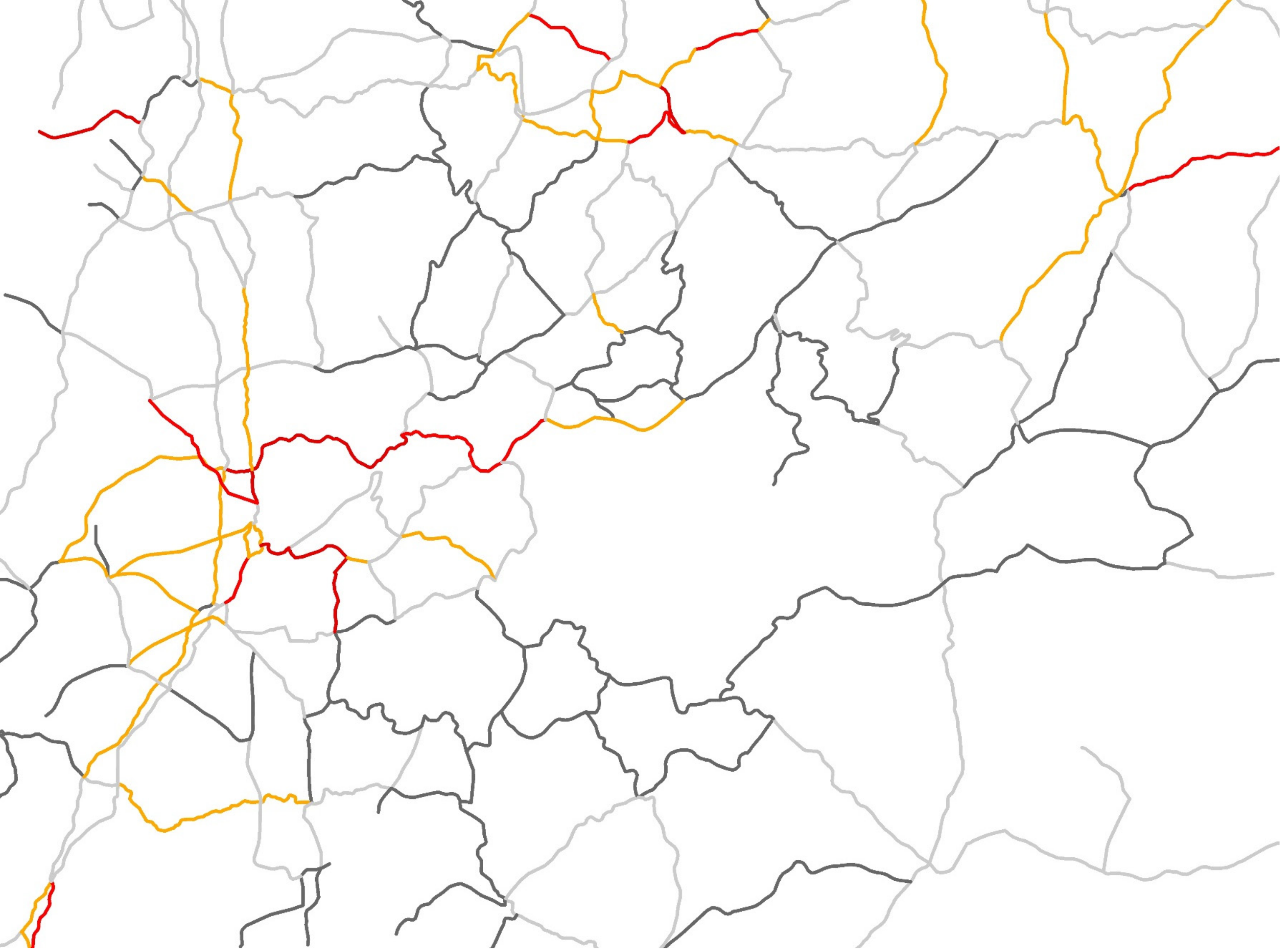

Susana da Costa Freiria

Critical infrastructure vulnerabilities. Road network connecting the territory

PhD Thesis in Territory, Risk and Public Policies, supervised by
Professor Rui Pedro de Sousa Pereira Monteiro Julião and Professor Alexandre Manuel Oliveira Tavares,
and submitted to the Institute for Interdisciplinary Research of the University of Coimbra

