas
		2.1%	*(0.1% of tot.)*	Non-irrigated arable land
		0.0%	*(0.0% of tot.)*	Vineyards
		0.0%	*(0.0% of tot.)*	Complex cultivation
		3.6%	*(0.2% of tot.)*	Water courses

Local integration core at risk	67.4% *(3,4% of tot.)*	78.3%	*(2.7% of tot.)*	Continuous urban fabric
		18.7%	*(0.6% of tot.)*	Discontinuous urban fabric
		0.0%	*(0.0% of tot.)*	Industrial or commercial units
		0.9%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Green urban areas
		0.0%	*(0.0% of tot.)*	Non-irrigated arable land
		0.0%	*(0.0% of tot.)*	Vineyards
		0.0%	*(0.0% of tot.)*	Complex cultivation
		2.1%	*(0.1% of tot.)*	Water courses

Global choice core at risk	33.1% *(4,2% of tot.)*	38.4%	*(1.6% of tot.)*	Continuous urban fabric
		51.2%	*(2.1% of tot.)*	Discontinuous urban fabric
		2.3%	*(0.1% of tot.)*	Industrial or commercial units
		0.0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Green urban areas
		2.5%	*(0.1% of tot.)*	Non-irrigated arable land
		1.1%	*(0.0% of tot.)*	Vineyards
		0.0%	*(0.0% of tot.)*	Complex cultivation
		4.6%	*(0.2% of tot.)*	Water courses

Table 3.2: Pisa - Percentages of network and syntactic cores at risk for each land use

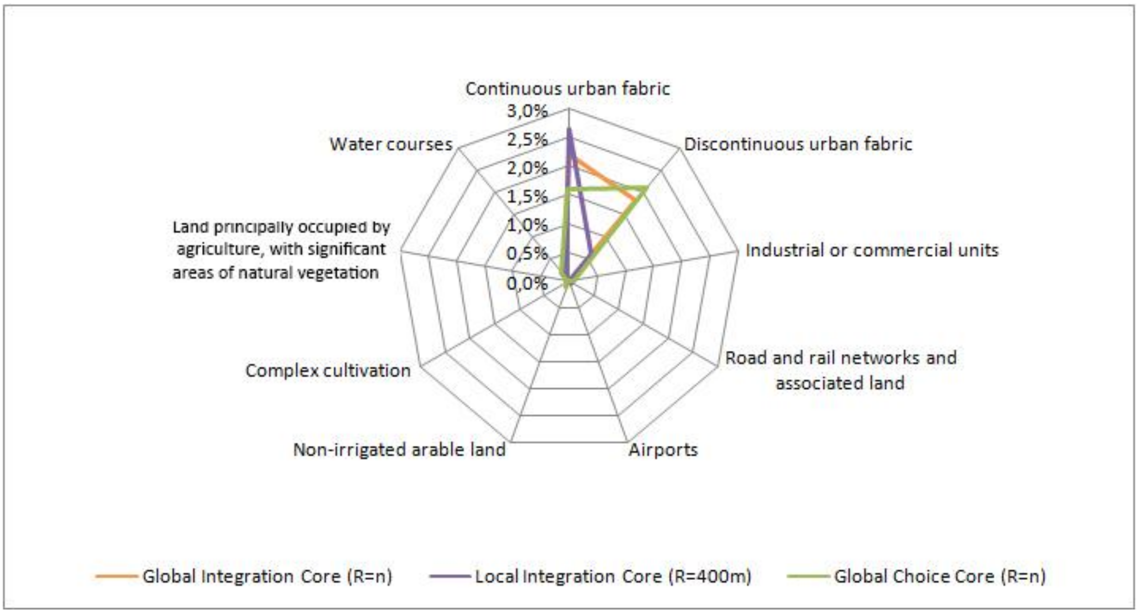

Figure 3.47: Pisa - Percentages of syntactic cores at risk for each land use

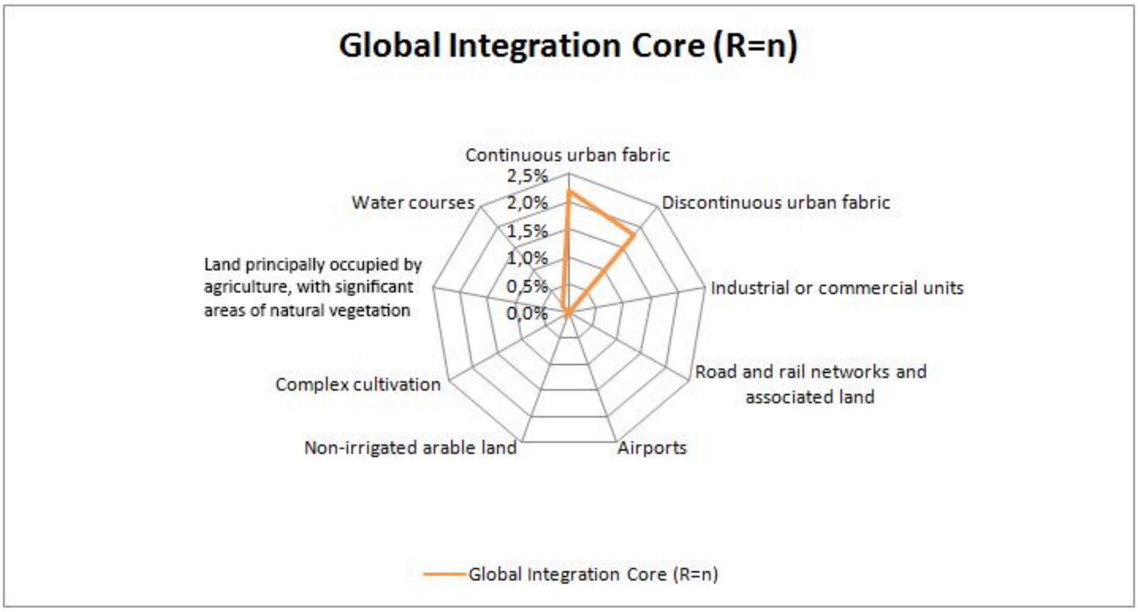

Figure 3.48: Pisa -Percentages of global integration core (R= n) at risk for each land use

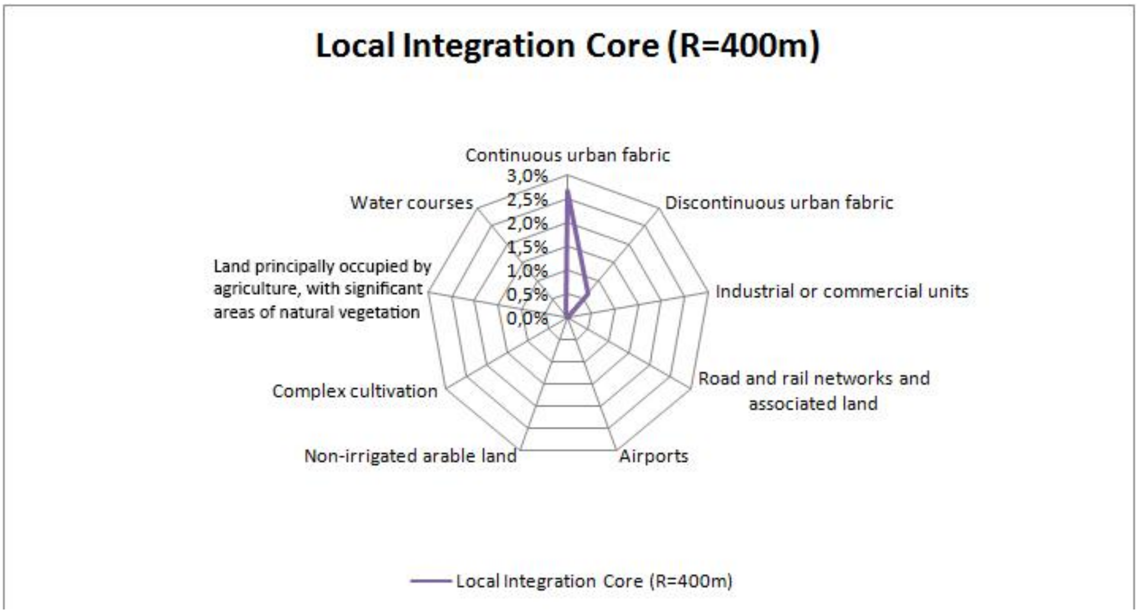

Figure 3.49: Pisa -Percentages of local integration core (R= 400m) at risk for each land use

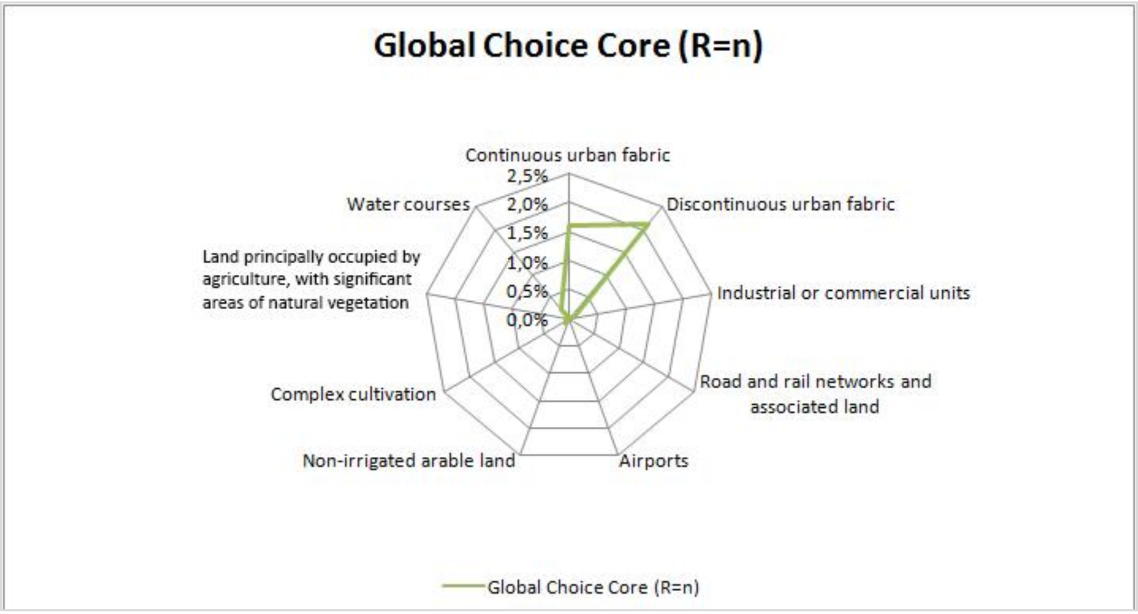

Figure 3.50: Pisa -Percentages of global choice core (R= n) at risk for each land use

Significant elements of vulnerability, pointed out through previous steps, are confirmed by values of network-based vulnerability and population at risk ("*STEP 3*"): the total value of all cores at risk V_{ntw} represents a percentage of 11.8% of the total network (V_{ntw1} = 4.3%; V_{ntw2} = 3.4%; V_{ntw3}= 4.2%) the percentage value of population potentially at risk results to be 35.4% of the total population of the study area (Fig. 3.51). Therefore, high levels both of structural vulnerability and human risks can be noticed.

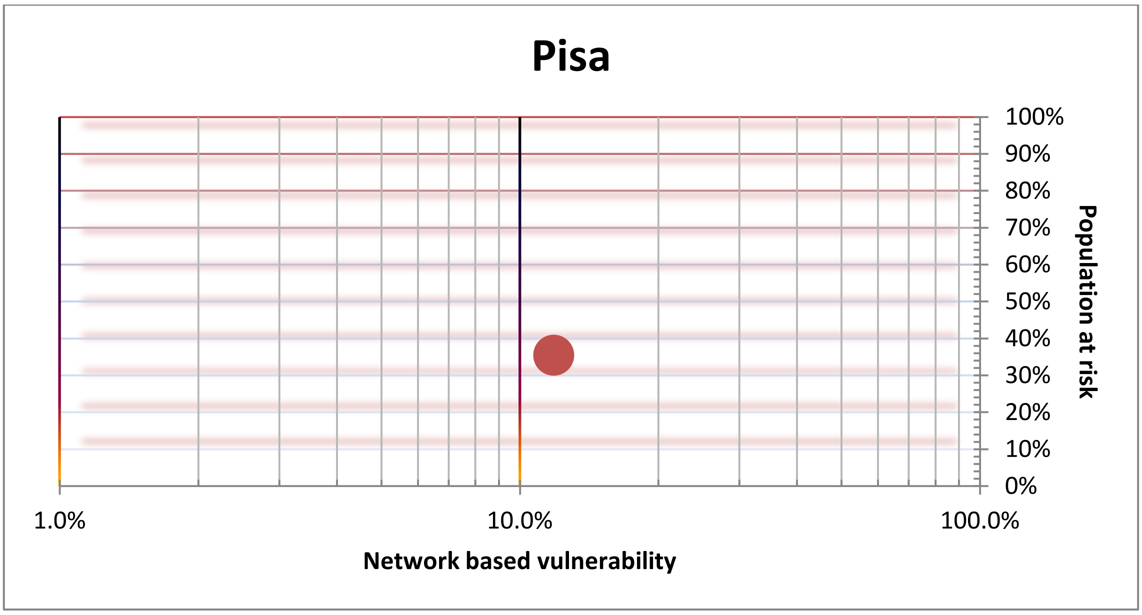

Figure 3.51: Pisa- Representation of vulnerability elements

Considering extent and location of *AAR*, flooded areas divide the study system in four smaller subsystems (Fig. 3.52), of various dimensions. In fact, the system is spatially broken and the modeled post-event configuration significantly differs from the actual configuration (Fig. 3.52- Fig. 3.57).

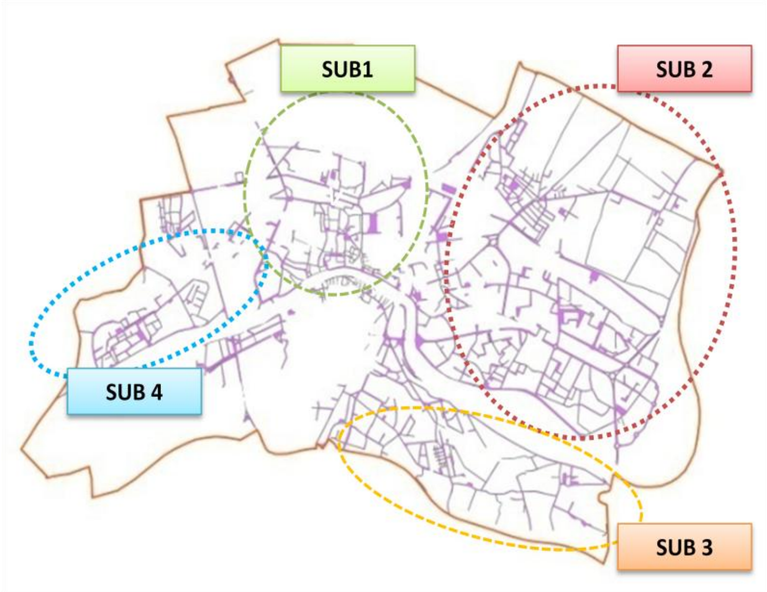

Figure 3.52: Pisa, *Scenario 1*. Post-event configuration and relative subsystems

Given that in *Scenario0*-configuration main cores are located along or across the river (Fig. 3.54, Fig. 3.56, Fig. 3.58), their structures and localisation is compromised by the event. Individually examining each subsystem, *ASA* outcomes provide cores located in discontinuous spaces (Fig. 3.53, Fig. 3.55, Fig. 3.57).

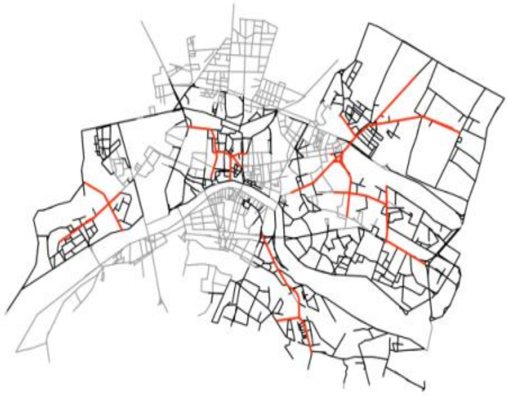

Figure 3.53: Pisa - *Scenario 1*, global integration core (R= n) (black: segment map; red: global integration core (R= n); blue: area at risk; grey: segments within flooded area)

Figure 3.54: Pisa - *Scenario 0* (black: segment map; red: global integration core (R= n); blue: area at risk)

Figure 3.55: Pisa - *Scenario 1*, local integration core (R= 400m) (black: segment map; red: local integration core (R= n); blue: area at risk; grey: segments within flooded area)

Figure 3.56: Pisa, *Scenario 0* (black: segment map; red: local integration core (R= 400m); blue: area at risk)

Figure 3.57: Pisa, *Scenario 1*, global choice core (R= n) (black: segment map; red: local integration core (R= n); blue: area at risk; grey: segments within flooded area)

Figure 3.58: Pisa, *Scenario 0* (black: segment map; red: global choice core (R= n); blue: area at risk)

The strong impact of the event can be also noticed examining frequency distribution of normalised indexes (Fig. 3.59, Fig. 3.60). Frequency curves relative to all examined configuration (i.e.: *Scenario0*-configuration and *Scenario1*-configuration as composed of four small urban areas) show that post-event conditions imply a significant reduction of high integration value. Global integration results particularly impacted: relative values does not following the same distribution shape in the *Scenarios*, meaning that high values are almost not any more reproduced after the event.

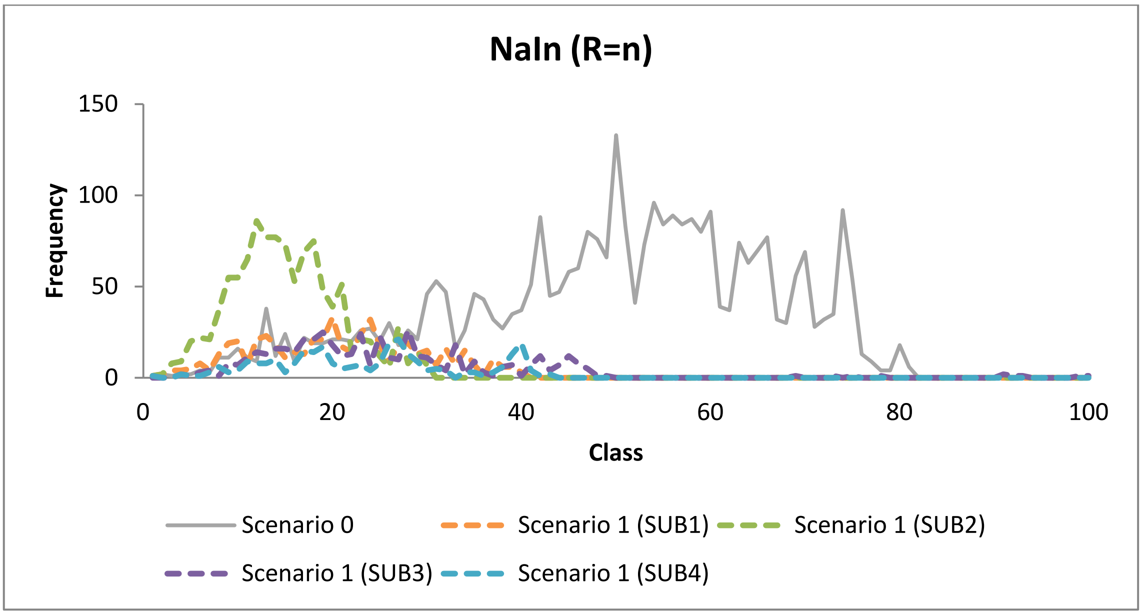

Figure 3.59: Pisa - Comparison between *Scenario*0 and *Scenario1* frequency distribution curve of normalised global integration values

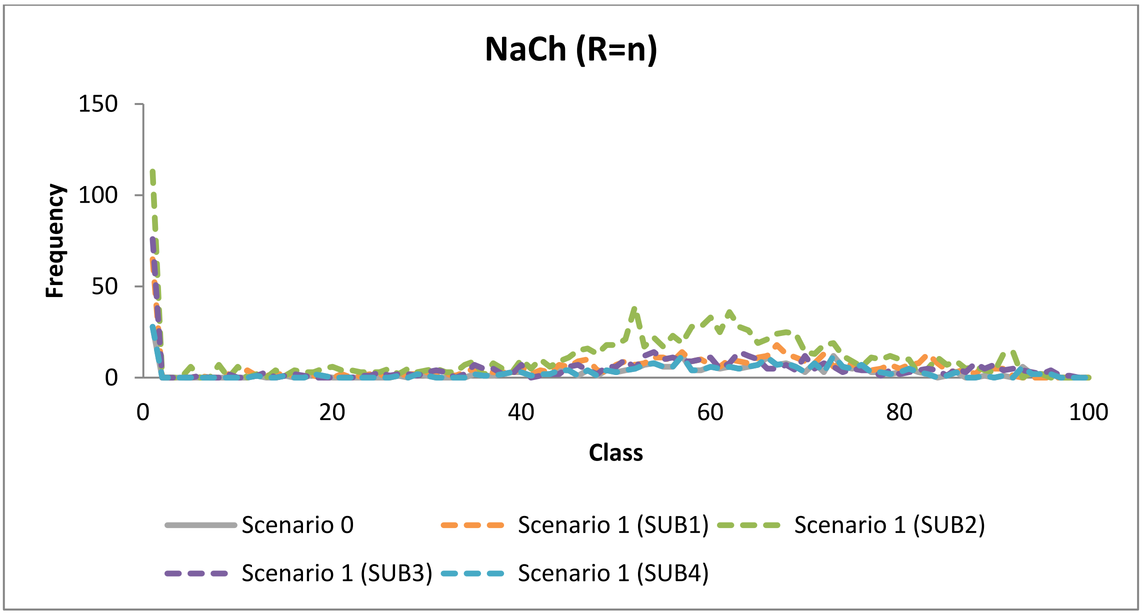

Figure 3.60: Pisa - Comparison between *Scenario 0* and *Scenario 1* frequency distribution curve of normalised global choice values

In order to achieve a global comparison between *Scenario0* and *Scenario1*, the correspondent two datasets of syntactic measures are processed applying *PCA/HCA*. According to *PCA* outcomes, both these datasets can be represented by two principal components (PC_1, PC_2), being satisfied all available criteria of selection of meaningful components (see Chap. 2, Par. 2.2.3):

- ***Scenario 0*** - Along with a large group of points with mean value of all examined variables (Fig. 3.62, black points; Fig. 3.63, black segments), a smaller cluster accounts for units with higher than average local indexes and global integration (Fig. 3.62, purple points; Fig. 3.63, purple segments). Spaces represented by this latter cluster are located just across the river, including a bridge. This outcome highlights that in this part of the grid the overlapping of global and local configurational properties is also linked to the important connection function between the banks. A second group corresponds to units with significant properties at the global scale, having high values of global choice (Fig. 3.62, light blue points; Fig. 3.63, light blue segments). Relative spaces show a well-distributed structure over the study area, including zones next to river and river crossings. A further group includes elements with higher than average segment length and global choice, but not well-integrated (Fig.3.62, blue points; Fig. 3.63, blue segments). (*Silhouette* = 0.401; *CCC*= 0.754; B_k *[Avg.-Single]*= 0.930; B_k *[Avg.-Complete]*= 0.767; B_k *[Avg.-Median]*= 0.789; B_k *[Avg.-Centroid]*= 0.930; B_k *[Avg.-Ward]*= 0.600).

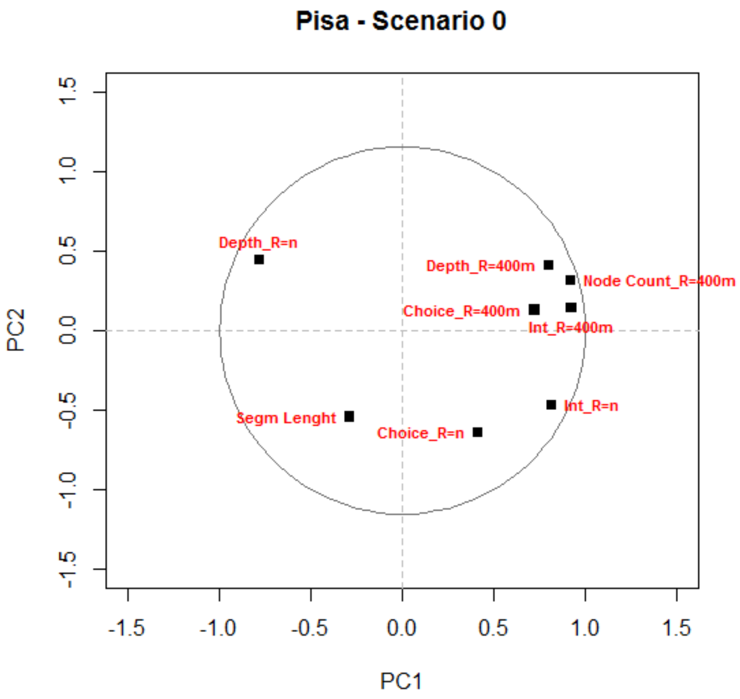

Figure 3.61: Pisa - *Scenario 0*, correlation circle

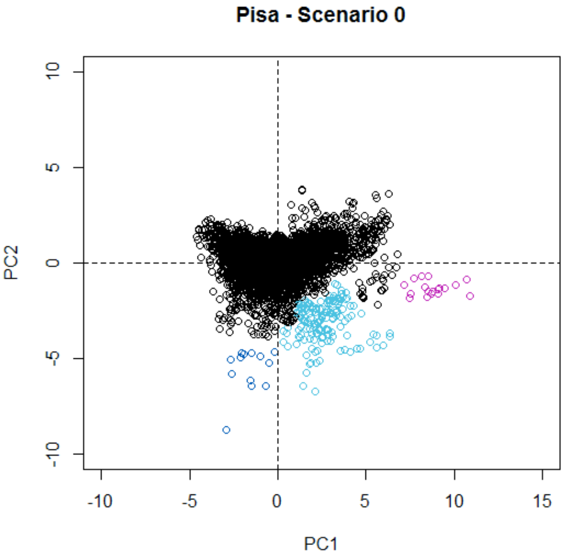

**Figure 3.62: Pisa - *Scenario 0*,
score plot**

**Figure 3.63: Pisa - *Scenario 0*. outcomes *PCA/HAC* procedure
(color range referred to relative score plot in Fig. 3.62)**

- ***Scenario 1*, SUB$_1$** - The dimension of the dataset (and of the relative segment map) results limited in respect of the initial configuration. A large part of all elements own average configurational properties (Fig. 3.65, black points; Fig. 3.66, black segments). A small cluster with both high local values and global integration can be found, corresponding to a well-defined area located not far from the river and mainly representing the local syntactic core of the subsystem (Fig. 3.65, purple points; Fig. 3.66, purple segments). A single element is included in a further cluster, as a long not-well integrated segment (Fig. 3.65, blue point; Fig. 3.66, blue segment). Having a significant value of global choice, this third cluster corresponds to an important internal connection between two distinct parts of *SUB$_1$*.
  (*Silhouette* = 0.387; *CCC*= 0.717;
  B_k *[Avg.-Single]*= 0.851; B_k *[Avg.-Complete]*= 0.699; B_k *[Avg.-Median]*= 0.771; B_k *[Avg.-Centroid]*= 0.864; B_k *[Avg.-Ward]*= 0.671).

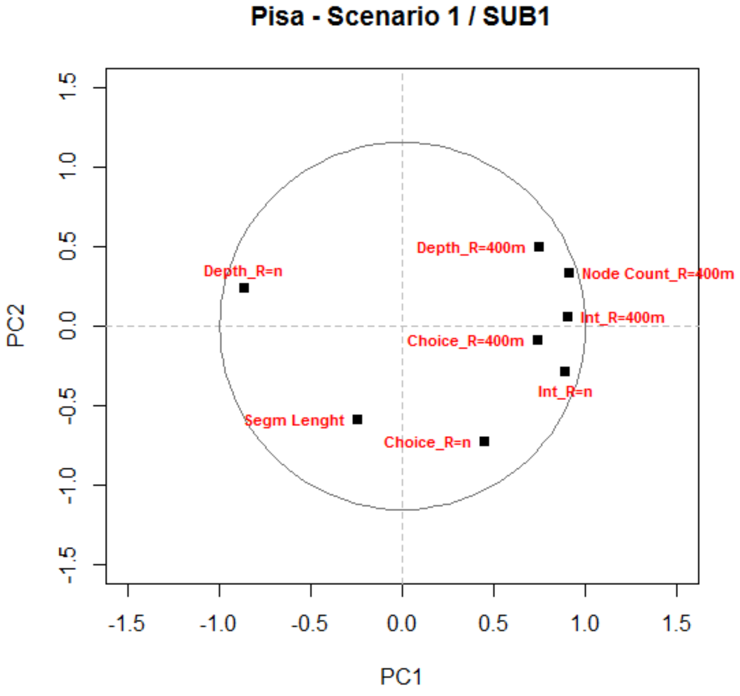

Figure 3.64: Pisa - *Scenario 1* (SUB$_1$), correlation circle

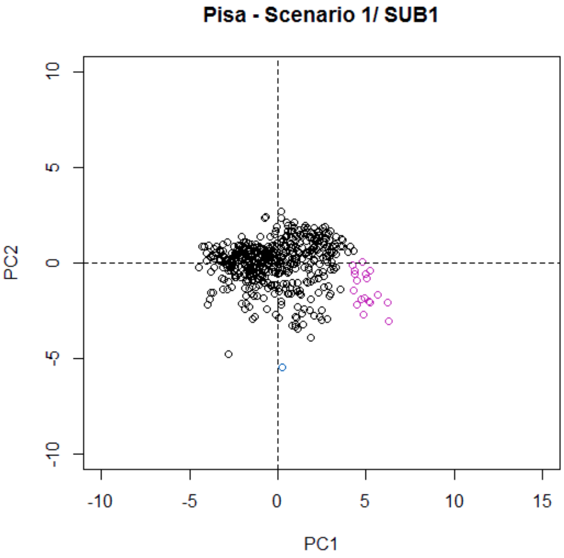

Figure 3.65: Pisa - *Scenario 1* (SUB$_1$), score plot

Figure 3.66: Pisa - *Scenario 1* (SUB$_1$), outcomes of *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.65)

- ***Scenario 1*, SUB$_2$** - Almost all spaces of this subsystem present average values of considered syntactic indexes (Fig. 3.68, black points; Fig. 3.69, black segments). A small number of units constitutes a limited group with high global integration and choice which actually correspond to a sort of connection between two parts of *SUB$_2$* (Fig. 3.68 orange points; Fig. 3.69, orange segments). Constituting both a linking corridor and a well-integrated area, this space assumes a significant role in respect of the global internal functioning of the subsystem.
(*Silhouette* = 0.637; *CCC*= 0.765;
B_k *[Avg.-Single*]= 0.989; B_k *[Avg.-Complete]*= 0.862; B_k *[Avg.-Median]*= 0.870; B_k *[Avg.-Centroid]*= 0.990; B_k *[Avg.-Ward]*= 0.798).

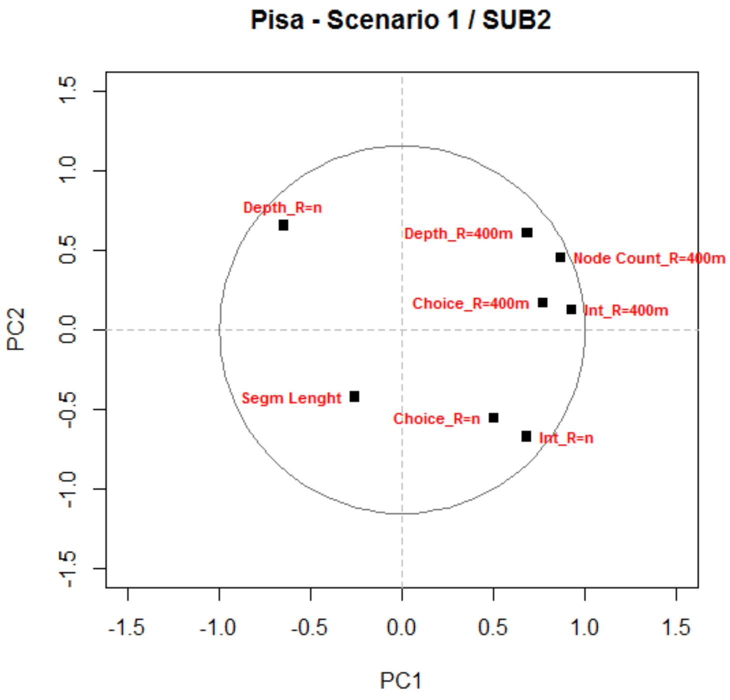

Figure 3.67: Pisa - *Scenario 1* (SUB$_2$), correlation circle

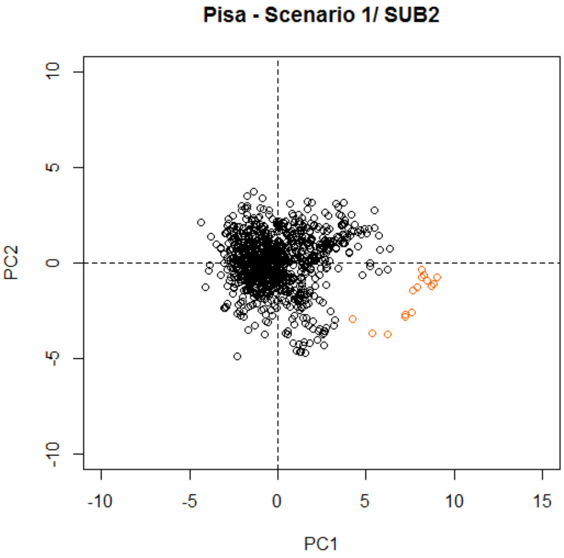

**Figure 3.68: Pisa - *Scenario 1* (SUB$_2$),
score plot**

**Figure 3.69: Pisa - *Scenario 1* (SUB$_2$), outcomes of *PCA/HAC* procedure
(color range referred to relative score plot in Fig. 3.68)**

- ***Scenario 1*, SUB$_3$** - In addition to a large group of spaces with average values of all examined configurational indexes (Fig. 3.71, black points; Fig. 3.72, black segments), a second cluster of elements presents high values of global integration and global choice (Fig. 3.71, red points; Fig. 3.72, red segments). Combining the two main movement processes at a global analysis scale, correspondent spaces assume a central role in setting most representative syntactic centralities. Elements characterised by low integration values and high global choice and segment length constitute a third group (Fig. 3.71, blue points; Fig. 3.72, blue segments). The latter mainly correspond to connections to reach segregated areas located near the area boundary.
  (*Silhouette* = 0.345; *CCC*= 0.748;
  B_k *[Avg.-Single]*= 0.883; B_k *[Avg.-Complete]*= 0.735; B_k *[Avg.-Median]*= 0.771; B_k *[Avg.-Centroid]*= 0.910; B_k *[Avg.-Ward]*= 0.709).

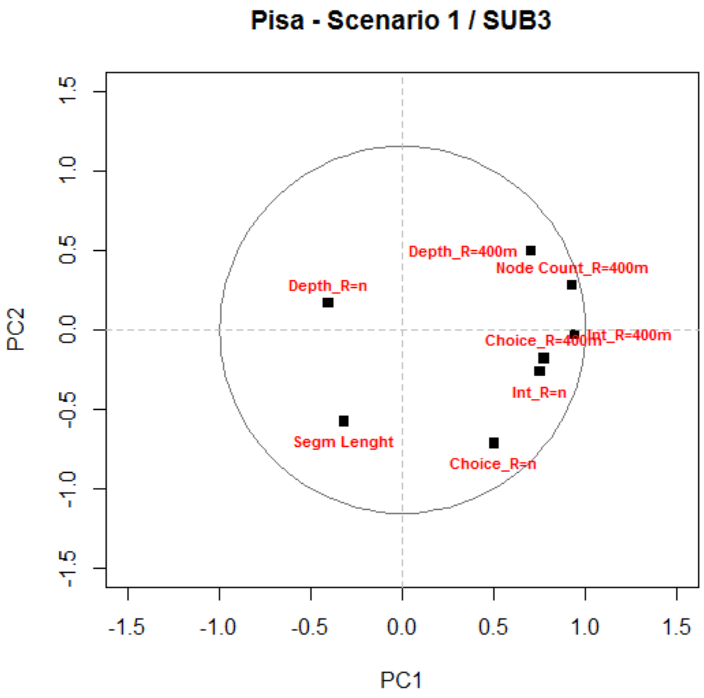

Figure 3.70: Pisa - *Scenario 1* (SUB$_3$), correlation circle

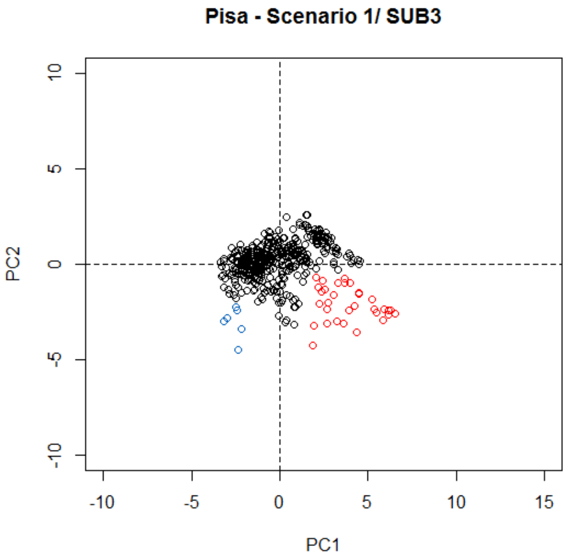

Figure 3.71: Pisa - *Scenario 1* (SUB$_3$), score plot

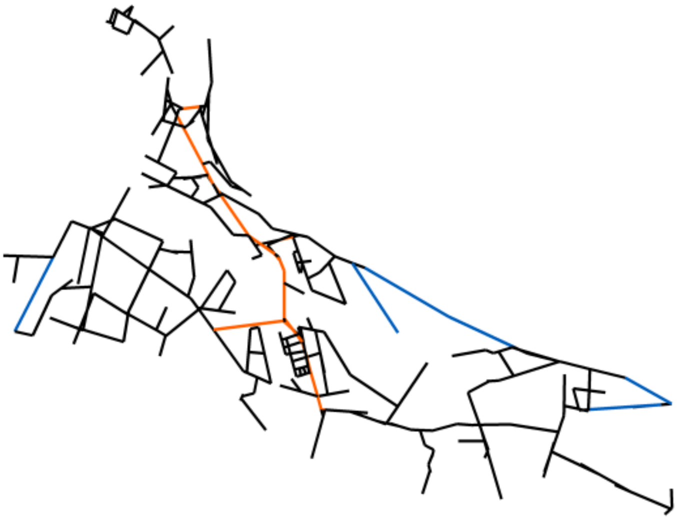

Figure 3.72: Pisa - *Scenario 1* (SUB$_3$), outcomes *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.71)

- ***Scenario 1*, SUB$_4$** - The network is almost completely characterised by average values of examined variables (Fig: 3.74, black points; Fig. 3.75, black segments). A distinct smaller group can be individuated, with elements longer than average having significant values of global choice, mainly constituting connections to the border of the subsystem (Fig: 3.74, blue points; Fig. 3.75, blue segments).

  (*Silhouette* = 0.404; *CCC*= 0.742;

  B_k *[Avg.-Single*]= 0.956; B_k *[Avg.-Complete]*= 0.725; B_k *[Avg.-Median]*= 0.845; B_k *[Avg.-Centroid]*= 0.953; B_k *[Avg.-Ward]*= 0.730).

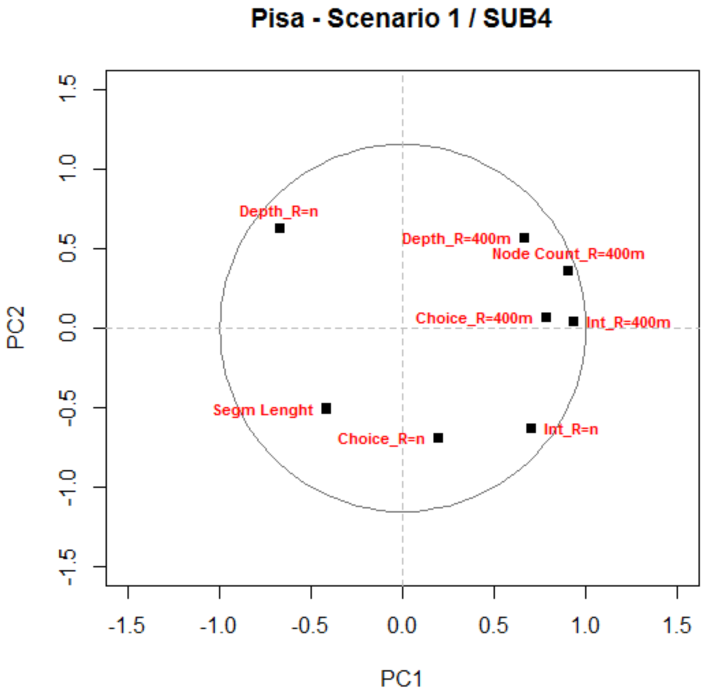

Figure 3.73: Pisa - *Scenario 1* (SUB$_4$), correlation circle

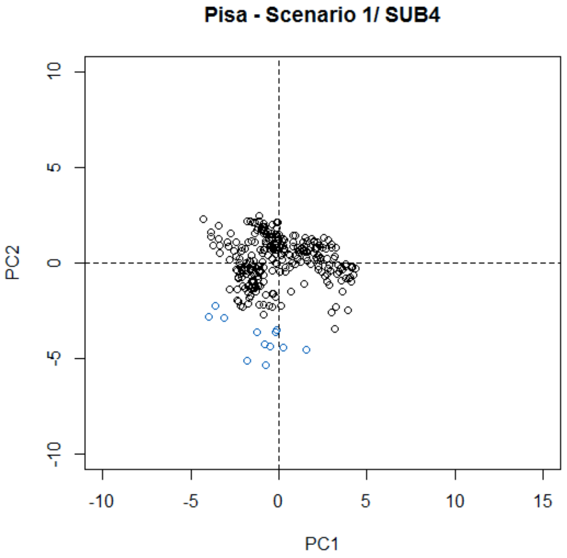

Figure 3.74: Pisa - *Scenario 1* (SUB$_4$), score plot

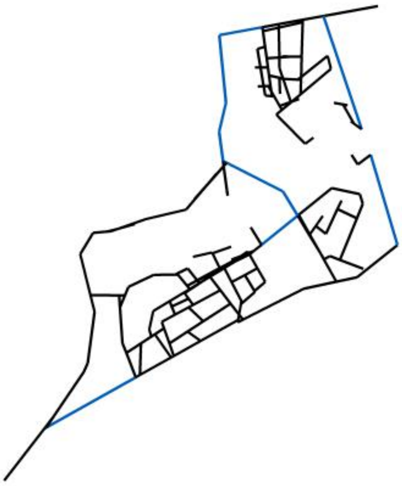

Figure 3.75: Pisa - *Scenario 1* (SUB$_4$), outcomes *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.74)

Outcomes of *PCA/HCA* globally show that the whole urban structure is noticeably affected by flooding. Large parts of syntactic cores located within floodable areas definitely contribute to determine an high vulnerability of the system, resulting into considerable changes between *Scenario0* and *Scenario1*. Firstly, a structural change can be noticed since the post-event configuration consists of four separated subsystems. Comparison between configurational features before and after the event allows to notice that flooding affects the distribution of spatial functions: some spaces assume more relevant syntactic roles than before the event, as new post-event centralities. At the same time, some other areas lose their relevance, assuming average values of configurational indexes. The derived new pattern of urban centralities results essential to define functional properties of each subsystem.

❖ Torino

The study area is located in the northern part of Italy, covering about 166.7 km^2. Water presence characterises the whole system: Dora Riparia, Stura di Lanzo and Po, respectively, cross the study area in its central, northern and east sides. The relative three river basins differ each other in their total extents (Dora Riparia: 1360 km^2; Stura di Lanzo: 885 km^2; Po: 74000 km^2) (Autorità di Bacino del fiume Po, 2006). River courses create four distinct subs-areas within the study system (Fig. 3.76):

- A_1, covering 86.1 km^2 between Po and Dora Riparia. This subsystem is a largely urbanised: 85.1% and 14.6% of A_1 area constitute, respectively, artificial surfaces and agricultural areas (based on CORINE2012 data).
- A_2, covering 33.2 km^2 between Stura di Lanzo and Dora Riparia. Similarly to A_1, the area is mostly artificially covered (84.2% of A_2 area). The remaining part of A_2 is covered by natural surfaces (15.3% of A_2 area), with a small percentage of forest and semi-natural areas (0.2% of A_2 area) (based on CORINE2012 data).
- A_3, covering 14.5 km^2 north of Stura di Lanzo river. This sub-area corresponds to a mix of artificially covered surfaces (68.8% of A_3 area), natural surfaces (24.2% of A_3 area) and forest and semi-natural areas (6.0% of A_3 area) (based on CORINE2012 data).

- A_4, covering 29.0 km^2 in the part east of Po river. This area mainly constitutes a natural environment (24.5% of A_2 area is artificially covered; 35.4% of A_2 area corresponds to natural surfaces; 38.4% of A_2 area represents forest and semi-natural areas) (based on CORINE2012 data).