February, 2015

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UNIVERSIDADE DE COIMBRA

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universidade de aveiro

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Abstract

For several decades critical infrastructure management remained within engineering domains. However, a new paradigm has emerged – a socio-technical paradigm where infrastructures are seen as critical because of their value for society and for a culture. Thus, critical infrastructure operate not only according to technical specifications but also according to constraints imposed by the social environment. The problem is how to integrate in the same model the linkages between infrastructure and social systems. The main goal of this thesis is to propose a new model, the Structural Functional Risk Model – SFRM- a model that identifies the roads that are more vulnerable to interruptions, based on an integrated approach of the structural and functional component of the road network- a critical infrastructure responsible for connecting people, assets and services separated in space. The model is applied to a real road network in a multidimensional perspective, the municipal and regional context. The case studies are from the Central Region of Portugal and Coimbra, a city located in this region. The system used as an example focus the road network as element of connection and access between the parishes and the nearest Hospital – a critical infrastructure of the health sector.

The methodological approach is composed of three main phases: firstly, the road network is assessed in a structural perspective based on the application of a new approach of the biclustering technique; the following phase is focused on the evaluation of the road network in a functional perspective based on a modified gravity model; the last phase is focused on the integration of structural and functional perspective, which resulted from the SFRM. Scenario based approaches are also relevant in this work, focusing on questions such as: what can happen? If it does happen, what are the consequences? A scenario-based approach can be a useful support for a more informed, strategic action. Thus, throughout this work road interruption scenarios will be simulated and analyzed.

The results confirmed the importance of an integrated approach to the structural and functional components. In the assessment of the road network structural component the results revealed that the Biclusters with the highest connectivity are mainly located in the most dynamic economically areas, such as the Coastal zone, and the Biclusters with the lowest connectivity are mainly located in less dynamic areas, such Beira and Transmontana. So, even when the analysis is focused on a network transformed into nodes and edges it is possible to identify relations with the territorial dynamics. The results of the road network functional component assessment point to a significant resource concentration in Coimbra municipality; in the regional context significant accessibility gaps across geographical areas and population groups were identified; even in a normal scenario there are significant disparities in terms of accessibility to health care, which can get worse in a road network interruption scenario. From the integration of the structural and functional component of the road network the SFRM was the result and a step forward, quantifying the share of accountability of each of the components in the road level of vulnerability. The results demonstrate that territorial constraints play a fundamental role in critical infrastructure management; the strategies used in this domain should take into account the specificities of each territory and population characteristics.

This thesis can be seen as a step forward in the consolidation of the socio-technical paradigm as well as a tool for the definition of efficient of prevention measures and the definition of strategies aiming for quick recovery of the system in case of a disruptive event.

Keywords: road network, critical infrastructure, vulnerability, biclustering, gravity model, Structural Functional Risk Model - SFRM; spatial modeling.

Resumo

Durante várias décadas a gestão das infra-estruturas críticas pertenceu ao domínio da engenharia; contudo surgiu um novo paradigma – o paradigma socio-técnico – as infra-estruturas são críticas pelo valor que representam para a sociedade e para a cultura. Neste sentido, o funcionamento das infra-estruturas críticas depende não só de especificidades técnicas, mas também é condicionado pelo meio social. O problema reside em saber como integrar no mesmo modelo as ligações existentes entre as infra-estruturas e os sistemas sociais. O principal objetivo deste trabalho é propor um novo modelo - Modelo de Risco Estrutural e Funcional – MREF- que identifica as vias mais vulneráveis a interrupções, numa abordagem integrada da componente estrutural e funcional da rede viária – uma infra-estrutura crítica que tem como função ligar pessoas, bens e serviços separados no espaço. O MREF é aplicado a uma rede viária real numa perspetiva multiescalar, os casos de estudo são a Região Centro de Portugal e Coimbra, um município localizado nesta Região. O sistema de análise, usado como exemplo, foca-se na rede viária como elemento de ligação e acesso entre as freguesias e os Hospitais – importantes infra-estruturas críticas do sector da saúde.