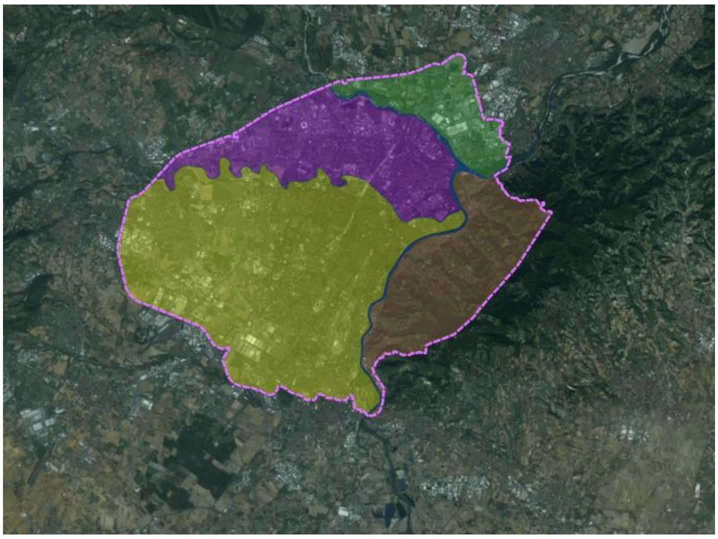

Figure 3.76: Torino - Study area boundary and subsystems (yellow zone: A_1; violet zone: A_2; green zone: A_3; brown zone: A_4)

Different grid structures can be identified within the study area: an orthogonal scheme characterises A_1, a radial structure can be noticed in A_2. *ASA* outcomes show that both global integration core (Fig. 3.77) and global choice core (Fig. 3.79) are distributed within the entire system; a large part of spaces is included in both these cores. Values of local integration (Fig. 3.78) also represent a structured pattern of local centralities within an almost well-delimited area actually located near Dora Riparia river. However, value of synergy ($S = 0.31$) shows that connection between local and global structure is not very strong.

Figure 3.77: Torino -Global integration core (R = n) (black: segment map; red: 10% highest values)

Figure 3.78: Torino - Local integration core (R = 400m) (black: segment map; red: 10% highest values)

Figure 3.79: Global choice core (R = n) (black: segment map; red: 10% highest values)

Several river crossings belong to the global integration core, respectively 33.0% of crossings of Stura di Lanzo river, 12.5% of river crossings of the Po river, 22.7% of crossings above Dora Riparia river. Differences in these percentages reflect various levels of inclusion of watercourses within the urban system as well as characteristics of areas located next to the rivers. In fact, the area east of Po river mainly constitutes a natural environment, with a relative low inclusion in the core; Stura di Lanzo and Dora Riparia cross urbanised and more integrated areas. Higher percentages can be obtained referring to the global choice core, as expected considering the meaning of choice index value and the basic connection role of bridges: 67.0% of connections across Stura di

Lanzo, 62.5% of crossings of the Po river and 50.0% of crossings of the Dora Riparia river are included in spaces with 10% of higher values of choice.

Even being crossed by three different rivers, Torino study area is completely included within Po river catchment. Referring to Po River Basin Authority data (1999), boundaries of *AAR* are individuated in reference to 500-years return period flood ("*STEP 0*"). Flood-prone areas constitute a percentage of 16.9% of the total study area, as well-defined zones constituting a sort of buffer along watercourses.

Figure 3.80: Torino - Area at risk
(yellow: 500-year floodplain; orange: open spaces constituting the urban grid)

Although areas at risk appear to be a relatively limited part of the grid, urban structure and location of cores in proximity of rivers provide a certain level of vulnerability of the network (Fig. 3.81 - Fig. 3.83). A percentage of 11.3% of the total length of the network is at risk.

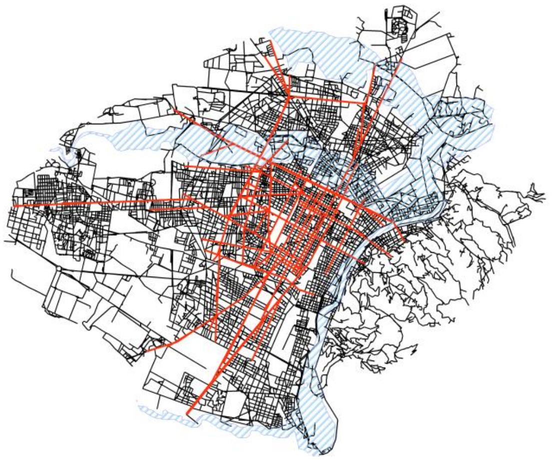

Figure 3.81: Torino - Global integration core at risk (black: segment map; red: global integration core (R= n); blue: area at risk)

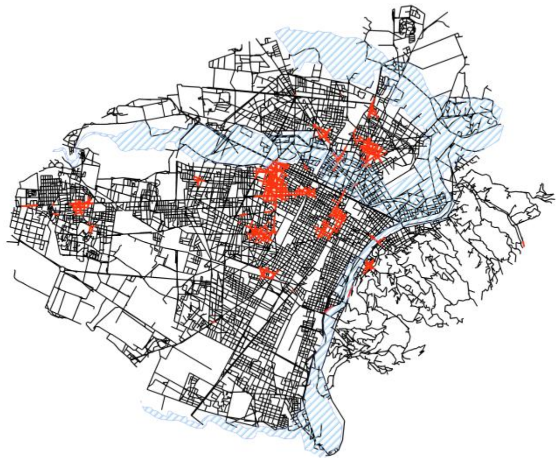

Figure 3.82: Torino - Local integration core at risk (black: segment map; red: local integration core (R= 400m); blue: area at risk)

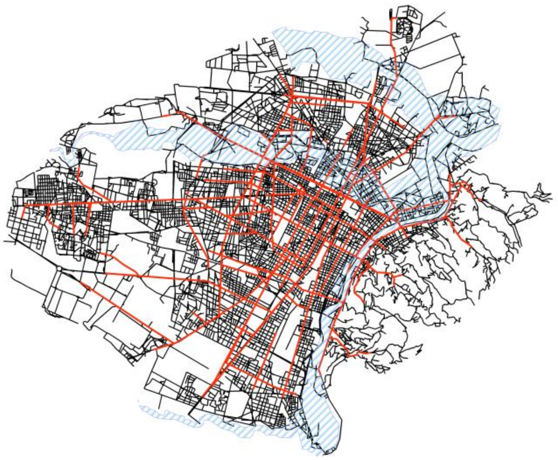

Figure 3.83: Torino - Global choice core at risk (black: segment map; red: global choice core (R= n); blue: area at risk)

Elements at risk are highlighted by frequency distributions of global integration (Fig. 3.84) and choice indexes (Fig. 3.86), as well as local integration index in all classes of values (Fig. 3.85) ("*STEP 1*"). Even accounting for a low degree of vulnerability of the network, susceptibility indicators show that elements with high global choice are most likely to be affected by flooding ($I_{s,\ int.\ (R=\ n),\ 10\%} = 0.09$; $I_{s,\ choice.\ (R=\ n),\ 10\%} = 0.13$; $I_{s,\ int.\ (R=\ 400m),\ 10\%} = 0.06$). Referring to the wider range of 30% highest values, small variations can be noticed, apart from an increasing number of element of local centralities at risk ($I_{s,\ int.\ (R=\ n),\ 30\%} = 0.10$; $I_{s,\ choice.\ (R=\ n),\ 30\%} = 0.11$; $I_{s,\ int.\ (R=\ 400m),\ 30\%} = 0.11$).

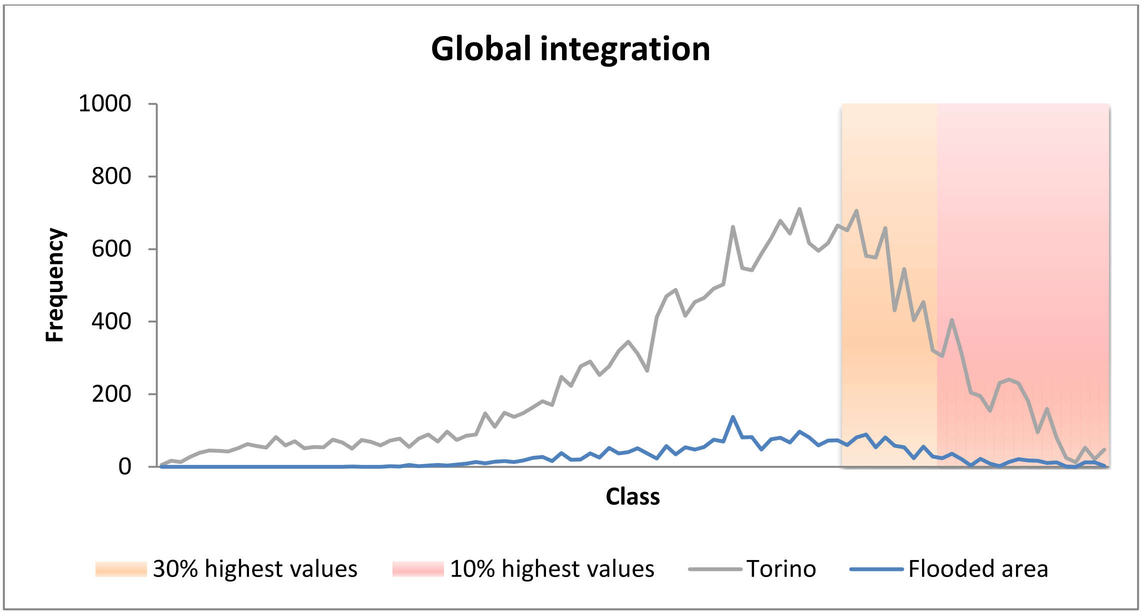

Figure 3.84: Torino - Frequency distribution curve of global integration index values (R= n)

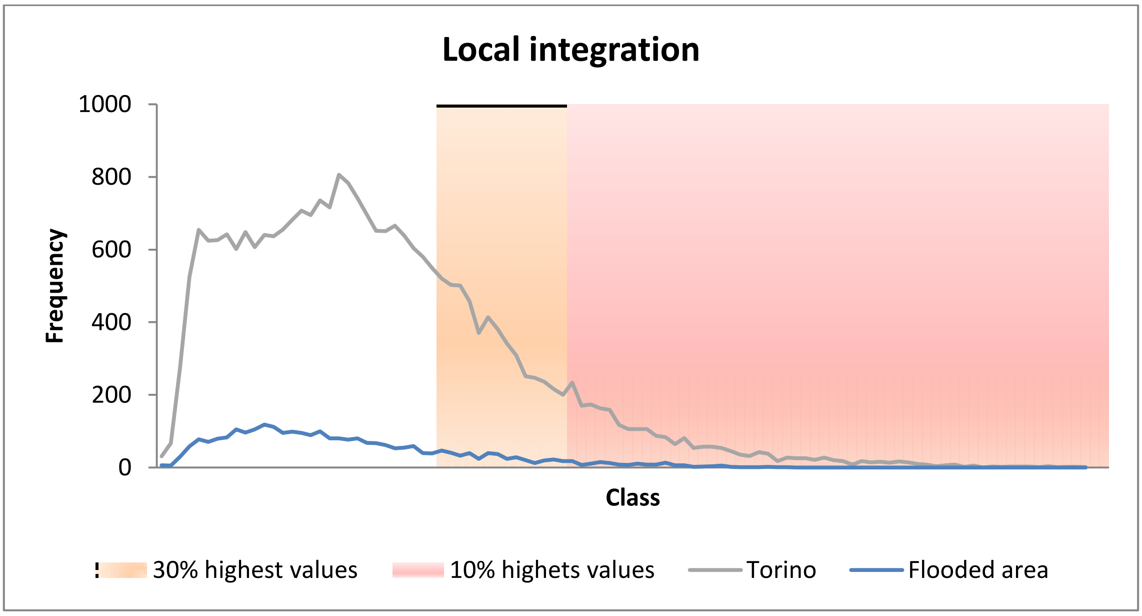

Figure 3.85: Torino - Frequency distribution curve of local integration index values (R= 400m)

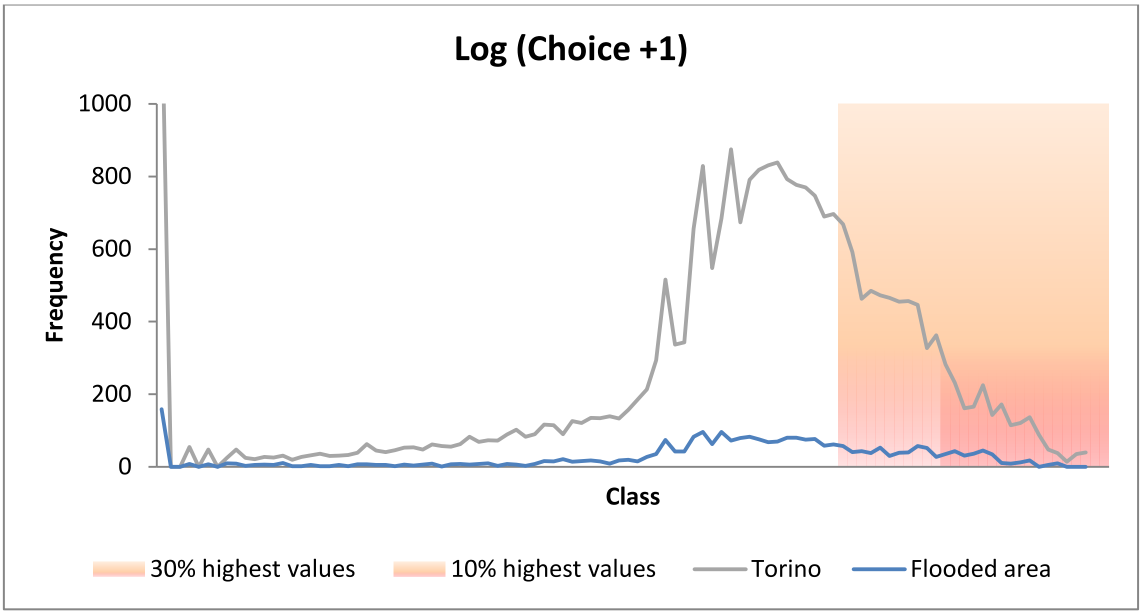

Figure 3.86: Torino - Frequency distribution curve of global choice index values (R= n)

Land uses characterisation (based on CORINE2012 data) provides a pattern of different landscapes (Fig. 3.87) ("*STEP 2*"), based on which it can be noticed that large parts of all examined cores belong to discontinuous urban fabric (Fig.3.88 - Fig. 3.91, Table 3.3). The largest contribute to network vulnerability is related to choice core at risk within discontinuous urban fabric land. Continuous urban fabrics, industrial and commercial districts, along with green areas, include small percentages of the said cores.

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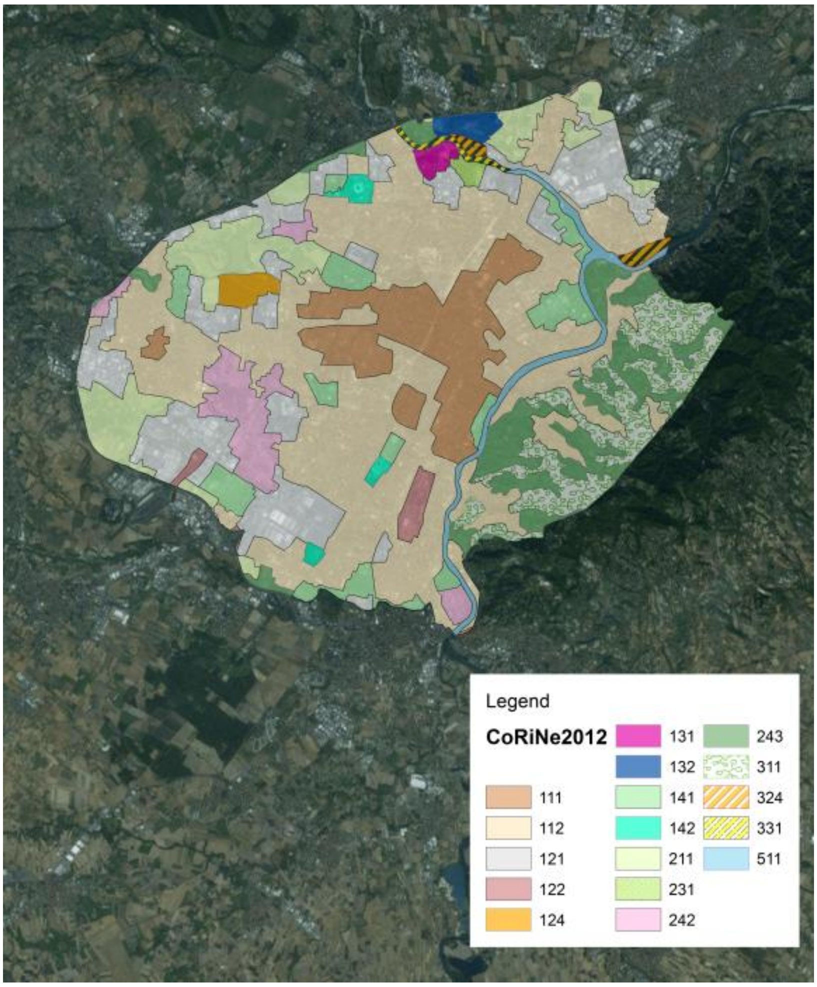


Figure 3.87: Torino - Land use (111: Continuous urban fabric; 112: Discontinuous urban fabric; 121: Industrial or commercial units and transport units 1.2.2. Road and rail networks and associated; 124: Airports; 131: Mineral extraction sites; 132: Dump sites; 141: Green urban areas; 142: Sport and leisure facilities; 211: Non-irrigated arable land; 231: Pastures; 242: Complex cultivation; 243: Land principally occupied by agriculture, with significant areas of natural vegetation; 311: Broad-leaved forest; 324: Transitional woodland shrub; 331: Beaches, dunes, and sand plains; 511: Water courses) (CORINE2012)

Segments at risk	11.3%			
Global integration core at risk	9.1% *(0.9% of tot.)*	8.7%	*(0.1% of tot.)*	Continuous urban fabric
		58.6%	*(0.5% of tot.)*	Discontinuous urban fabric
		8.4%	*(0.1% of tot.)*	Industrial or commercial units
		0.0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Airports
		0.0%	*(0.0% of tot.)*	Mineral extraction sites
		0.0%	*(0.0% of tot.)*	Dump sites
		19.1%	*(0.2% of tot.)*	Green urban areas
		0.0%	*(0.0% of tot.)*	Sport and leisure facilities
		0.4%	*(0.0% of tot.)*	Non-irrigated arable land
		0.0%	*(0.0% of tot.)*	Pastures
		0.0%	*(0.0% of tot.)*	Complex cultivation
		0.0%	*(0.0% of tot.)*	Land principally occupied by agriculture, with significant areas of natural vegetation
		0.0%	*(0.0% of tot.)*	Broad-leaved forest
		0.0%	*(0.0% of tot.)*	Transitional woodland shrub
		4.9%	*(0.04% of tot.)*	Water courses

Local integration core at risk	5.8% *(0.3% of tot.)*	57.6%	*(0.2% of tot.)*	Continuous urban fabric
		28.7%	*(0.1% of tot.)*	Discontinuous urban fabric
		0.0%	*(0.0% of tot.)*	Industrial or commercial units
		0.0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Airports
		0.0%	*(0.0% of tot.)*	Mineral extraction sites
		0.0%	*(0.0% of tot.)*	Dump sites
		0.0%	*(0.0% of tot.)*	Green urban areas
		0.0%	*(0.0% of tot.)*	Sport and leisure facilities
		0.0%	*(0.0% of tot.)*	Non-irrigated arable land
		0.0%	*(0.0% of tot.)*	Pastures
		0.0%	*(0.0% of tot.)*	Complex cultivation
		7.5%	*(0.02% of tot.)*	Land principally occupied by agriculture, with significant areas of natural vegetation
		0.0%	*(0.0% of tot.)*	Broad-leaved forest
		0.0%	*(0.0% of tot.)*	Transitional woodland shrub
		6.3%	*(0.02% of tot.)*	Water courses

Global choice core at risk	12.9% *(1.4% of tot.)*	13.4%	*(0.2% of tot.)*	Continuous urban fabric
		65.5%	*(0.9% of tot.)*	Discontinuous urban fabric
		4.0%	*(0.1% of tot.)*	Industrial or commercial units
		0.0%	*(0.0% of tot.)*	Road and rail networks and associated land
		0.0%	*(0.0% of tot.)*	Airports
		0.0%	*(0.0% of tot.)*	Mineral extraction sites
		0.0%	*(0.0% of tot.)*	Dump sites
		8.2%	*(0.1% of tot.)*	Green urban areas
		0.0%	*(0.0% of tot.)*	Sport and leisure facilities
		0.2%	*(0.0% of tot.)*	Non-irrigated arable land
		0.0%	*(0.0% of tot.)*	Pastures
		0.0%	*(0.0% of tot.)*	Complex cultivation
		3.8%	*(0.1% of tot.)*	Land principally occupied by agriculture, with significant areas of natural vegetation
		0.0%	*(0.0% of tot.)*	Broad-leaved forest
		0.0%	*(0.0% of tot.)*	Transitional woodland shrub
		4.9%	*(0.1% of tot.)*	Water courses

Table 3.3: Torino - Percentages of network and syntactic cores at risk for each land use

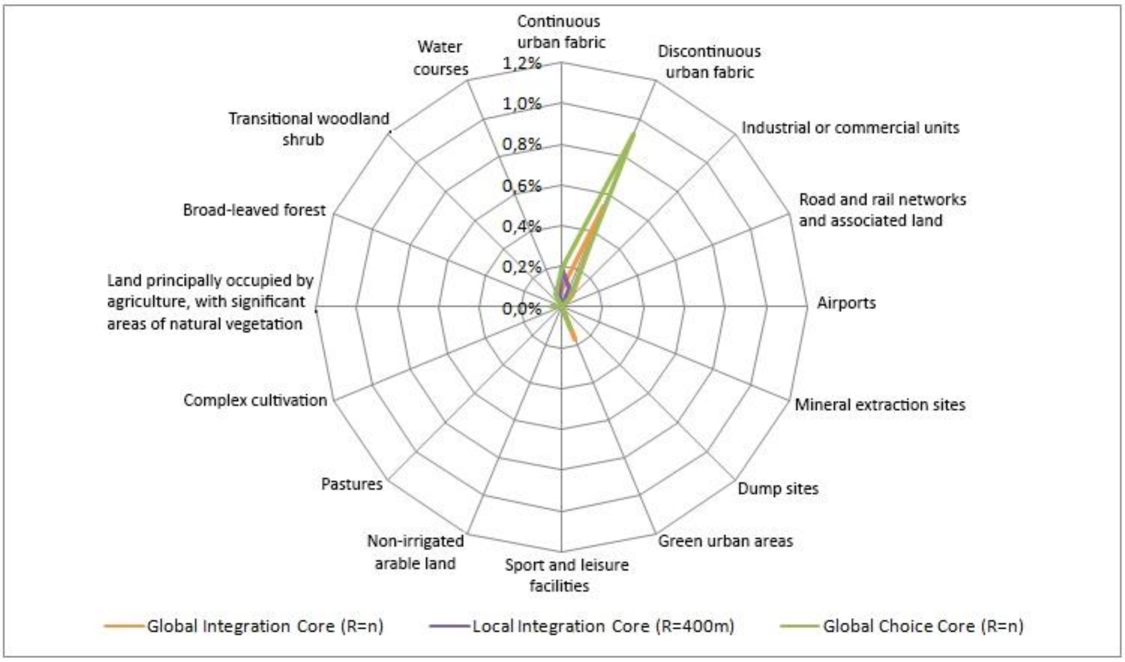


Figure 3.88: Torino - Percentages of segments at risk for each land use

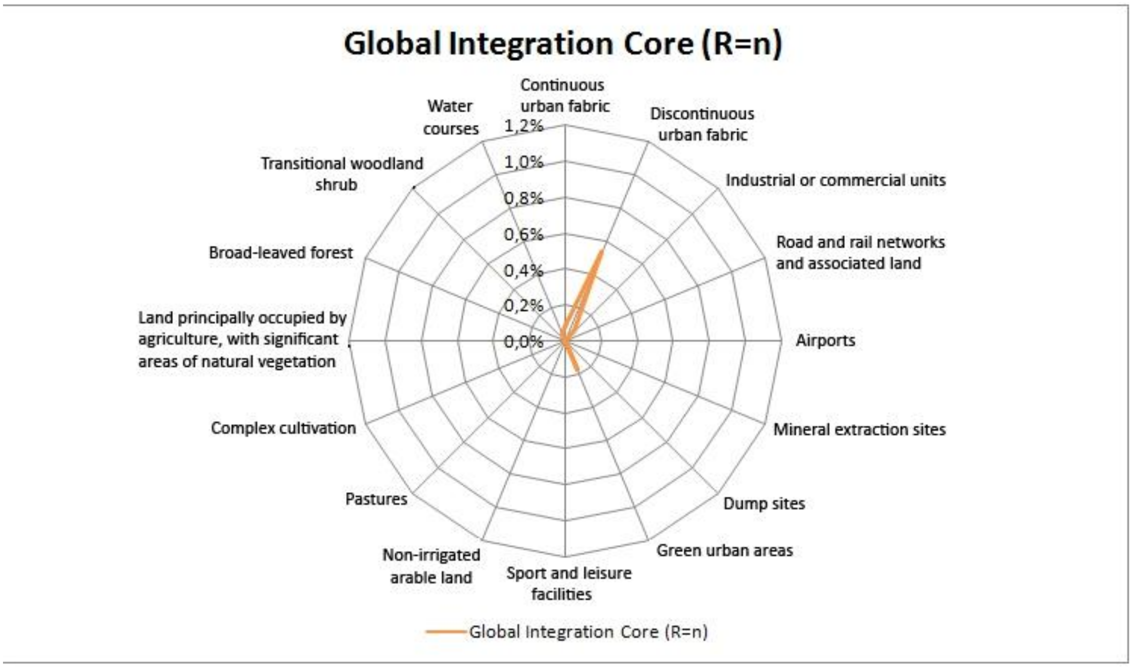


Figure 3.89: Torino - Percentages of global integration core (R= n) at risk for each land use

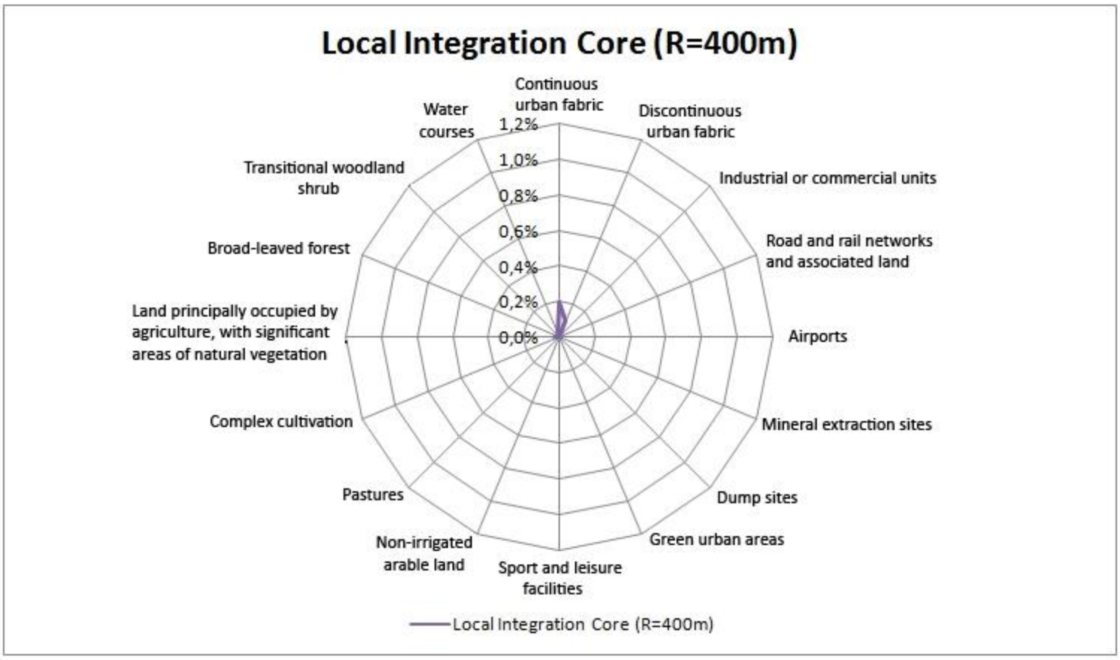


Figure 3.90: Torino - Percentages of local integration core (R= 400m) at risk for each land use

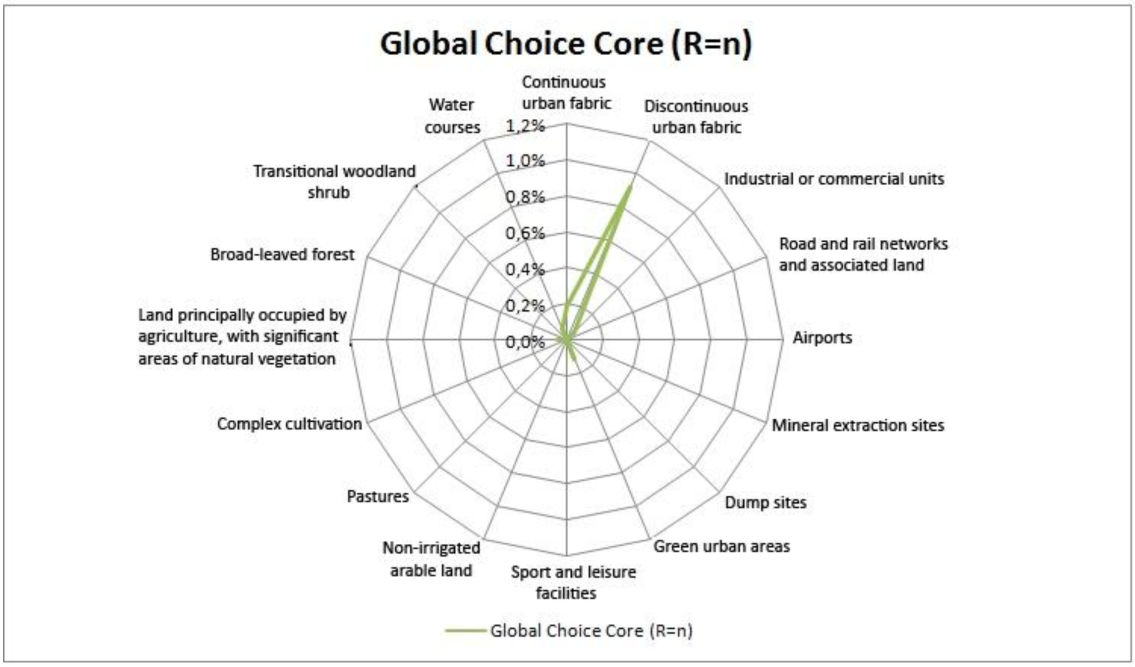


Figure 3.91: Torino - Percentages of global choice core (R= n) at risk for each land use

Small percentages of cores at risk (V_{ntw1} = 0.9%; V_{ntw2} = 0.3%; V_{ntw3}= 1.4%) determine a low degree of network-based vulnerability (V_{ntw} = 2.6%). Population at risk constitutes a percentage of 9.2% of the total population of the study area (Fig. 3.92) ("*STEP 3*").

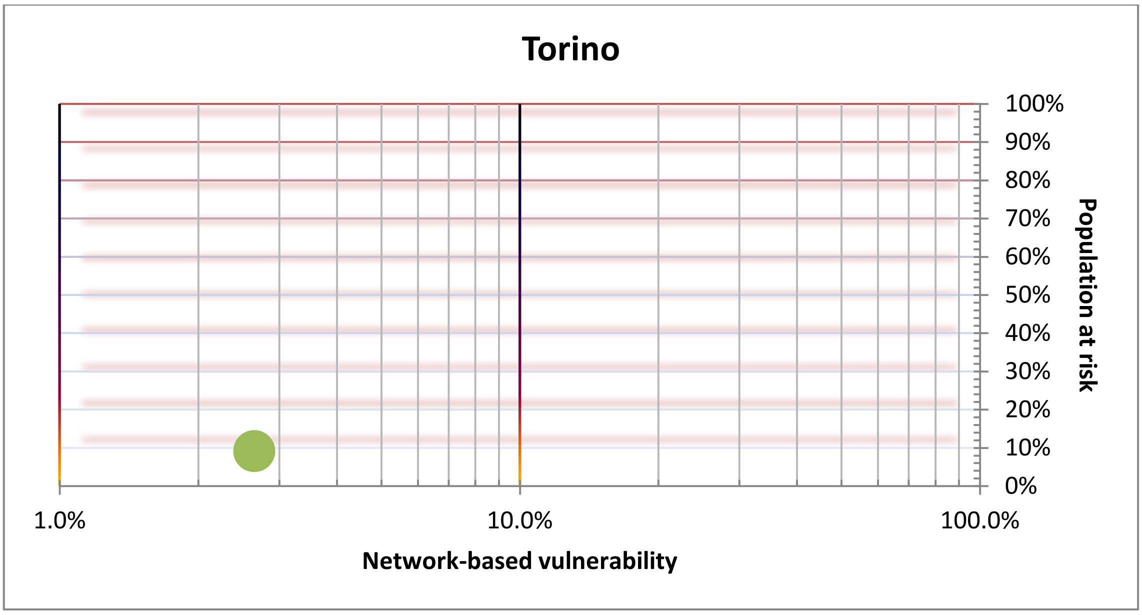


Figure 3.92: Torino - Representation of vulnerability elements

Floodplains divide *Scenario0*-configuration in four subsystems reflecting the above described four sub-areas. However, post-event analyses are focused just on two of them: SUB_1 and SUB_2, as non flooded areas (Fig. 3.93). This assumption is deduced considering that SUB_3 results to be too small in respect of the other subsystems, and SUB_4 mainly represents a natural environment. Therefore, *Scenario1*-configuration consists of SUB_1 and SUB_2 areas.

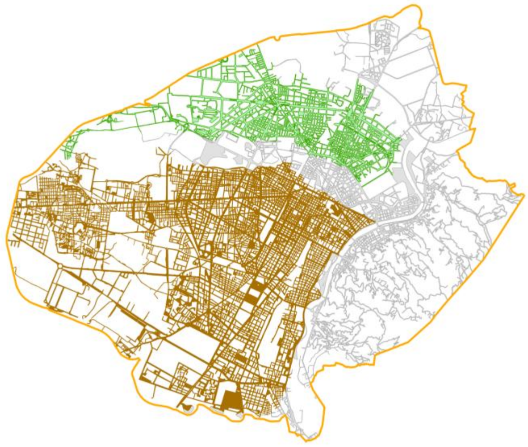


Figure 3.93: Torino - Post event subsystems constituting *Scenario 1*-configuration (orange: study area boundary, brown: open space SUB_1, green: open space SUB_2, grey: open space *Scenario* 0)

According to *ASA* outcomes (Fig. 3.94 - Fig. 3.99), after the event global centralities arise in each subsystem: in SUB_1 all considered cores show a structure very similar to relative pre-event event cores; in $SUB_{2,}$ a the lack some parts of the local integration cores can be pointed out, together with new global centralities both in regard of integration and choice. Becoming an isolated zone due to the event, SUB_2 internally changes its structure modifying the pattern of syntactic centralities.

Figure 3.94: Torino - *Scenario 1*, global integration core (R= n) (black: segment map; red: global integration core (R= n); grey: segments within flooded area)

Figure 3.95: Torino - *Scenario 0* (black: segment map; red: global integration core (R= n); blue: area at risk)

Figure 3.96: Torino- *Scenario 1*, local integration core (R= 400m) (black: segment map; red: local integration core (R= 400m); grey: segments within flooded area)

Figure 3.97: Torino- *Scenario 0* (black: segment map; red: local integration core (R= 400m); blue: area at risk)

Figure 3.98: Torino- *Scenario 1*, global choice core (R= n) (black: segment map; red: global choice core (R= n); grey: segments within flooded area)

Figure 3.99: Torino- *Scenario 0* (black: segment map; red: global choice core (R= n); blue: area at risk)

Frequency distributions of normalised values (Fig. 3.100, Fig. 3.101) highlight that SUB_2 generally shows lower indexes than SUB_1 and *Scenario0:* although new cores can be individuated, integration and choice values within SUB_2 result to be lower if compared to the other two examined structures. Covering a large part of *Scenario0*-configuration, SUB_1 area results not particularly different from the relative pre-event configuration. Indexes values in SUB_1 follow the same trend of *Scenario0*, corresponding to the less affected part.

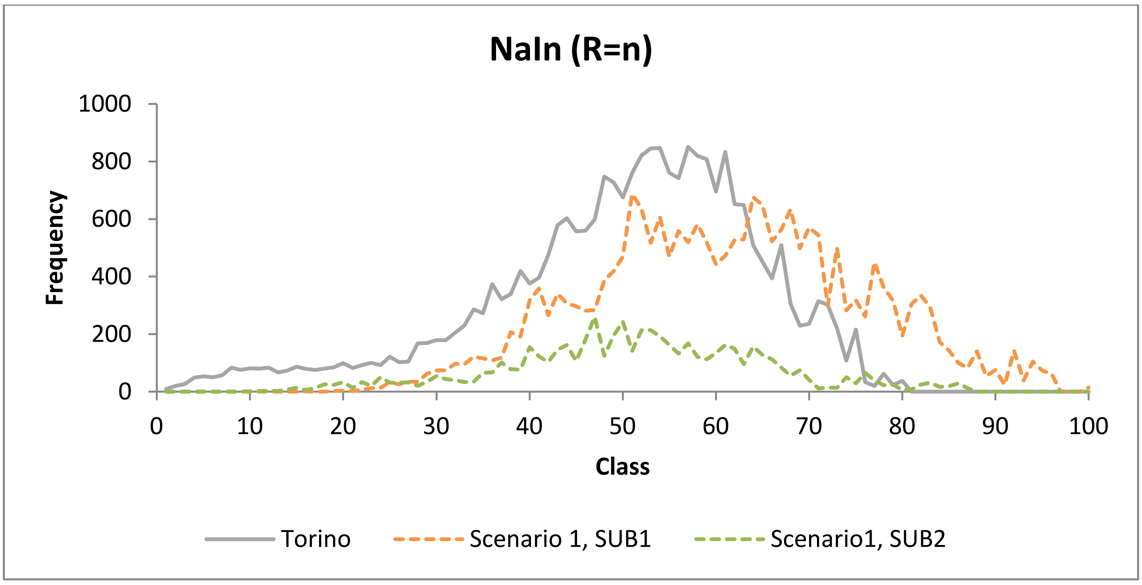


Figure 3.100: Comparison between *Scenario 0* and *Scenario 1* frequency distribution curve of normalised global integration values

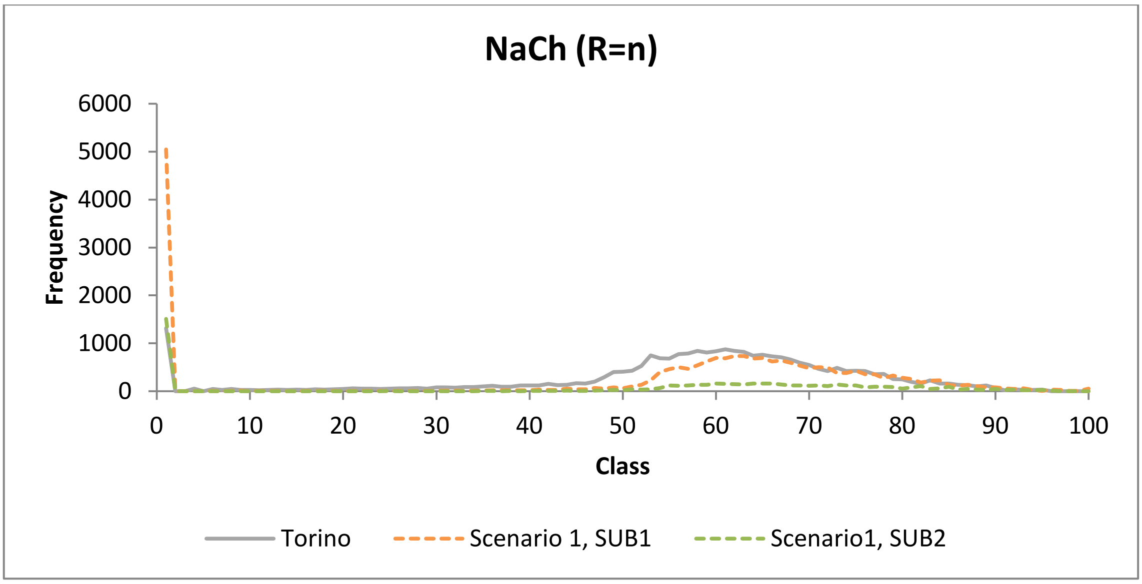


Figure 3.101: Comparison between *Scenario 0* and *Scenario 1* frequency distribution curve of normalised global choice values

Datasets of syntactic measures corresponding to *Scenario0* and *Scenario1* urban structures are further examined through *PCA/HCA* methods. All analysed datasets result to be suitably described by two principal components (PC_1, PC_2), according to all available criteria to select meaningful principal components (see Chap. 2, Par. 2.2.3):

- ***Scenario 0*** - The specific distribution of points within the score plot allows to clearly point out different clusters (Fig. 3.103). In addition to a large group of units with values of all processed indexes close to relative averages (Fig. 3.103, black points; Fig. 3.104, black segments), two further clusters can be defined: the first one, containing elements with distinct high local value (Fig. 3.103, purple points; Fig. 3.104, purple segments) and, the second one, representative of elements with high global choice and, at the same time, not well-integrated at the local scale (Fig. 3.103, light blue points; Fig. 3.104, light blue segments). Basically these two clusters highlight small local centralities and long elements, the latter being important connections across the whole system (*Silhouette* = 0.486; *CCC*= 0.759;
  B_k *[Avg.-Single*]=0.981; B_k *[Avg.-Complete]=* 0.744; B_k *[Avg.-Median]=* 0.828; B_k *[Avg.-Centroid]=* 0.980; B_k *[Avg.-Ward]=* 0.662).

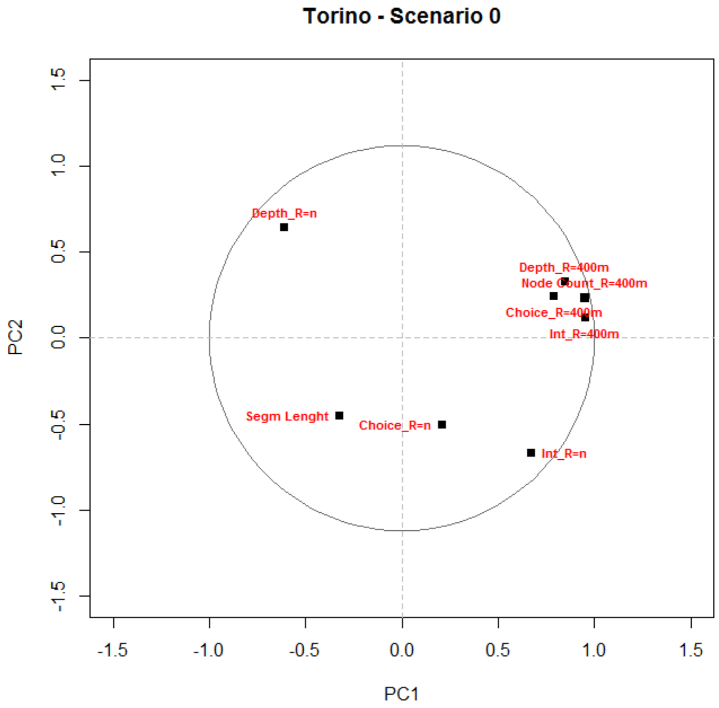


Figure 3.102: Torino - *Scenario 0*, correlation circle

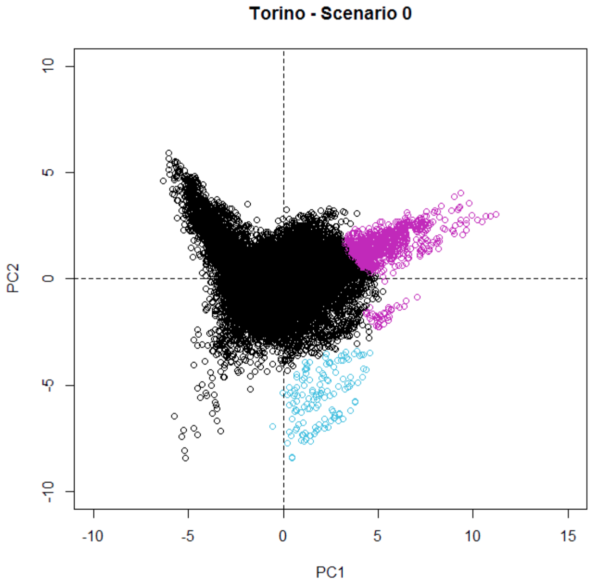


Figure 3.103: Torino - *Scenario 0*, score plot

Figure 3.104: Torino - *Scenario 0*, outcomes *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.103)

- ***Scenario 1*, SUB$_1$** - Elements mostly own average values of all indexes (Fig. 3.106, black points; Fig. 3.107, black segments) However, global and local properties are distinctly identifiable in two small groups: a cluster of elements with high local indexes (Fig. 3.106, green points; Fig. 3.107, green segments) and a second group of elements with high global choice (Fig. 3.106, orange points; Fig. 3.107, orange segments). These latter points correspond to elements of the map which constitute connection axes across the subsystem. Relative spatial distribution of this cluster shows a longitudinal linking elements, leaving the southern part of this subsystem not globally connected with the rest of *SUB$_1$.* (*Silhouette* = 0.575; *CCC*= 0.712;
  B_k *[Avg.-Single]*= 0.986; B_k *[Avg.-Complete]*= 0.716; B_k *[Avg.-Median]*= 0.802; B_k *[Avg.-Centroid]*= 0.987; B_k *[Avg.-Ward]*= 0.606).