A metodologia usada neste trabalho é constituída por três fases: numa primeira fase a rede viária é avaliada sob o ponto de vista estrutural com base numa nova abordagem da técnica de biclustering; a fase seguinte foca-se na avaliação da rede viária sob o ponto de vista funcional com base num modelo gravitacional adaptado aos objetivos do presente trabalho; a última fase foca-se na integração da avaliação estrutural com a funcional da qual resulta o MREF. As abordagens com base em cenários também assumem relevância neste trabalho, focando questões como: O que pode acontecer? Caso aconteça, quais são as consequências? Os resultados desta abordagem contribuem para ação mais informada e estratégica. Neste sentido, ao longo do trabalho serão apresentados e avaliados vários cenários de interrupção de vias.

Os resultados demonstram a importância de uma abordagem integrada da componente funcional e da estrutural. Aquando da avaliação da rede viária sob o ponto de vista estrutural os resultados indicaram que os biclusters com maior nível de conectividade se encontram essencialmente localizados nas áreas economicamente mais dinâmicas – como a zona costeira, enquanto os biclusters com menor nível de conectividade se encontram essencialmente localizados nas áreas economicamente mais deprimidas – como a Beira Transmontana. Conclui-se que mesmo quando a análise se foca na rede viária enquanto conjunto de nós e ligações é possível identificar relações com a dinâmica territorial. Os resultados da avaliação da rede viária sob o ponto de vista funcional indicam uma significativa polarização de recursos no município de Coimbra, no contexto regional foram identificadas expressivas diferenças em termos de áreas geográficas e grupos populacionais; estas significativas disparidades poderão ser agravadas num cenário de interrupção de vias. O MREF resulta de uma abordagem integrada das componentes estruturais e funcionais da rede viária, um modelo que pode ser visto como um passo em frente uma vez que são definidas e quantificadas as variáveis que influenciam a vulnerabilidade da rede viária. Os resultados demonstram que as condicionantes territoriais devem constituir uma componente fundamental na gestão das infra-estruturas críticas; as estratégias definidas neste âmbito devem ter em atenção as especificidades do território e as características da população.

O presente trabalho pode ser visto como contributo para a consolidação do paradigma sociotécnico assim como um instrumento para a definição de medidas de prevenção eficientes e definição de estratégias que tenham em vista o rápido restabelecimento do funcionamento do sistema num cenário disruptivo.

Palavras-chave: rede viária, infra-estruturas críticas, vulnerabilidade, biclustering, modelo gravitacional, Modelo de Risco Estrutural e Funcional – MREF; modelação espacial.

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I would like to extend my gratitude to Professor Bruno Santos that, even after leaving University of Coimbra to start a new challenge at Delft University of Technology, continued to be available to debate and clarify some issues concerning the road network dynamics.

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1. Introduction

Society is highly dependent upon interconnected critical infrastructure. As technology continues to advance, man-made disasters will likely reach a frequency and magnitude never thought possible (Fagel, 2011).

This thesis intends to contribute to better understanding and management of a changing world. Critical infrastructure is no longer confined to the engineering research field, but also risk management can no longer rely only on historical data to identify the threats and hazards that affect the system.

The main goal of this thesis is to propose the Structural Functional Risk Model (SFRM) – a model that identifies road network vulnerabilities in an integrated approach of the structural and functional components. The work will be particularly focused on the identification of the most vulnerable links in the road network, an interesting case because this is a critical infrastructure whose importance lies in the critical infrastructure which is responsible for making connections. So, the vulnerability of a road, and thus its importance, is related to the consequences of its failure in the network's flow (Taylor and Susilawti, 2012; Jenelius, 2015). There may be large costs associated with remedies and restoration of the transport system to a fully operational state. It is thus of interest to study the magnitude and distribution of impacts due to disruptions in different parts of a network, so that resources for prevention, mitigations and restoration can be suitably allocated (Jenelius, 2015). The focus is to find the system vulnerabilities, this will affect the choice of mitigation strategies to consider, either constructing barriers to protect the system from threats or hazards (risk analysis approach) or constructing a less vulnerable system that copes with strains regardless of the type of threat or hazard that affects the system (vulnerability analysis approach) (Johannsson, 2011). A good decision support system is determinant in the costs of natural hazards (Figure 1-1). There is a need for appropriate tools, guidance and knowledge transfer to support decision makers when integrating cost assessment figures into their decision making process. Such tools or frameworks should delineate and consider uncertainties in cost figures and ensure the transparency of the decision making rules (Meyer et al, 2013).

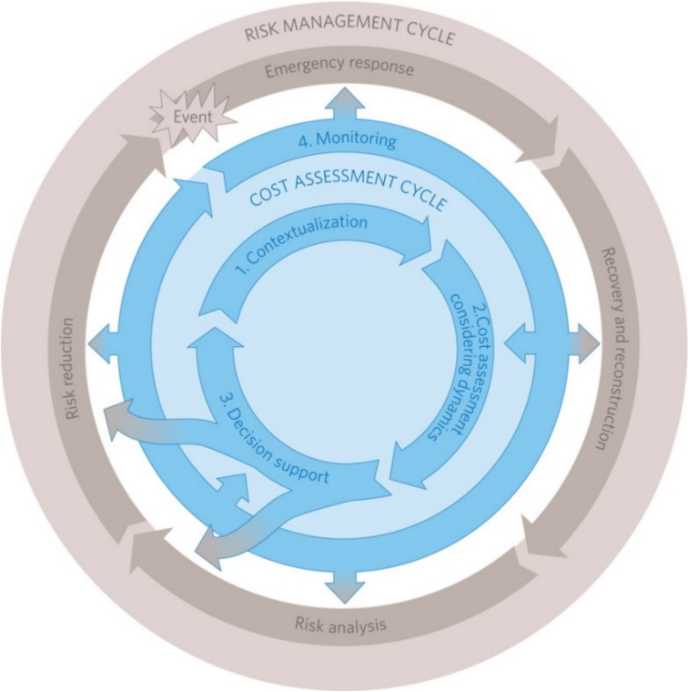

Figure 1-1: Cost assessment cycle and risk management cycle
Source: Kreibich *et al*, 2014

There have been cases where unfortunately, the emergency response was not adequate to the situation. The Fukushima nuclear radioactive leakage, in Japan in 2011, triggered by earthquakes and tsunamis still has serious impacts on the lives of Japanese people and their daily activities (Wang et al, 2012). The explosion of the Deepwater Horizon drilling rig in the Gulf of Mexico in 2010 is another case of the confusion with regard to the authority of governing agencies impaired in response efforts (Park et al, 2011). With regard to the L'Aquila Earthquake, in 2009, Alexander (2010) considered that Italy’s Achilles’ heel is the failure to complete the system by fully articulating the means of planning for emergencies, managing them and dealing with disaster risk at all levels of government and society. Concerning Hurricane Katrina in New Orleans in 2005, government response was handicapped by institutional and personnel failures and multiple failures of support infrastructures (e.g., power, health, communications, transportation) (Colten and Sumpter 2009). Cases such as these indicate two things: firstly, the increasing losses due to disasters show that classical risk management approaches are unable to give answers and demand new ways of thinking about risk, with special relevance to emergency management; secondly it is not possible to prevent every kind of situation.

Also, the terrorist attacks (September 2001 - New York, March 2004 - Madrid and July 2005 - London) were turning points for the way that critical infrastructures are seen. In the 20th Century the works developed concerning critical infrastructures were mostly related to the engineering research field. However, during the first decade of the 21st Century, the social sciences have risen to become a relevant area for the design of better strategies for understanding the link between infrastructures and society which has become a necessity.

The identification of the most important roads and a deeper knowledge of what makes them more vulnerable provide criteria for decision-makers and policy-makers to take into consideration during the course of the policy decision-making process (Murphy and Gardoni, 2007). The development and use of evaluation criteria and performance metrics that result in the most effective prioritization of transportation projects is critical (Novak et al, 2012). Network vulnerability is not just an interesting topic for research by transport network modellers; it is also of great importance to modern society (Taylor and Susilawati, 2012).