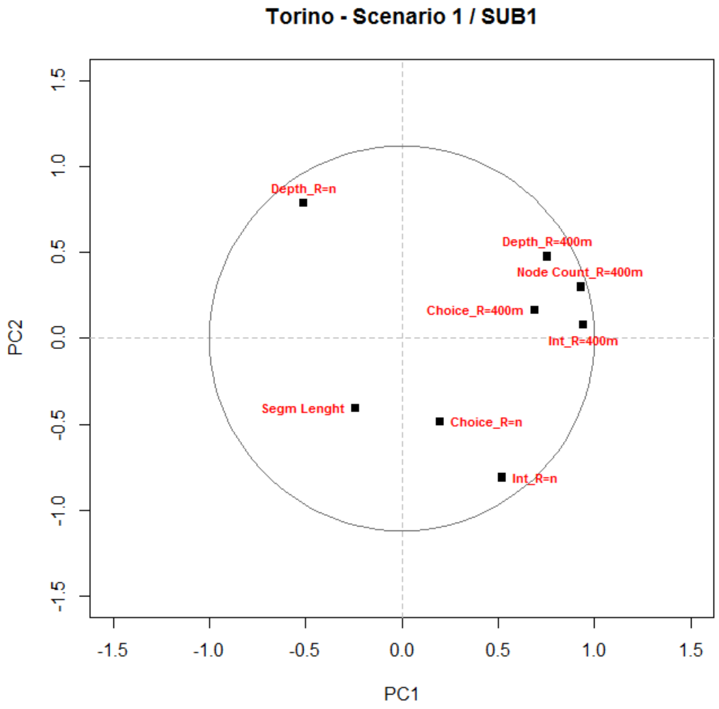


Figure 3.105: Torino - *Scenario 1* (SUB$_1$), correlation circle

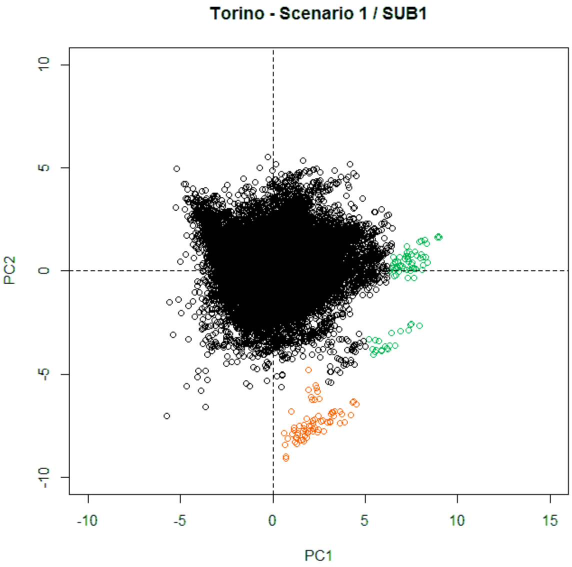


Figure 3.106: Torino - *Scenario 1* (SUB$_1$), score plot

Figure 3.107: Torino - *Scenario 1* (SUB$_1$), outcomes of *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.106)

- ***Scenario1*****, SUB$_2$** - The partition shows a group of units generally owning high value of global choice and segment length (Fig. 3.109, orange points; Fig. 3.110), and a cluster of elements with average values of indexes (Fig. 3.109, black points, Fig. 3.110). This grouping solution highlighting the absence of areas with high local indexes.
  (*Silhouette* = 0.465; *CCC*= 0.680;
  B_k *[Avg.-Single*]= 0.970; B_k *[Avg.-Complete]*= 0.893; B_k *[Avg.-Median]*= 0.875; B_k *[Avg.-Centroid]* 0.968; B_k *[Avg.-Ward]*= 0.741).

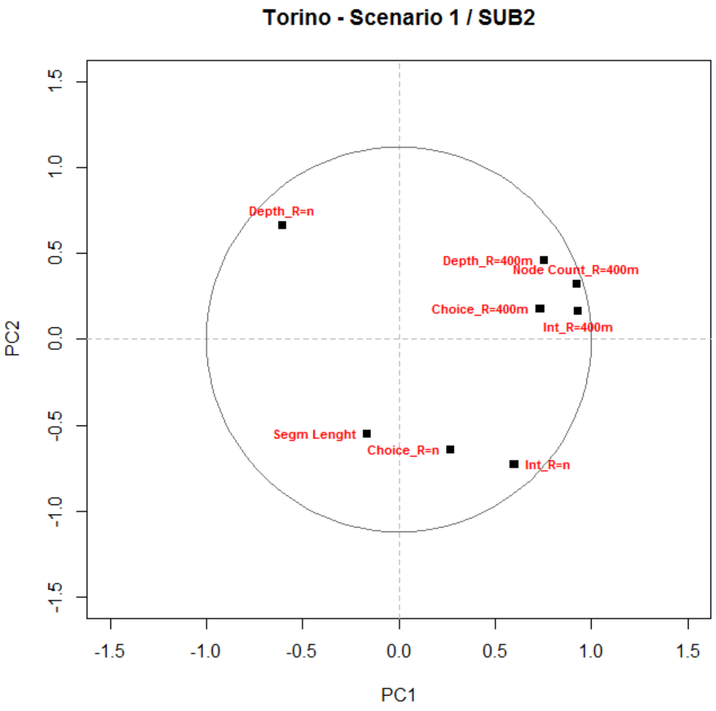


FIgure 3.108: Torino - *Scenario 1* (SUB$_2$), correlation circle

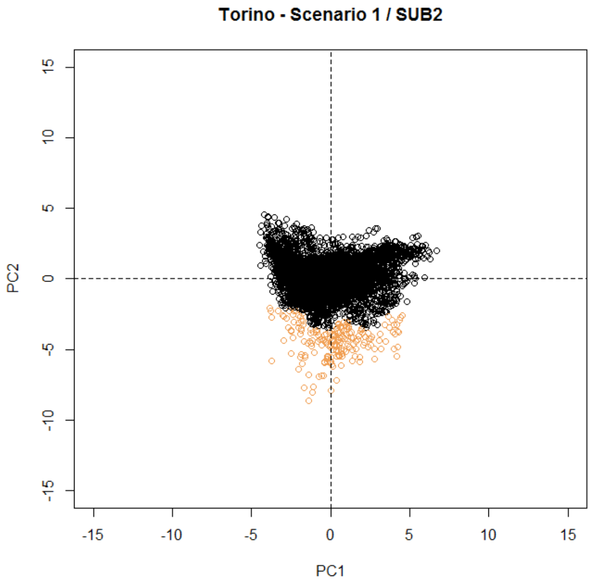


Figure 3.109: Torino - *Scenario 1* (SUB$_2$), score plot

Figure 3.110: Torino - *Scenario 1* (SUB$_2$), outcomes of *PCA/HAC* procedure (color range referred to relative score plot in Fig. 3.109)

Apart from the absence of local centralities in *SUB$_2$*, *PCA/HCA* outcomes highlight the new pattern of high choice connections determined after the flood occurrence. Less evident configurational variations can be noticed in *SUB$_1$*, which almost maintains the same characteristics it presents in reference to pre-event conditions.

3.2 Results and discussion

Assuming urban resilience as a process, the proposed methodology allows to investigate elements assumed as part of the said process. Examined case studies are considerably different from one another: distinct urban structures and relative river locations determine diverse configurational properties, resulting in various characteristics in reference to urban resilience to flood events. The geometrical properties of each urban layout provide a first overview of urban structure in reference to river banks. Analysing the urban grid of the first case study (Alessandria), the river appears to divide the area in two smaller parts. Land use and configurational measures show that urbanised areas and syntactic centralities are mostly located in the southern sub-area. A different structure can be noticed for the second case study (Pisa). The river acts as an attractor of urban activities, as shown by network properties as well as land uses of areas next to the watercourse. A mix of these two conditions can be found as regards the third case study (Torino). East part of the study area mainly covers natural lands, differing from the rest of the system. Therefore, due to the specific territorial morphology, the Po river separates two distinct parts. The other two rivers (Dora Riparia and Stura di Lanzo) cross the study area in its central part. Spatial distribution of urbanised areas and syntactic centralities show a significant degree of river inclusion within the urban system. However, a better inclusion can be noticed for Dora Riparia river than Stura di Lanzo.

According to the structure of the developed resilience assessment methodology, relative analysis methods and techniques, the whole procedure allows to achieve considerations and outcomes that are not related to the dimension of the analysed urban systems. It follows the possibility to comparatively examine different urban structures to characterise relative resilience to floods.

A comparative analysis of outcomes can help in highlighting further aspects both of resilience and of the methodology (Table 3.4).

	ALESSANDRIA	**PISA**	**TORINO**
Area at risk *[% of tot.]*	43.7%	38.4%	16.9%
Network at risk *[% of tot.]*	35.2%	33.1%	11.3%
Population at risk *[% of tot.]*	26.3%	35.4%	9.2%
$I_{s,\ int.\ (R=n),\ 10\%}$	0.17	0.46	0.09
$I_{s,\ int.\ (R=n),\ 30\%}$	0.17	0.43	0.10
$I_{s,\ int.\ (R=400m),\ 10\%}$	0.23	0.67	0.06
$I_{s,\ int.\ (R=400m),\ 30\%}$	0.37	0.56	0.11
$I_{s,\ choice\ (R=n),\ 10\%}$	0.30	0.33	0.13
$I_{s,\ choice\ (R=n),\ 30\%}$	0.37	0.31	0.11
V_{Ntw1}	1.3%	4.3%	0.9%
V_{Ntw2}	1.4%	3.4%	0.3%
V_{Ntw3}	2.8%	4.2%	1.4%
V_{Ntw}	5.5%	11.8%	2.6%

Table 3.4: Results

Based on the examined measures and urban characteristics, Alessandria shows the largest area at risk to be flooded, as well as the highest percentage of network at risk. However, syntactic cores are not located within flood-prone areas or most densely inhabited zones. Therefore, even showing a certain degree of network vulnerability, the main syntactic parts of the system are not significantly exposed to risk. Extents of floodable areas and percentage length of network at risk noticeably increase referring to Pisa. These circumstances are also combined with remarkable values of population and cores at risk, determining an overall high level of vulnerability. Torino shows areas at risk considerably smaller than the previous two case studies, also because of flood defence along rivers in the urbanised zones. According to how resilience is assumed in the adopted approach, these structural measures permit to increase river resistance, the latter defined as a component of river-city resilience to floods. A limited part of the urban grid is at risk and cores are basically in non floodable areas. In all presented cases, highest percentages of cores at risk are located in urbanised areas (such as continuous or discontinuous urban fabric). This result reflects the consistency of the syntactic structure, with urban centralities corresponding zones with high concentration of people and activities.

This comparative analysis highlights the importance of considering an integrated approach to examine urban resilience. All main components of resilience to floods are characterised by matching hydro-morphology, river system, urban structure and space use, demographic features; moreover, elements which contribute to determine vulnerability are pointed out. A comprehensive plot can provide an inclusive graphical representation of these outcomes (Fig. 3.111), taking into account three different dimensions:

- "*network-based vulnerability*", representative of all the cores at risk (x-axis);
- *"population at risk"* (y-axis)
- "*total susceptibility indicator*" ("$I_{s,\ 30\%}$"), assumed complete the description of how the system is likely to be affected in its main syntactic parts. The value is obtained as the sum of the three "*susceptibility indicator*"($I_{s,int(R=\ n)\ 30\%}$; $I_{s,int(R=\ 400m)\ 30\%}$; $I_{s,choice(R=\ n)\ 30\%}$) of measured syntactic indexes (dimensions of dots within the graph).

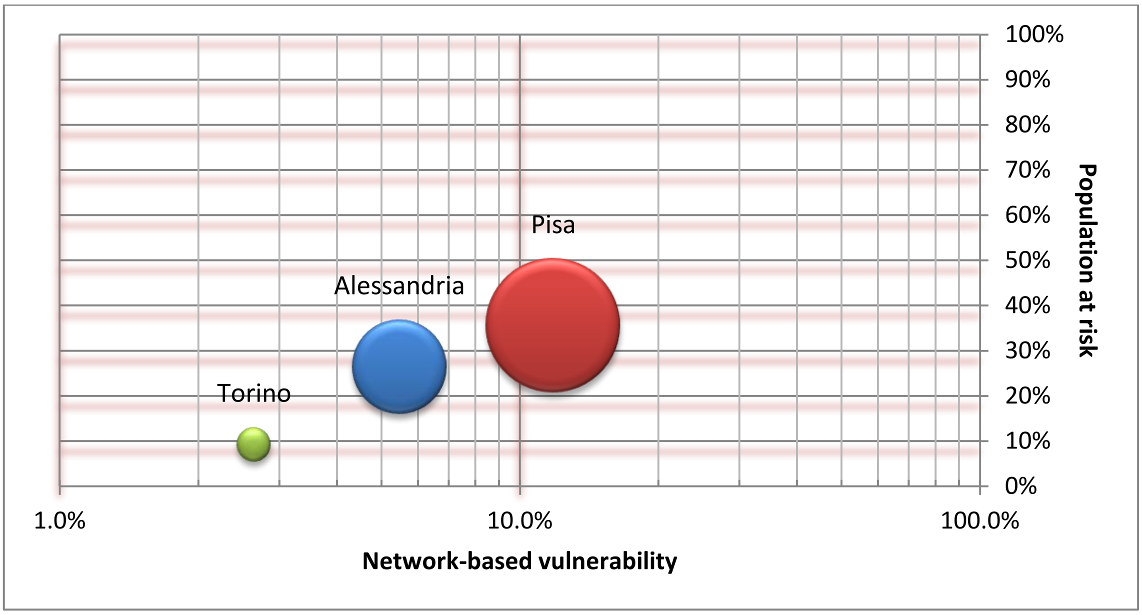


Figure 3.111: Representation of vulnerability elements

Comparison between pre and post-event configurations provides further elements to understand resilience degree. In all cases, the original 8-dimensional dataset of syntactic measures was suitably described by two principal components. Values of silhouette and cophenetic in all cases accounted for a meaningful partitioning solution. Moreover, according to B_k values (and relative confidence intervals) (see APPENDIX C), partitions were not influenced by the chosen linkage method. All B_k values were close to 1, so partitions similar to the analysed ones would have been obtained applying the hierarchical cluster analysis with a different linkage distance. After the event, Alessandria basically preserves global properties, also creating new local centralities in non-flooded areas. Therefore, even being considerably vulnerable, flood-induced effects are almost limited thanks to a moderate adaptive capacity of the grid. Configurational properties of Pisa structure appear notably affected by the event, as a result of the significant vulnerability to floods. Relative post-event configuration consists of four distinct areas, almost all of them having strategic spaces with high values both of integration and choice -at the same time- or just one of these two indexes. A high vulnerability level corresponds to a significant need of adaptive capacity. Few elements at risk in reference to Torino, non-related to syntactic cores, account for the almost non-changed structure of the southern part of the study area.

Definition of new corridors with significant choice index shows a good adaptability of the northern subsystem to flood-induced changes.

Combining deduced information related to affected elements, factors representative of system vulnerability and event consequences, the methodology permits to understand resilience through a framework of factors which could undermine the ability to resiliently face floods, or rather it outlies elements which actually allow to expect an appropriate capacity of withstand flooding.

4
Conclusions

4.1 Conclusions

This thesis focused on examining the concept of urban resilience to flood risk through a spatial analysis approach.

The concept of urban resilience to natural hazards has been introduced in the field of disaster risk following a progressive evolution of the disaster risk management: from handling emergency situations, or just preventing major natural events, to rather assume hazards occurrence as a critic circumstance to cope with and recover by. The complexity of the concept and the variety of resilience applications revealed the difficulty of individuating a unique definition of urban resilience. Focusing on flood events, the technical literature offered several approaches to assess flood impact and resilience, based on different purposes of study: social, economic and structural factors are usually investigated. This circumstance relates to the variety of possible consequences of disasters in urban area, depending on the specific type of hazard, event characteristics and several features of the affected zones. Similarly, analysis of the relevant literature showed that different approaches have been developed so far to evaluate urban resilience; all these approaches resulted to be strictly related to how resilience is defined. Measures of resilience appeared in the literature to be often achieved through sectorial analysis, qualitative evaluations or assuming some variables as proxies of resilience itself. Without underestimating the contribution of all these available approaches, it was examined the further characterisation of urban resilience resulting from examining how flood events impact urban structure, the latter considered as a network of spaces closely related to human activities. Main principles of the configurational theory of Space Syntax were illustrated, outlining the functional, social and cognitive issues that the configurational properties permit to investigate. Matching the syntactic properties and the spatial effects induced by flooding in urban areas, validity of applying the configurational approach to investigate spatial resilience to flood events was substantiated.

According to Space Syntax theory, space owns a functional meaning, as an element able to affect people behavior, rather than being just a pattern of open spaces and buildings. Changes of spatial geometry determine a modified spatial perception and different spatial layouts induce diverse use of space. As a consequence, spatial configuration can be examined to describe resilience of buildings and urban structures. The description of works developed so far to evaluate a syntactic-based resilience completed this theoretical overview (Chapter 1). However, a deep analysis of the said previous approaches showed some limitations in reference to their applicability to the specific case of flood events.

Based on the capability of configurational properties to describe how urban space is used and perceived, application of Space Syntax approach was examined in reference to the possibility to analyse different spatial layouts and relative resilience to flood events. Adopting the configurational perspective of analysis, presence of flooded areas was investigated in reference to its influence on human dynamics and the modifications of spatial perception it could determine. On this background, an integrated definition of urban resilience to flood risk was provided to set the conceptual framework needed towards developing a resilience assessment methodology. Urban resilience was assumed as cyclic process made up by different interrelated components, or rather basically resistance, vulnerability, impacts and adaptation. Focusing on river floods, resistance was referred to characteristics of the river system, as well as presence of protective measures. Vulnerability, impacts and adaptive capacity were referred to the affected urban system, in its structural and functional elements. Following this conceptual framework, a methodology was introduced (Chapter 2) to assess urban resilience to flooding through subsequent stages of analysis:

- the preliminary *analysis of urban structure and its configurational properties*, to investigate the mutual influence between cities and rivers they are crossed by. The derived knowledge informs about the role that watercourses have been played in regard of urban development and human activities in areas located next to rivers. Significance of this analysis lies in that actual urban structures, which constitute the element analysed at this stage. Actual configuration of settlements located on river banks can be interpreted as a probable pre-event configuration, or rather a potentially impacted system.

- the subsequent *analysis of areas at risk*, to determine urban vulnerability, notably exposure to floods. Through multiple steps, different urban characteristics were taken into account. As related to urban vulnerability, analysing exposure contributes to understand potential effects of a given event, as well as to individuate possible causes and trigger factors of making flood events disasters. Areas at risk to be flooded can be known modelling potential calamitous scenarios to define floodplain zones.
- the further *analysis of possible post-event conditions* through a scenario analysis, to point out flood-induced spatial changes. Capability to objectively individuate and assess syntactic changes within affected settlements requires suitable ways to compare different urban configurations (notably related to circumstances before and after the event). The need to identify a consistent approach to evaluate these changes was addressed through a statistical-based analysis.

Each one of these stages was also operatively structured and relative outcomes of syntactic and urban analyses were examined and processed through graphical, spatial and statistical-based methods. The described methodology was implemented to some river-cities assumed as illustrative applications (Chapter 3). The analysed case studies were chosen in order to obtain a significantly differentiated set of case studies. Presence of river courses was the common element among these selected urban areas, being all them crossed by watercourses. However, study area extents and relative locations in relation to river banks, territorial morphology, specificity of each river ecosystem and flood-prone zones varied among them. This diversity allowed to test the methodology in reference to different urban configurations and features. According to the different phases of analysis through which the approach was structured, each actual urban configuration, relative elements at risk and probable post-event conditions, were examined for each case, applying a scenario approach. Furthermore, a comprehensive framework of outcomes was achieved comparatively examining derived outcomes. As a result, an overall evaluation of how each urban system copes with floods was provided. This operative stage also permitted to assess the methodological validity of the procedure in reference to different urban structures.

The capability of the developed approach to assess urban resilience to flooding confirms the achievement of the main purposes this study set out to reach: *i*) to consider spatial and functional properties to define urban resilience; *ii*) to individuate a methodology to evaluate urban resilience, based on quantitative measures; *iii*) to ensure the objectivity of the said methodology, being the latter structured to be suitably applied to different urban structures allowing relative comparisons among the latter.

Significance of introducing resilience in dealing with disasters mainly consists in the possibility it could lead to improve disaster risk governance. Considering causal factors, main effects and consequences of hazardous events, resilience assessments are essential to define resilience -focused strategies. The latter, in turn, represent an opportunity to develop or increase the capacity of risk exposed settlements to face hazardous conditions, across all the different phases of disasters. According to how the whole procedure is structured, different phases of flood events are investigated: pre-event conditions as well the post-event phase, the latter resulting as the emergency derived from considering the presence of flooded areas within affected settlements.

Each stage contributes to overall assessing the degree of urban resilience. Outcomes of the whole methodology lead to an objective assessment, based on quantitative indicators as well as measures not related to the specific system they are referred (in terms of dimensions). These aspects firstly result into the significant opportunity to examine resilience by linking syntactic features to urban morphology. Moreover, the approach permits to compare different urban configurations. The latter can be referred to distinct settlements, which can be compared each other to assess and characterise their resilience. According to the syntactic approach, distinct urban layouts of a given area also represent different configurations; urban layout can be modified as a result of implementing urban plans or applying urban design measures (which could affect urban pattern and use of urban space). It follows the significant opportunity to analyse these changes in reference to their influence on resilience degree: examining these aspects *before* the occurrence of flood events to contribute to improve and facilitate the urban response *after* the event. Therefore, the methodology can be considered a supporting tool for urban planning, emergency management and, more generally, flood risk management. The further advantage of measuring resilience through configurational features allows to consider the not-directly measurable cognitive and social phenomena that the configurational indexes account for. In this view, the whole methodology represents a contribution to usual risk assessment, considering aspects and disaster impacts not usually examined. Even having been applied to flood events, the described approach remains still methodologically valid for every event able to affect the urban grid in a way that relative affected areas can be spatially well-defined.

4.2 Further developments

Some aspects of the presented approach can be pointed out as to be further detailed, constituting, at the same time, a basis for possible developments of the study. These aspects can regard both the whole methodology and the specific applied methods of analysis.

Syntactic measures constitute proxies of people movement and activities. However, the information they account for can be further completed considering other urban characteristics. In the broader context of a syntactic evaluation of urban resilience, the detailed analysis that could be achieved leads to an improved characterisation of resilience property. On this basis, the described multi-step approach to investigate vulnerability could be enhanced adding further steps: other information (e.g.: presence and location of strategic urban functions, rescues location, population structure) could be taken into account in addition to the already considered urban morphology or demographic characteristics.

Moreover, flood event features clearly influence extent of areas at risk, also affecting some elements of the methodology (such as the percentage of network or people at risk). Areas at risk basically correspond to floodplains which, in turn, are referred to a given event, or rather a certain value of return period. Assuming different events, i.e. various return period, the proposed methodology could provide a comparison between correspondent distinct scenarios. Relative outcomes constitute an opportunity to explore whether and to what extent each component of resilience varies in reference to event magnitude. The derived information could represent a sensitivity analysis aimed at describe how resilience varies in respect of severity of flooding.

On the basis of the technical literature focused on examining the relationship between syntactic measures and human wayfinding, further applications of the presented methodology could be achieved. Relating wayfinding process, flood-induced changes and centralities location after the event, the methodology could lead to point out appropriate evacuation corridors. According to the aspects taken into account, these corridors would be based on human perception of space and cognitive aspects. As an outcome, appropriate strategies in emergencies can be derived.

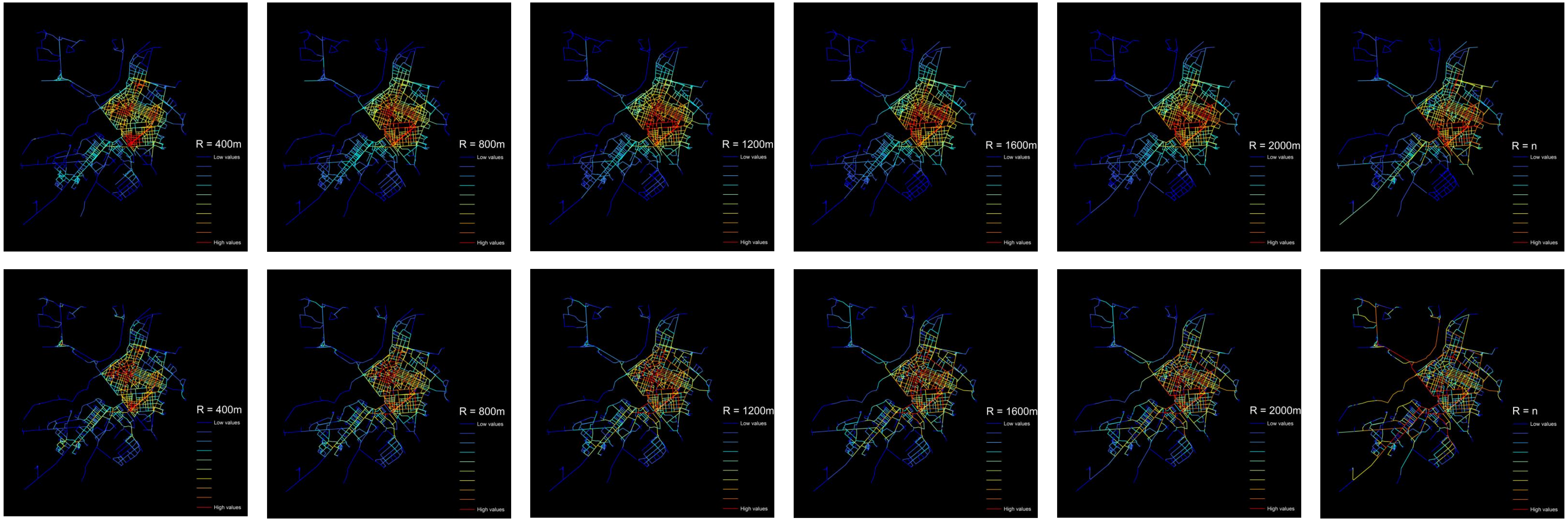


Figure A.1: Alessandria - *Scenario 0*. Spatial distribution of integration indexes (*upper row*) and choice index (*lower row*), at different radii ("*R*")
(Blue: Low values, Red: High values; 10-intervals quantile classification)

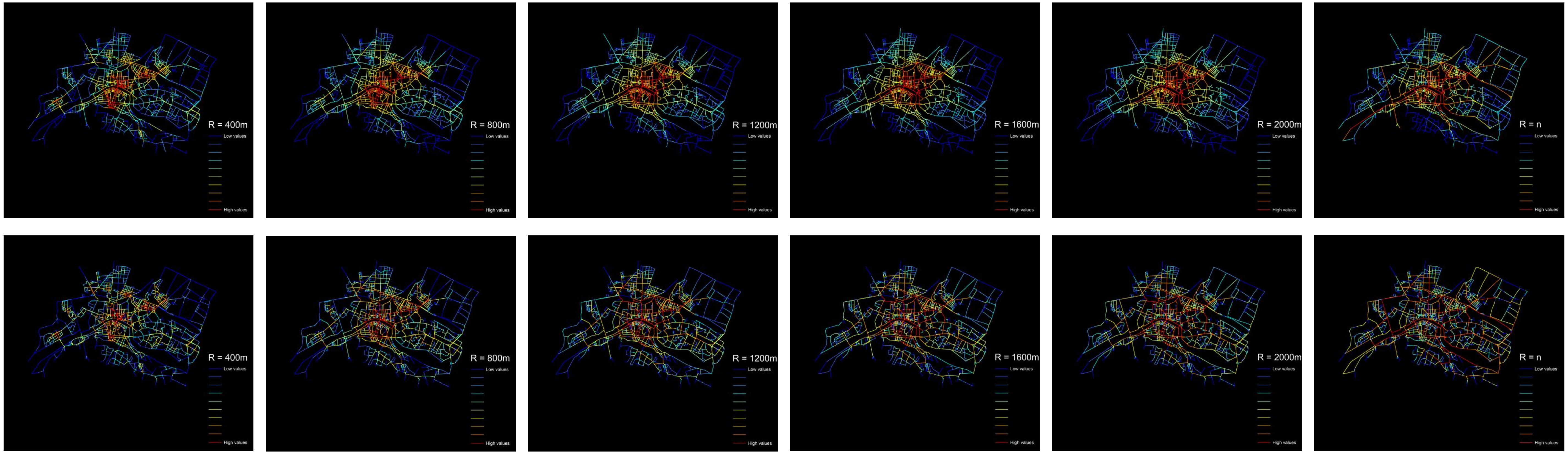


Figure A.2: Pisa - *Scenario 0*. Spatial distribution of integration indexes (*upper row*) and choice index (*lower row*), at different radii ("*R*") (Blue: Low values, Red: High values; 10-intervals quantile classification)

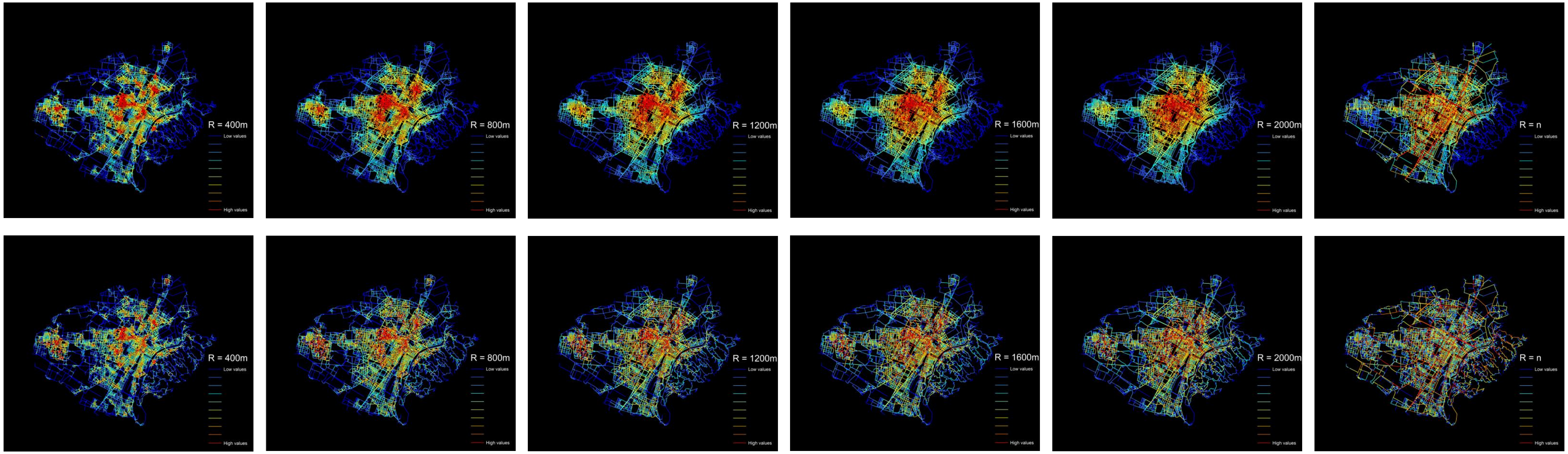
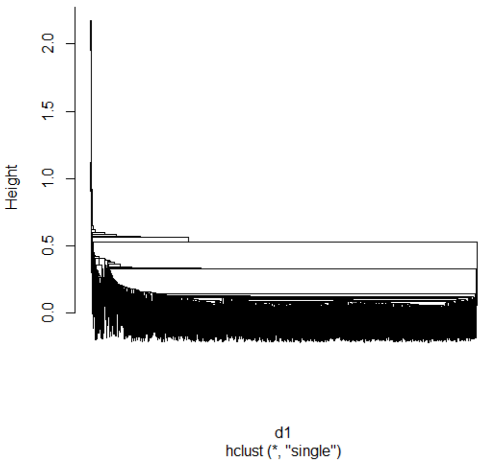


Figure A.3: Torino - *Scenario 0*. Spatial distribution of integration indexes (*upper row*) and choice index (*lower row*), at different radii ("*R*")
(Blue: Low values, Red: High values; 10-intervals quantile classification)

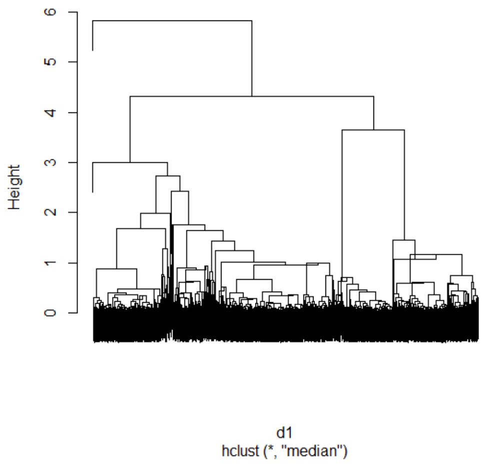
APPENDIX B

Hierarchical cluster analysis with different linkage methods (Dendrograms)

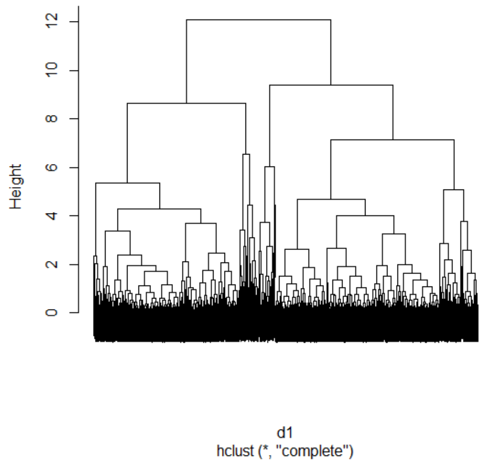
Alessandria - Scenario 0, Single Linkage



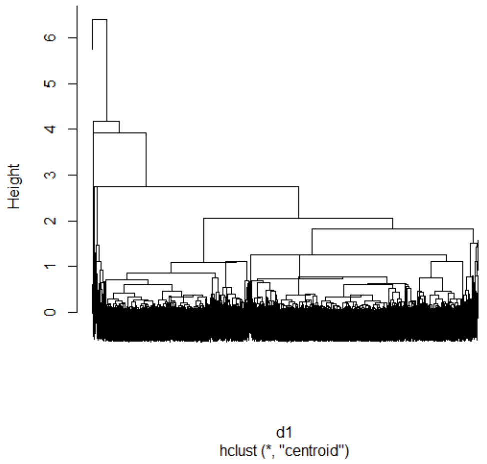
Alessandria - Scenario 0, Median Linkage



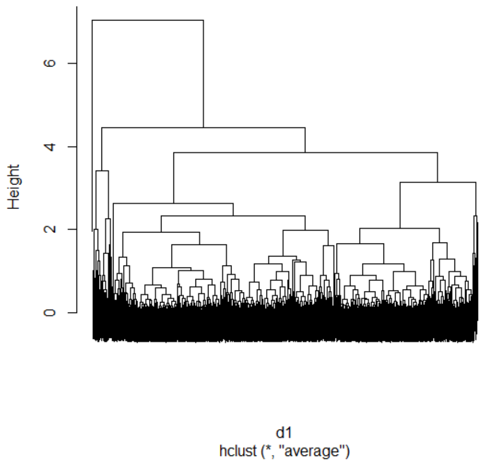
Alessandria - Scenario 0, Complete Linkage



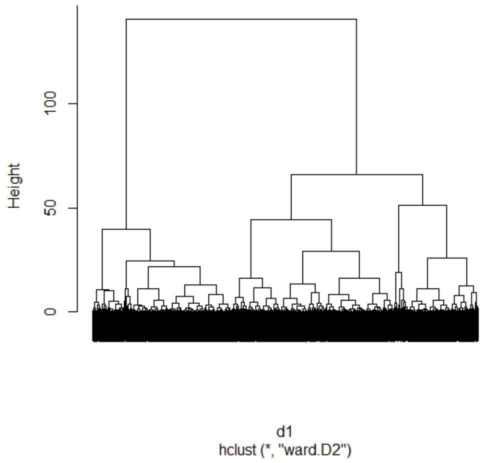
Alessandria - Scenario 0, Centroid Clustering

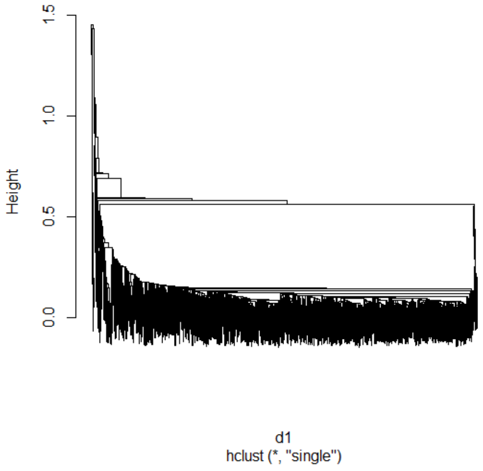


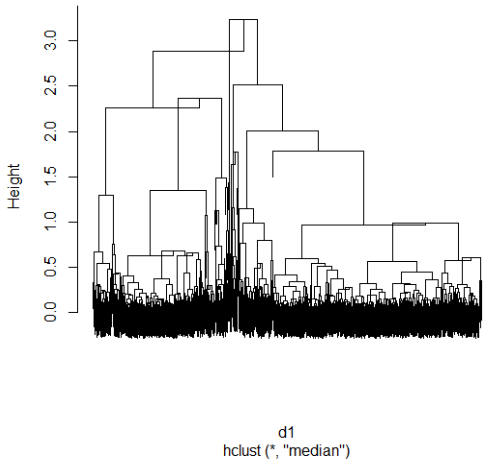
Alessandria - Scenario 0, Average Linkage

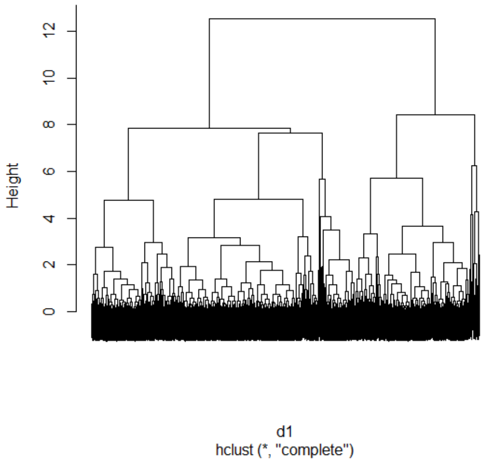


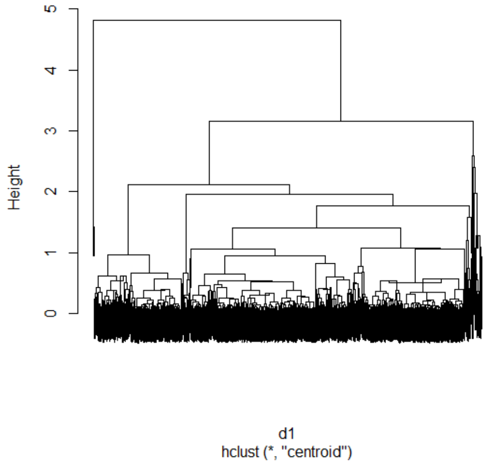
Alessandria - Scenario 0, Ward

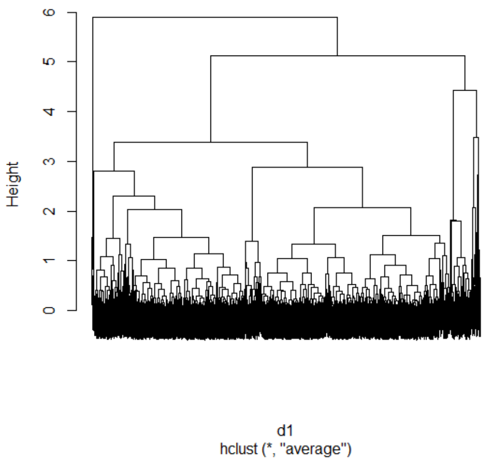


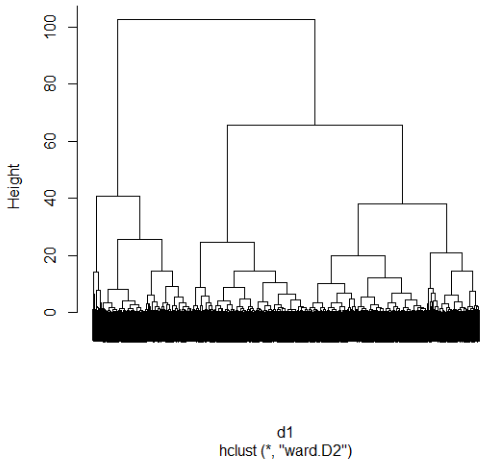

Alessandria - Scenario 1, Single Linkage

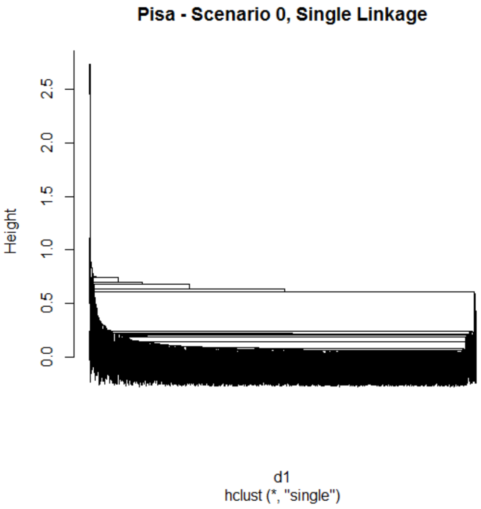

Alessandria - Scenario 1, Median Linkage

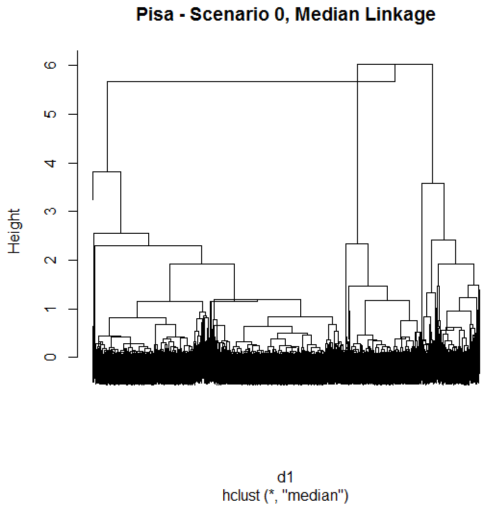

Alessandria - Scenario 1, Complete Linkage

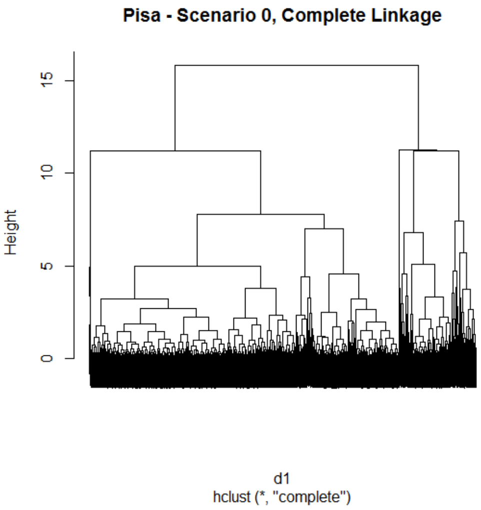

Alessandria - Scenario 1, Centroid Clustering


Alessandria - Scenario 1, Average Linkage


Alessandria - Scenario 1, Ward


Pisa - Scenario 0, Single Linkage


Pisa - Scenario 0, Median Linkage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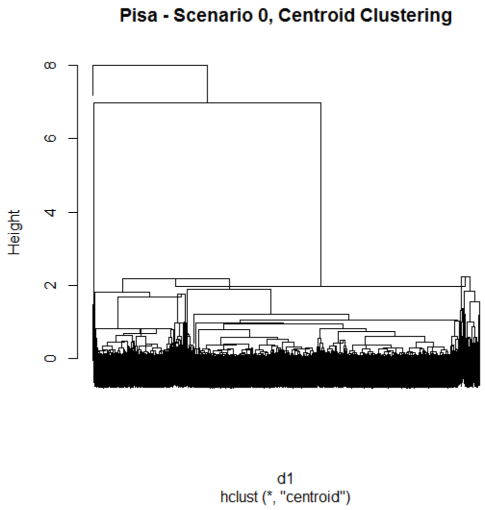
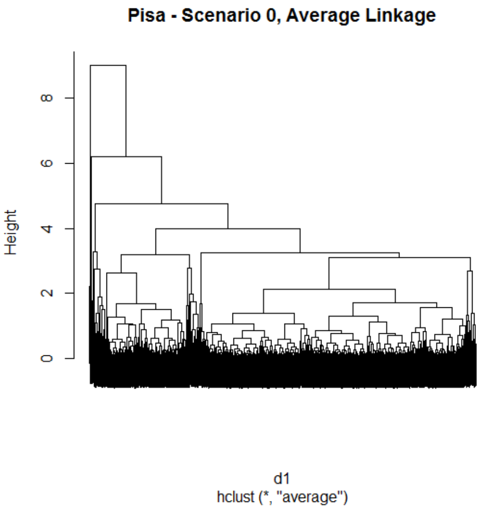
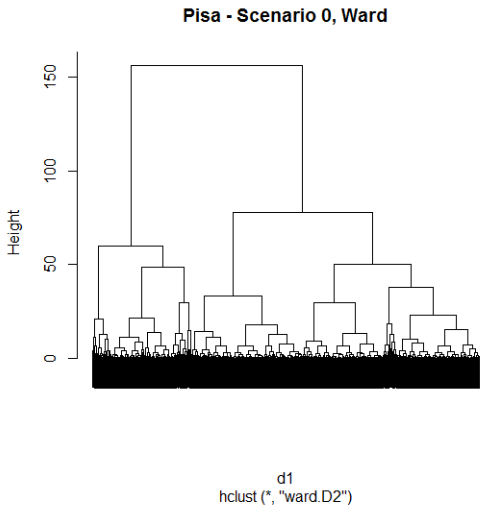
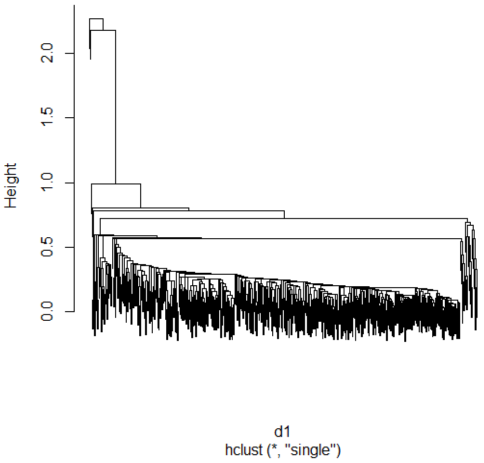
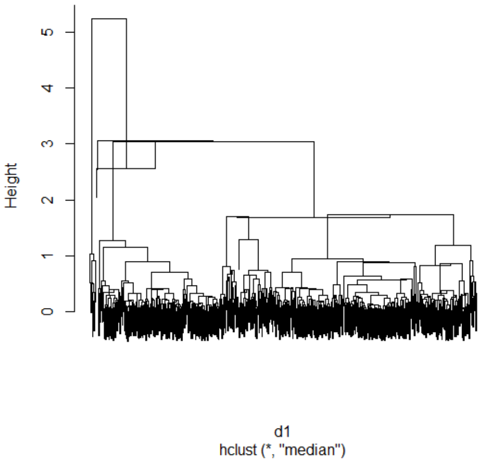