The road network vulnerabilities will be assessed in a multi-scale perspective. Scales are an important element in vulnerability assessments for different reasons: place-based analysis seeks to detect vulnerability at a certain locality implying the selection of a certain unit of analysis; systems and processes operate at a wide variety of spatial and temporal scales requiring a holistic overview of processes at multiple scales; cross-scale interaction exerts a crucial influence on outcomes at a given scale (Fekete, 2010). Still, authors such Porta et al (2004) and Vragovic et al (2005) have developed works concerning networks vulnerabilities and compared several areas, but usually on the same scale. In addition most of the analyses proposed are not applicable to large networks (Zhang et al, 2011; Grubesic et al, 2011; and Jenelius et al, 2006) and multi-scalar analysis is therefore not possible. Scale is not only relevant in terms of the unit of analysis used in research, but is also a compatibility issue in decision-making (Eakin, 2006; Mendes et al, 2009).

In general terms, this research can be outlined in Figure 1-2.

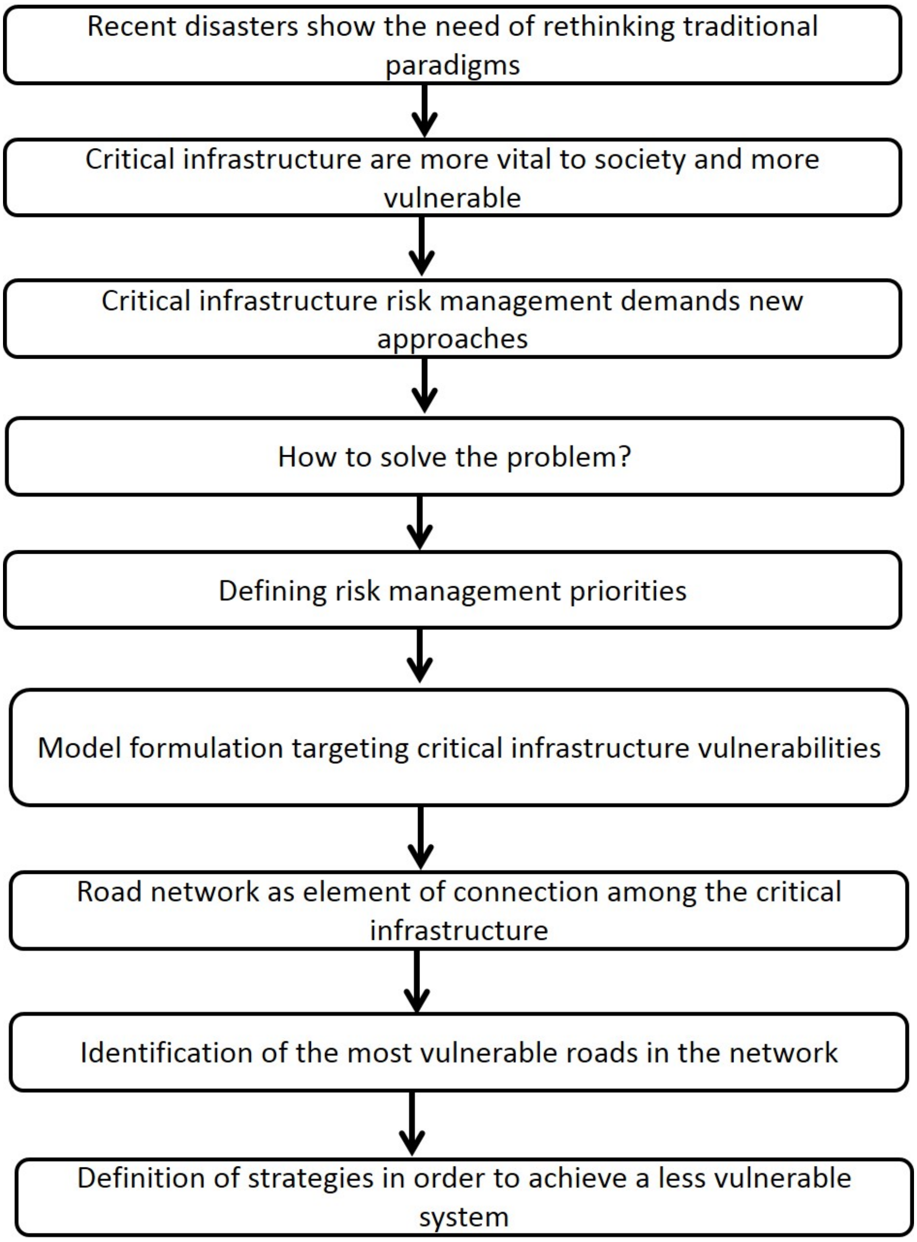

Figure 1-2: Flowchart of the research problem

The point of departure is based on the problem that there have been more and more disasters with greater consequences demanding ever a more efficient emergency response. Society is increasingly dependent on the normal functioning of critical infrastructure and more vulnerable because of it. Intentional attacks as well as accidents are more unpredictable, thus risk management cannot rely on historical data, new approaches are required. The next step is focused on how to solve the problem, as a solution a model is proposed targeting the critical infrastructure vulnerabilities. Since it is not possible to cover the entire critical infrastructure, the model is focused on the road network, as an element of connection among other critical infrastructure. The final output is the identification of the most vulnerable roads in the network, for the purpose of achieving a less vulnerable system.

In a more detailed perspective, the thesis is organized into five parts: the first part is focused on setting the scene as presenting an overview of the world concerning critical infrastructure and risk management. Based on that the motivation of this work is presented and sequentially, the problem formulation. In this first part the main concepts and definitions of the research are clarified, as a basis for the work that has been developed. Once the goals of the research and the conceptual foundations are set, the following phase focuses on the methodology used in this work, and the methods and tools are presented and explained. Afterwards, the proposed solution will be applied to a case study at regional scale. Although the proposed model is to be applied at the regional scale, the multiscale dynamics won't be neglected. Thus, in the thesis, the results of the regional scale will be compared and analyzed taking into account the local scale. A municipality located in the regional case study will be selected. The presentation of the case studies will be particularly focused on explaining why the selected areas are