Pisa - Scenario 0, Centroid Clustering


Pisa - Scenario 0, Average Linkage


Pisa - Scenario 0, Ward



Pisa - Scenario 1 / SUB1, Single Linkage



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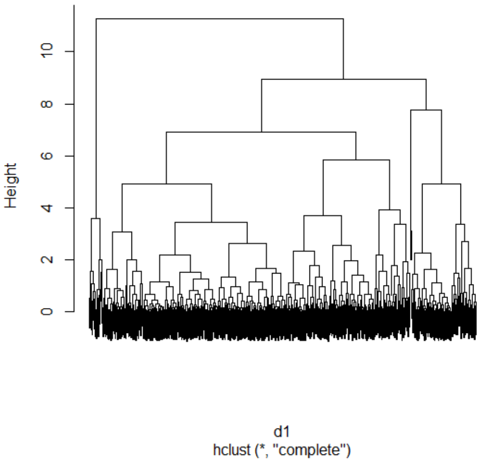

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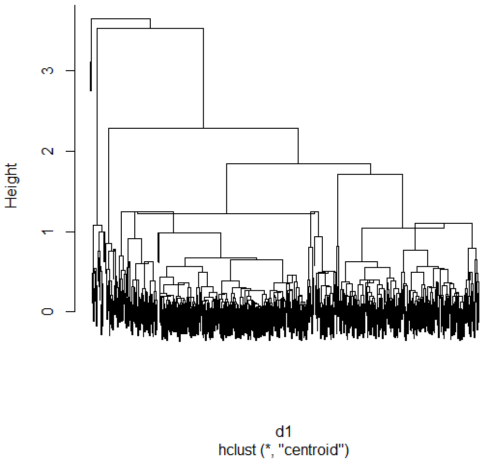
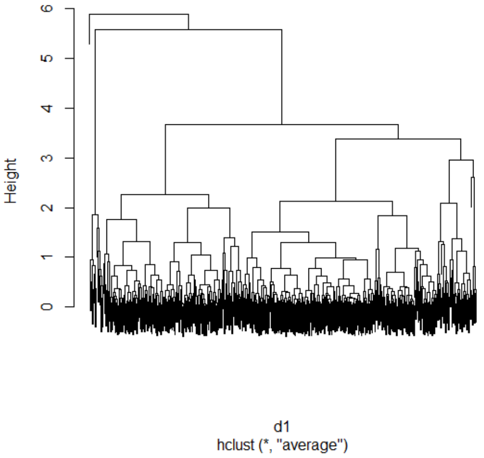


Pisa - Scenario 1 / SUB1, Centroid Clustering



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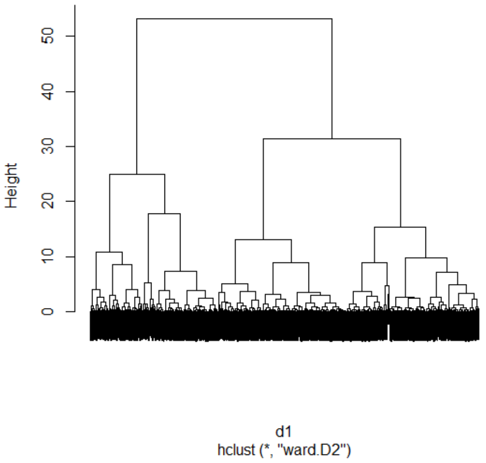
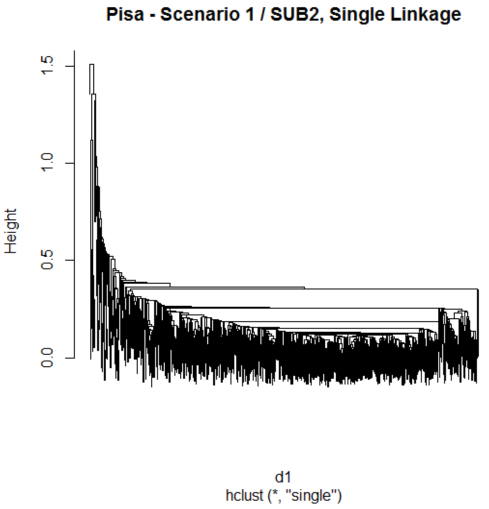
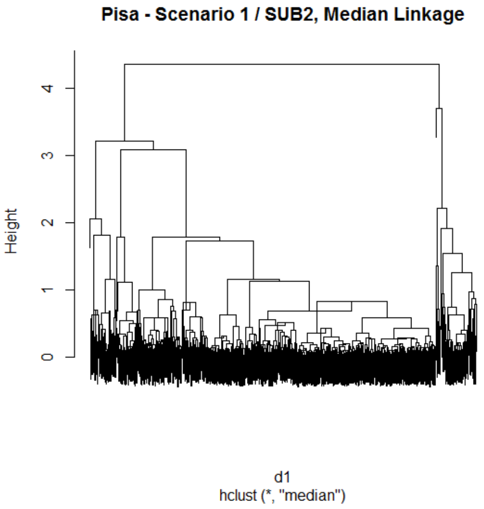


Pisa - Scenario 1 / SUB1, Ward


Pisa - Scenario 1 / SUB2, Single Linkage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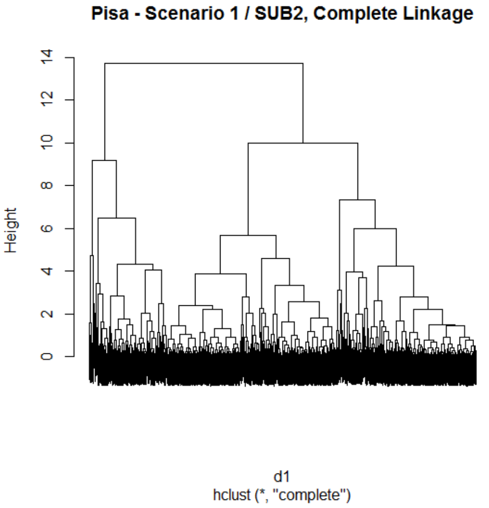
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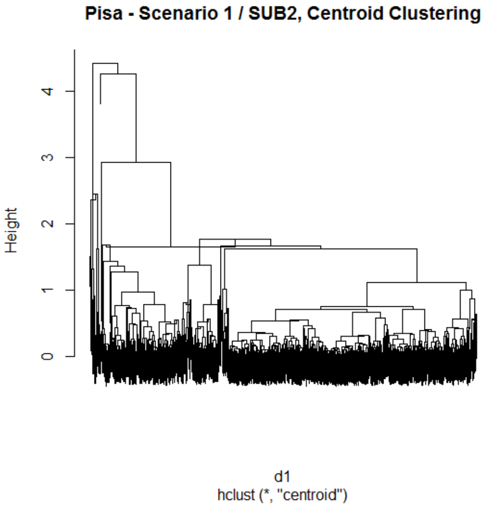
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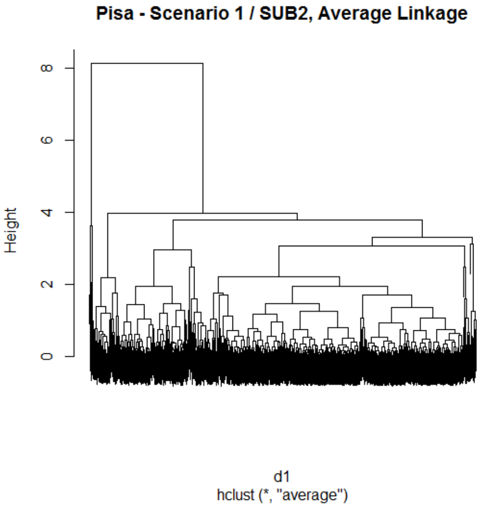
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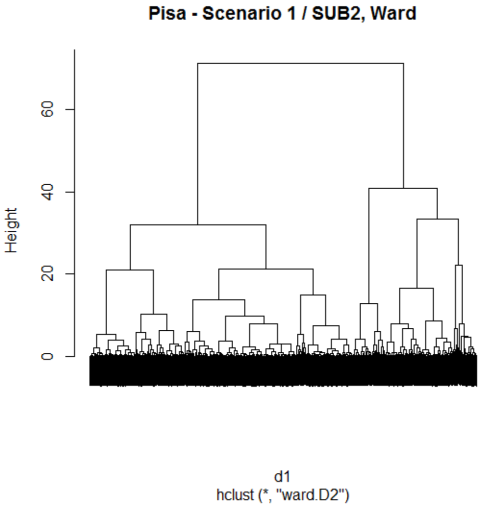
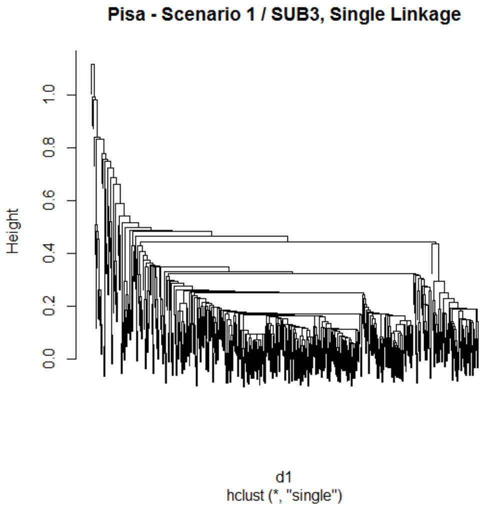

Pisa - Scenario 1 / SUB2, Ward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0.6
0.8
1.0
d1
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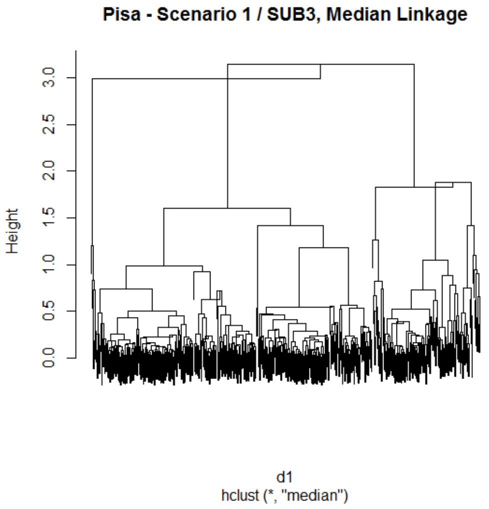
Pisa - Scenario 1 / SUB3, Median Linkage
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2.5
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d1
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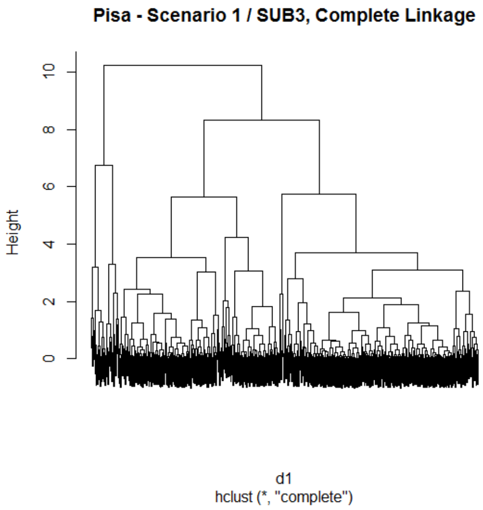
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8
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d1
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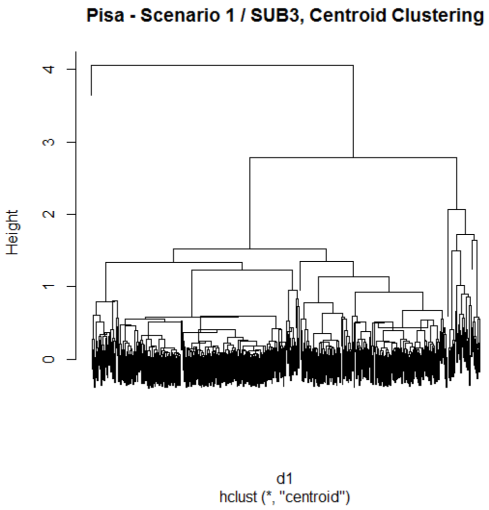
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4
d1
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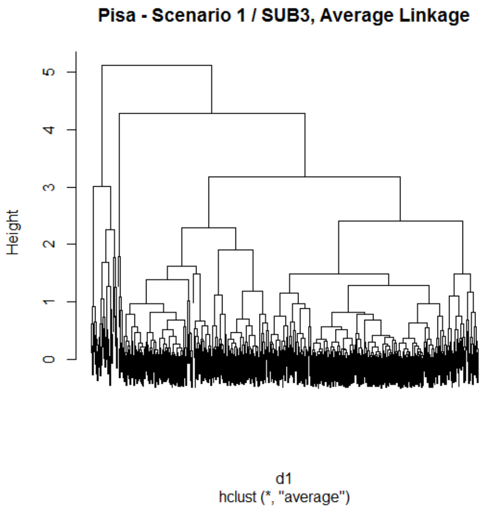
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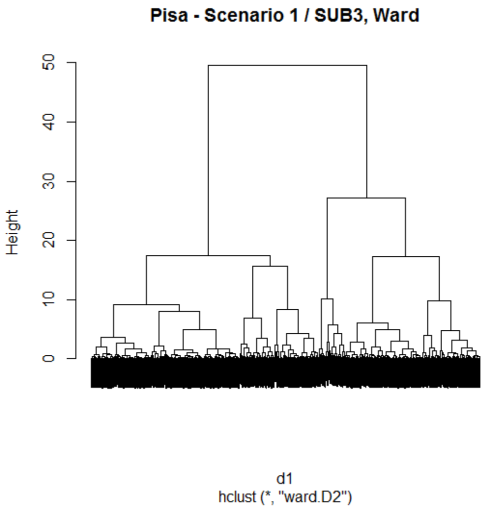
2
3
4
5
d1
hclust (*, "average")


Pisa - Scenario 1 / SUB3, Ward
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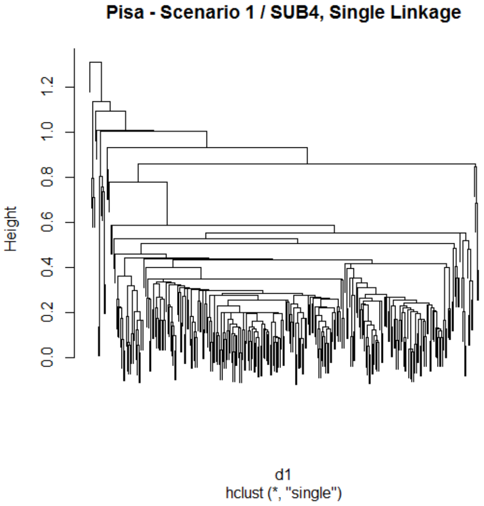
10
20
30
40
50
d1
hclust (*, "ward.D2")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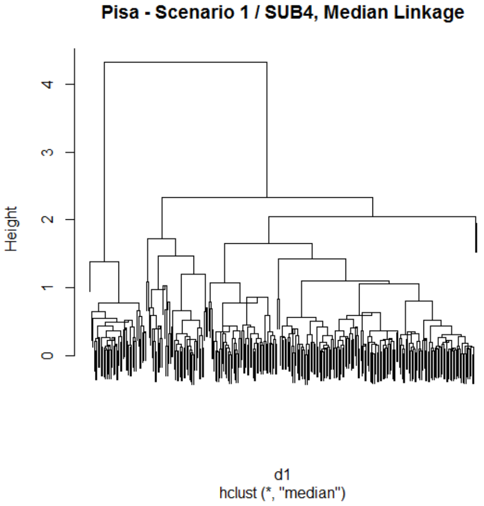
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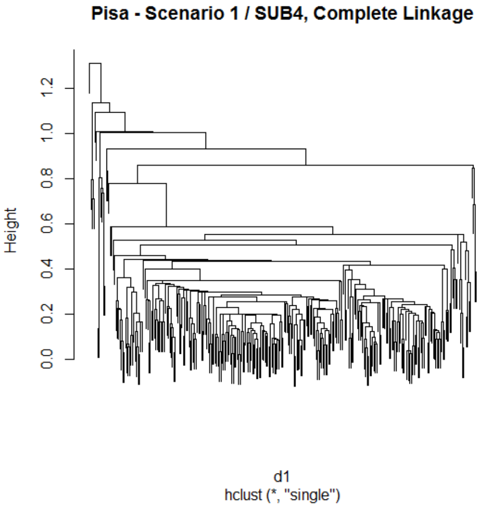
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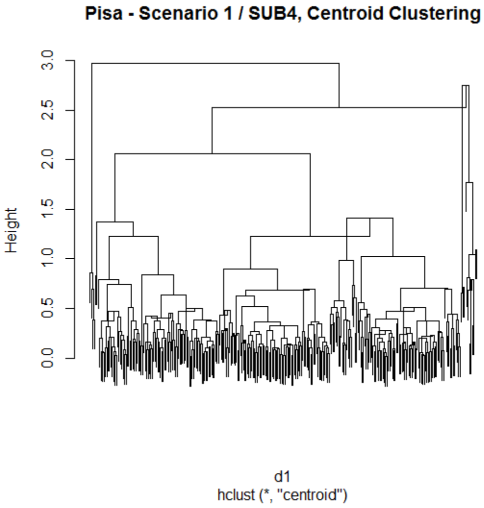
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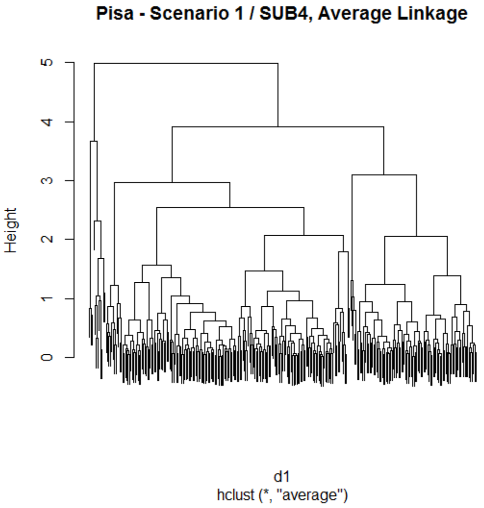
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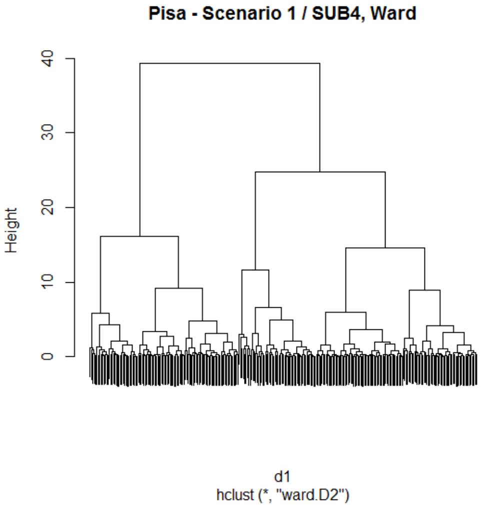
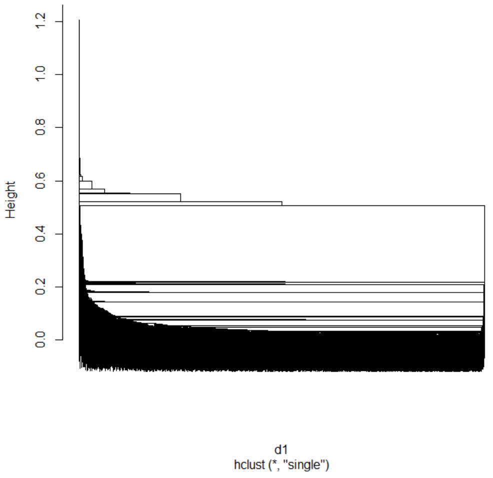
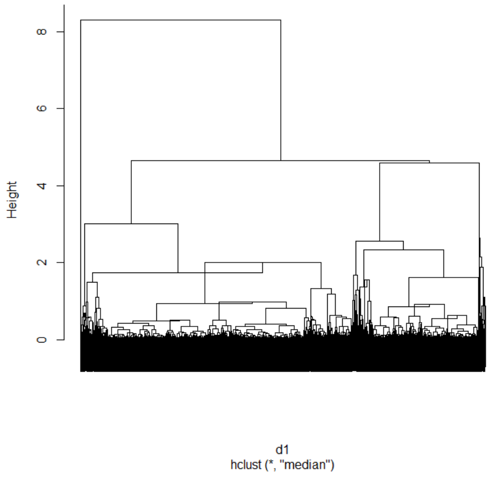
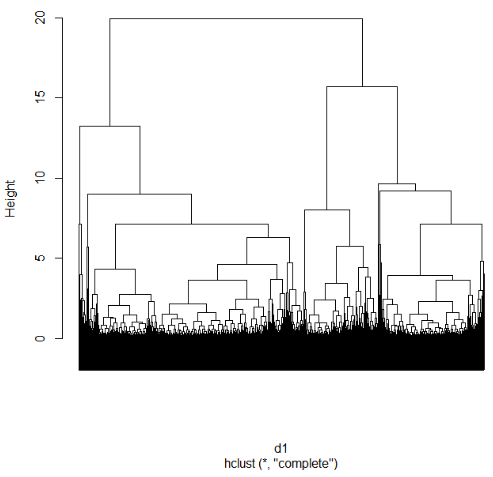
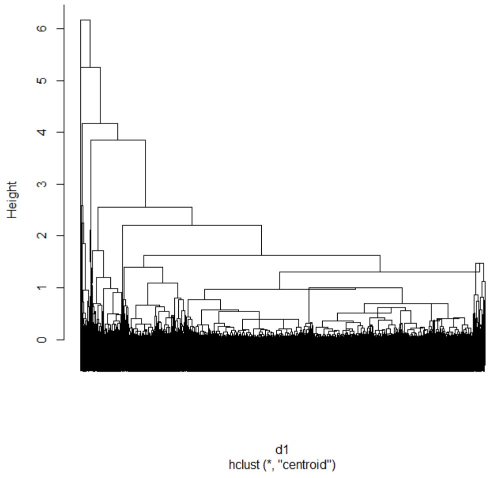
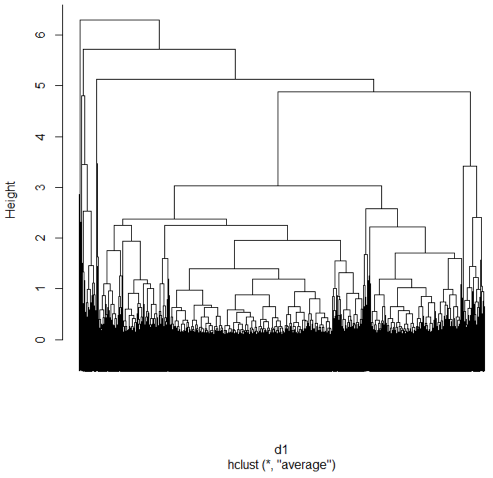