an interesting choice for the application and testing of the proposed methodologies of this work. After presenting the methodology and the case study, the following phase focuses on the presentation of results from the model application, complemented by a scenario-based approach in order to test the model and to assess the consequences of road interruptions. Afterwards a discussion of the results will be made and the challenges associated to what is problematic in discussion will be given special attention. The last part is focused on how to manage the road network as a critical infrastructure of connectivity to other critical infrastructure and to propose new strategies aiming to make risk management more proactive and less reactive.

Objectives:

The main goal of this research is to propose a model of identification of the most important roads in an integrated approach of the structural and functional component. This research has followed the goals:

- Consolidation the concept and the role of critical infrastructure in the emergency management framework;
- Demonstration the importance of road network as infrastructure of connectivity between other critical infrastructure;
- Develop performance metrics for structural vulnerability analysis, identifying scenarios that can lead to large consequences at regional and local scale:
    - Identify the role that various topological variables have in maintaining network connectivity;
    - Demonstrate the relation between connectivity and network's vulnerability;
    - Identify the roads with higher levels of connectivity, which interruption would cause more consequences in the network flow;
- Develop performance metrics for functional vulnerability analysis, identifying scenarios that can lead to large consequences at regional and local scale:
    - Show that the accessibility to critical infrastructure is more than the distance;
    - Show the importance of population spatial mobility capacities in the accessibility to critical infrastructures;
    - Show the importance of an integrated approach in the accessibility to critical infrastructures evaluation;
    - Identify the roads with higher levels of accessibility, which interruption would cause more consequences in the network flow;
- Demonstrate the importance and applicability of a vulnerability analysis approach to critical infrastructure management;
- Provide a decision-making framework for a risk management more proactive.

2. Setting the scene

Setting the scene (Figure 2-1) is composed of the following parts: firstly, the importance of critical infrastructure to society will be analyzed, the reasons why this theme should be an object of concern will also be presented and why it should have been more developed by this time; how critical infrastructure are conceptualized in different world contexts and how risk related to critical infrastructure has been managed. *Setting the scene* can be defined as the founding framework of the problem that this research proposes to solve. In the problem formulation phase the first step is to identify and define the core concepts based on the works that have been developed concerning this issue. Finally, some solutions for the formulated problem will be outlined.