Pisa - Scenario 1 / SUB4, Ward

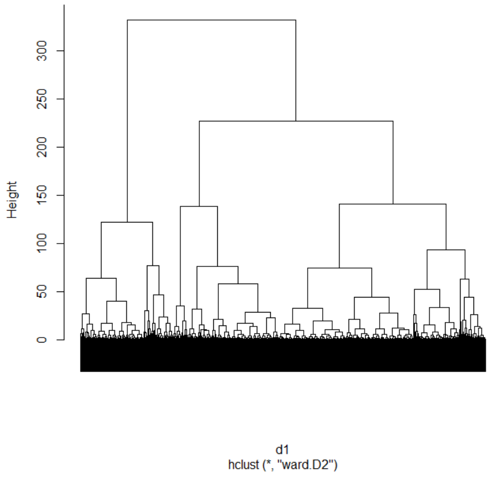

Torino - Scenario 0, Single Linkage

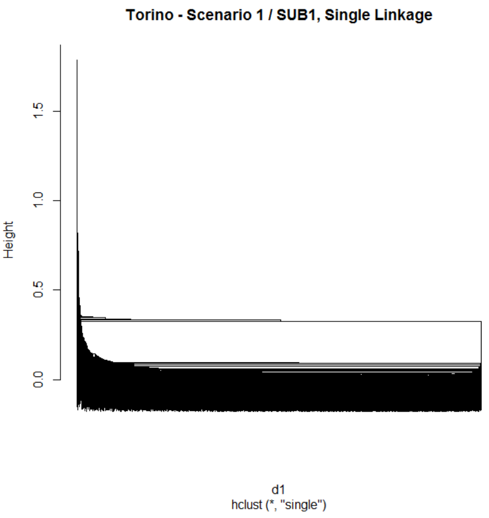

Torino - Scenario 0, Median Linkage

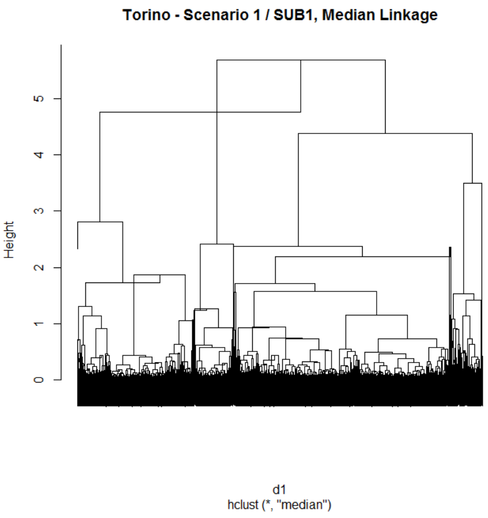

Torino - Scenario 0, Complete Linkage

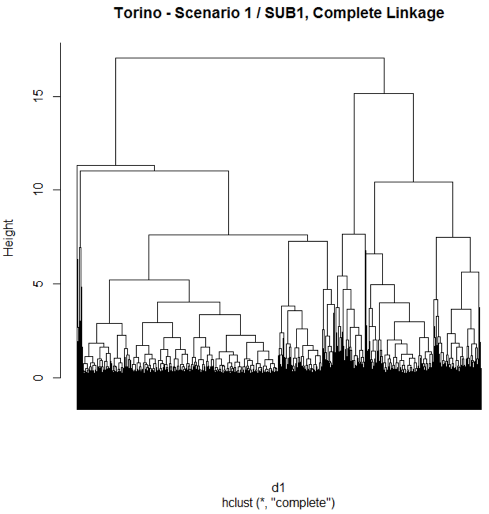

Torino - Scenario 0, Centroid Clustering

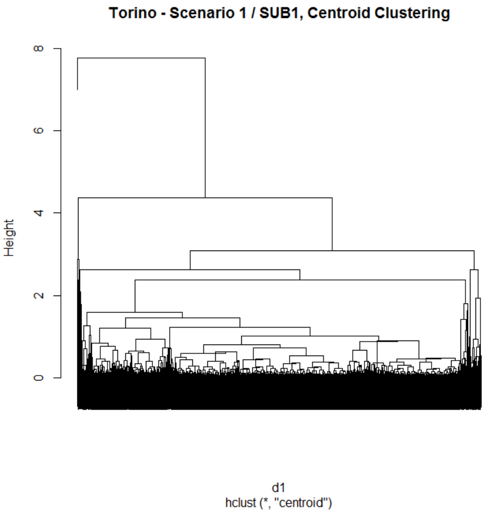

Torino - Scenario 0, Average Linkage

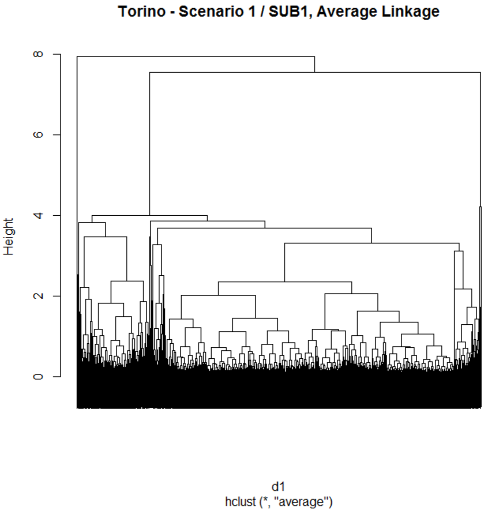

Torino - Scenario 0, Ward

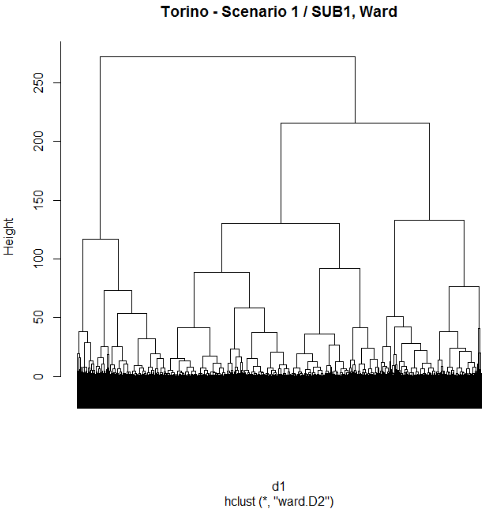

Torino - Scenario 1 / SUB1, Single Linkage


Torino - Scenario 1 / SUB1, Median Linkage

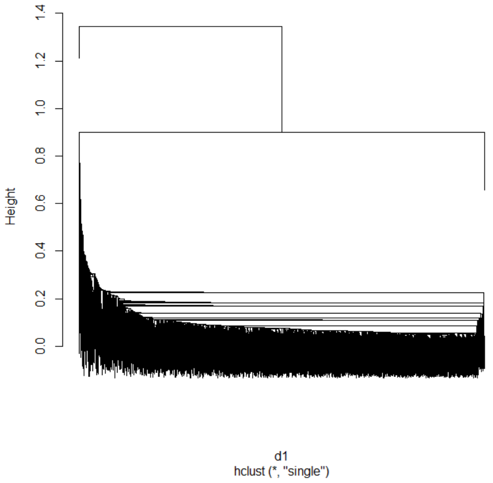

Torino - Scenario 1 / SUB1, Complete Linkage


Torino - Scenario 1 / SUB1, Centroid Clustering

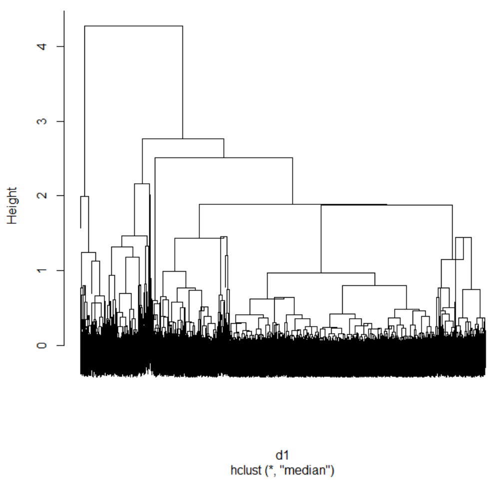

Torino - Scenario 1 / SUB1, Average Linkage


Torino - Scenario 1 / SUB1, Ward

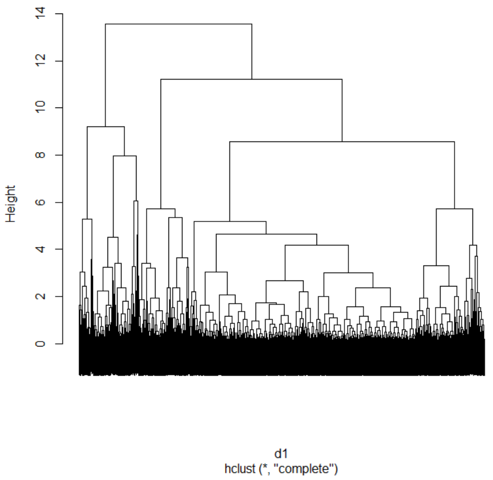
Torino - Scenario 1 / SUB2, Single Linkage



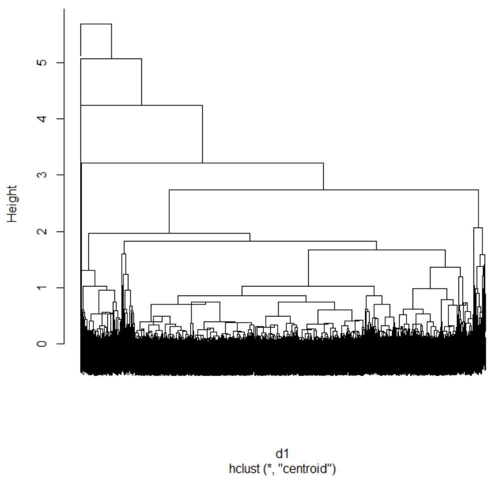
Torino - Scenario 1 / SUB2, Median Linkage



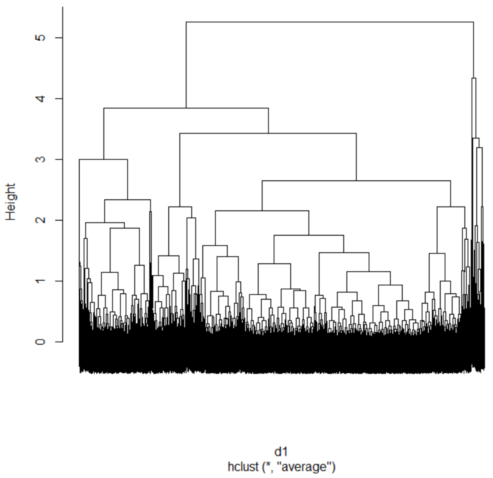
Torino - Scenario 1 / SUB2, Complete Linkage



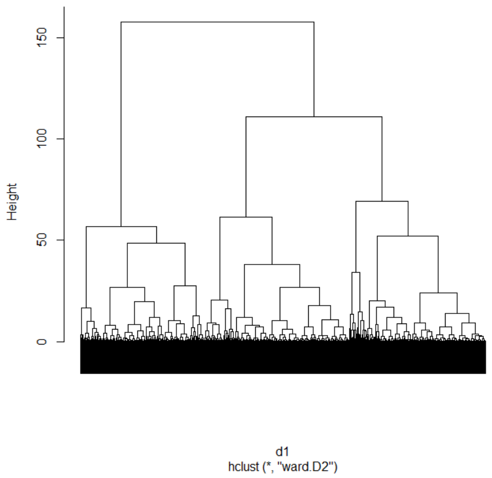
Torino - Scenario 1 / SUB2, Centroid Clustering



Torino - Scenario 1 / SUB2, Average Linkage



Torino - Scenario 1 / SUB2, Ward



APPENDIX C
Similarity between hierarchical clusterings

❖ Alessandria

Scenario 0	B_k	CI $_{95\%}$
Single Linkage - Complete Linkage	0.705	(0.587; 0.818)
Single Linkage - Average Linkage	0.916	(0.673; 0.994)
Single Linkage - Median Linkage	0.767	(0.590; 1.000)
Single Linkage - Centroid Linkage	0.994	(0.735; 1.000)
Single Linkage - Ward's Linkage	0.618	(0.572; 0.683)
Complete Linkage - Average Linkage	0.710	(0.549; 0.929)
Complete Linkage -Median Linkage	0.690	(0.515; 0.867)
Complete Linkage - Centroid Linkage	0.704	(0.569; 0.841)
Complete Linkage - Ward's Linkage	0.685	(0.507; 0.872)
Average Linkage - Median Linkage	0.748	(0.563; 0.994)
Average Linkage - Centroid Linkage	0.916	(0.673; 1.000)
Average Linkage - Ward's Linkage	0.640	(0.558; 0.885)
Median Linkage - Centroid Linkage	0.766	(0.583; 1.000)
Median Linkage - Ward's Linkage	0.636	(0.506; 0.804)
Centroid Linkage - Ward's Linkage	0.616	(0.556; 0.736)

Scenario 1	B_k	CI $_{95\%}$
Single Linkage - Complete Linkage	0.667	(0.574; 0.833)
Single Linkage - Average Linkage	0.819	(0.692; 0.984)
Single Linkage - Median Linkage	0.742	(0.588; 0.948)
Single Linkage - Centroid Linkage	0.950	(0.834, 0.997)
Single Linkage - Ward's Linkage	0.570	(0.504; 0.626)
Complete Linkage - Average Linkage	0.680	(0.543; 0.921)
Complete Linkage -Median Linkage	0.650	(0.516; 0.866)
Complete Linkage - Centroid Linkage	0.676	(0.568; 0.860)
Complete Linkage - Ward's Linkage	0.652	(0.517; 0.852)
Average Linkage - Median Linkage	0.707	(0.519; 0.946)
Average Linkage - Centroid Linkage	0.833	(0.645; 0.998)
Average Linkage - Ward's Linkage	0.631	(0.511; 0.764)
Median Linkage - Centroid Linkage	0.734	(0.560; 0.965)
Median Linkage - Ward's Linkage	0.601	(0.485; 0.727)
Centroid Linkage - Ward's Linkage	0.579	(0.498; 0.688)

❖ Pisa

Scenario 0	**B_k**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.751	(0.602; 0.922)
Single Linkage - Average Linkage	0.930	(0.759; 0.996)
Single Linkage - Median Linkage	0.804	(0.597; 0.997)
Single Linkage - Centroid Linkage	0.981	(0.938; 0.999)
Single Linkage - Ward's Linkage	0.578	(0.518; 0.647)
Complete Linkage - Average Linkage	0.767	(0.581; 0.949)
Complete Linkage -Median Linkage	0.709	(0.506; 0.919)
Complete Linkage - Centroid Linkage	0.756	(0.602; 0.938)
Complete Linkage - Ward's Linkage	0.631	(0.503; 0.789)
Average Linkage - Median Linkage	0.789	(0.567; 0.980)
Average Linkage - Centroid Linkage	0.930	(0.763; 0.998)
Average Linkage - Ward's Linkage	0.600	(0.516; 0.725)
Median Linkage - Centroid Linkage	0.802	(0.589; 0.994)
Median Linkage - Ward's Linkage	0.591	(0.461; 0.737)
Centroid Linkage - Ward's Linkage	0.580	(0.517; 0.666)

***Scenario 1* - SUB$_1$**	**B_k**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.686	(0.587; 0.818)
Single Linkage - Average Linkage	0.851	(0.673; 0.994)
Single Linkage - Median Linkage	0.822	(0.590; 1.000)
Single Linkage - Centroid Linkage	0.958	(0.735; 1.000)
Single Linkage - Ward's Linkage	0.618	(0.572; 0.684)
Complete Linkage - Average Linkage	0.699	(0.549; 0.929)
Complete Linkage -Median Linkage	0.675	(0.515; 0.867)
Complete Linkage - Centroid Linkage	0.690	(0.569; 0.841)
Complete Linkage - Ward's Linkage	0.661	(0.507; 0.872)
Average Linkage - Median Linkage	0.771	(0.563; 0.994)
Average Linkage - Centroid Linkage	0.864	(0.673; 1.000)
Average Linkage - Ward's Linkage	0.671	(0.558; 0.885)
Median Linkage - Centroid Linkage	0.813	(0.583; 1.000)
Median Linkage - Ward's Linkage	0.632	(0.506; 0.804)
Centroid Linkage - Ward's Linkage	0.624	(0.556; 0.736)

***Scenario 1* - SUB$_2$**	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.858	(0.705; 0.992)
Single Linkage - Average Linkage	0.989	(0.951; 1.000)
Single Linkage - Median Linkage	0.872	(0.700; 1.000)
Single Linkage - Centroid Linkage	0.988	(0.964; 1.000)
Single Linkage - Ward's Linkage	0.796	(0.719; 0.915)
Complete Linkage - Average Linkage	0.863	(0.698; 0.999)
Complete Linkage -Median Linkage	0.806	(0.603; 0.989)
Complete Linkage - Centroid Linkage	0.862	(0.698; 0.998)
Complete Linkage - Ward's Linkage	0.825	(0.641; 0.983)
Average Linkage - Median Linkage	0.871	(0.695; 1.000)
Average Linkage - Centroid Linkage	0.991	(0.954; 1.000)
Average Linkage - Ward's Linkage	0.798	(0.714; 0.920)
Median Linkage - Centroid Linkage	0.871	(0.692; 1.000)
Median Linkage - Ward's Linkage	0.777	(0.594; 0.936)
Centroid Linkage - Ward's Linkage	0.798	(0.715; 0.921)

***Scenario 1* - SUB$_3$**	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.702	(0.613; 0.879)
Single Linkage - Average Linkage	0.883	(0.669; 0.989)
Single Linkage - Median Linkage	0.785	(0.598; 0.993)
Single Linkage - Centroid Linkage	0.943	(0.823; 1.000)
Single Linkage - Ward's Linkage	0.662	(0.583; 0.740)
Complete Linkage - Average Linkage	0.736	(0.598; 0.964)
Complete Linkage -Median Linkage	0.699	(0.526; 0.927)
Complete Linkage - Centroid Linkage	0.719	(0.619; 0.949)
Complete Linkage - Ward's Linkage	0.740	(0.552; 0.962)
Average Linkage - Median Linkage	0.772	(0.568; 0.982)
Average Linkage - Centroid Linkage	0.910	(0.685; 1.000)
Average Linkage - Ward's Linkage	0.709	(0.576; 0.963)
Median Linkage - Centroid Linkage	0.782	(0.587; 0.989)
Median Linkage - Ward's Linkage	0.673	(0.514; 0.888)
Centroid Linkage - Ward's Linkage	0.678	(0.577; 0.788)

***Scenario 1* - SUB$_4$**	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.737	(0.693; 0.846)
Single Linkage - Average Linkage	0.956	(0.746; 1.000)
Single Linkage - Median Linkage	0.871	(0.700; 1.000)
Single Linkage - Centroid Linkage	0.978	(0.937; 1.000)
Single Linkage - Ward's Linkage	0.741	(0.699; 0.813)
Complete Linkage - Average Linkage	0.725	(0.663; 0.905)
Complete Linkage -Median Linkage	0.728	(0.573; 0.973)
Complete Linkage - Centroid Linkage	0.731	(0.674; 0.847)
Complete Linkage - Ward's Linkage	0.792	(0.556; 1.000)
Average Linkage - Median Linkage	0.845	(0.671; 1.000)
Average Linkage - Centroid Linkage	0.953	(0.741; 1.000)
Average Linkage - Ward's Linkage	0.730	(0.675; 0.973)
Median Linkage - Centroid Linkage	0.865	(0.684; 1.000)
Median Linkage - Ward's Linkage	0.735	(0.585; 0.974)
Centroid Linkage - Ward's Linkage	0.736	(0.682; 0.818)

❖ Torino

Scenario 0	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.747	(0.590; 0.968)
Single Linkage - Average Linkage	0.981	(0.945; 0.999)
Single Linkage - Median Linkage	0.833	(0.621; 0.997)
Single Linkage - Centroid Linkage	0.988	(0.958; 1.0009
Single Linkage - Ward's Linkage	0.667	(0.594; 0.777)
Complete Linkage - Average Linkage	0.744	(0.579; 0.978)
Complete Linkage -Median Linkage	0.680	(0.506; 0.919)
Complete Linkage - Centroid Linkage	0.745	(0.586; 0.974)
Complete Linkage - Ward's Linkage	0.628	(0.494; 0.804)
Average Linkage - Median Linkage	0.828	(0.611; 0.992)
Average Linkage - Centroid Linkage	0.981	(0.940; 0.999)
Average Linkage - Ward's Linkage	0.662	(0.584; 0.783)
Median Linkage - Centroid Linkage	0.830	(0.614; 0.993)
Median Linkage - Ward's Linkage	0.634	(0.502; 0.792)
Centroid Linkage - Ward's Linkage	0.664	(0.586; 0.783)

Scenario 1 - SUB$_1$	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.716	(0.589; 0.926)
Single Linkage - Average Linkage	0.986	(0.935; 0.999)
Single Linkage - Median Linkage	0.806	(0.603; 0.999)
Single Linkage - Centroid Linkage	0.996	(0.988; 1.000)
Single Linkage - Ward's Linkage	0.611	(0.578; 0.666)
Complete Linkage - Average Linkage	0.716	(0.582; 0.931)
Complete Linkage -Median Linkage	0.638	(0.474; 0.873)
Complete Linkage - Centroid Linkage	0.716	(0.587; 0.929)
Complete Linkage - Ward's Linkage	0.561	(0.455; 0.724)
Average Linkage - Median Linkage	0.802	(0.596; 0.995)
Average Linkage - Centroid Linkage	0.987	(0.938; 1.000)
Average Linkage - Ward's Linkage	0.606	(0.559; 0.665)
Median Linkage - Centroid Linkage	0.805	(0.601; 0.996)
Median Linkage - Ward's Linkage	0.573	(0.465; 0.702)
Centroid Linkage - Ward's Linkage	0.609	(0.576; 0.666)

Scenario 1 - SUB$_2$	**B$_k$**	**CI $_{95\%}$**
Single Linkage - Complete Linkage	0.891	(0.709; 0.984)
Single Linkage - Average Linkage	0.970	(0.935; 1.000)
Single Linkage - Median Linkage	0.892	(0.708; 1.000)
Single Linkage - Centroid Linkage	0.995	(0.956; 1.000)
Single Linkage - Ward's Linkage	0.763	(0.707; 0.863)
Complete Linkage - Average Linkage	0.893	(0.688; 0.993)
Complete Linkage -Median Linkage	0.812	(0.603; 0.984)
Complete Linkage - Centroid Linkage	0.889	(0.707; 0.985)
Complete Linkage - Ward's Linkage	0.688	(0.535; 0.813)
Average Linkage - Median Linkage	0.875	(0.683; 0.994)
Average Linkage - Centroid Linkage	0.968	(0.913; 1.000)
Average Linkage - Ward's Linkage	0.741	(0.673; 0.843)
Median Linkage - Centroid Linkage	0.889	(0.707; 1.000)
Median Linkage - Ward's Linkage	0.706	(0.565; 0.866)
Centroid Linkage - Ward's Linkage	0.761	(0.700; 0.861)

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