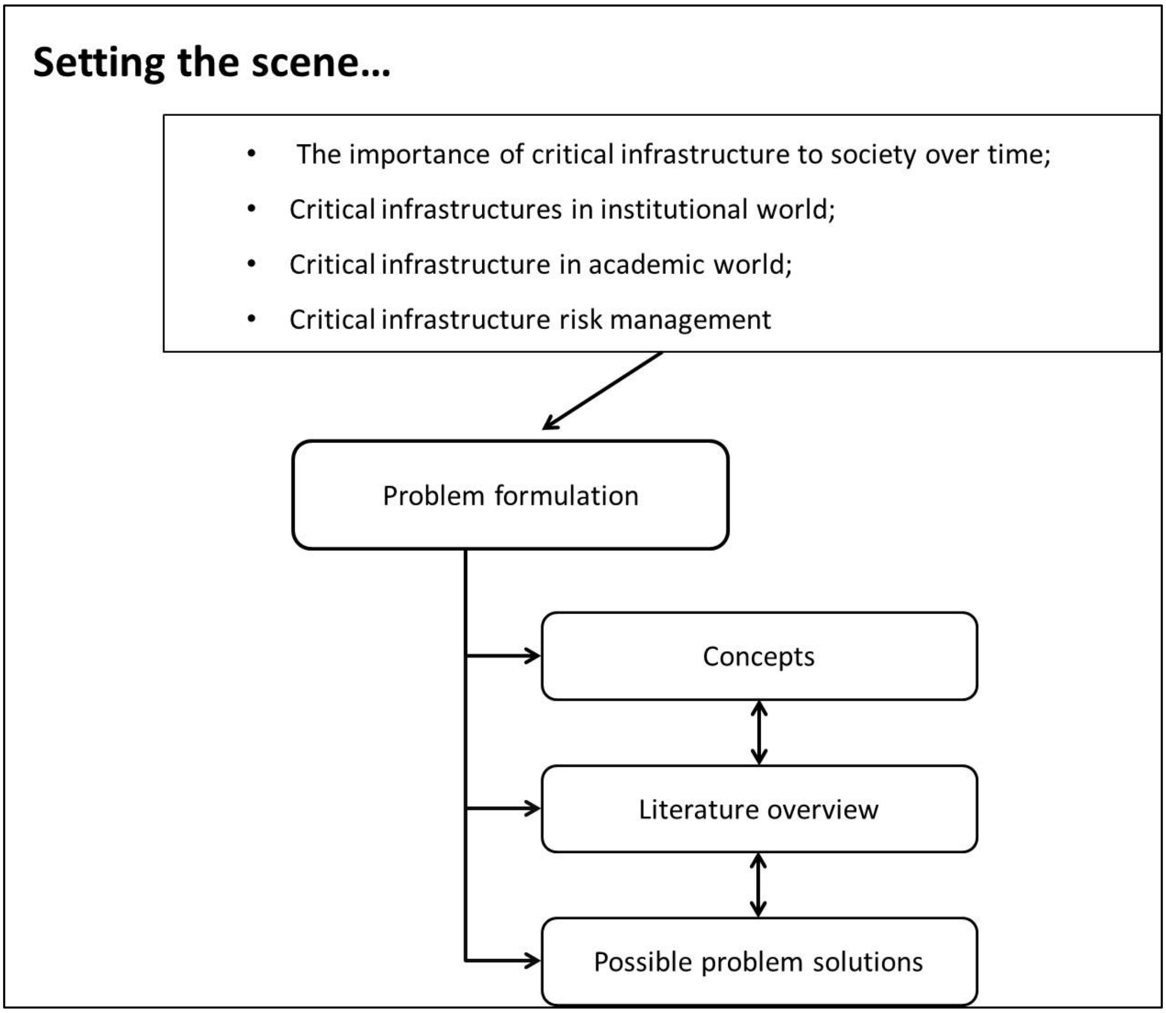

Figure 2-1: Setting the scene

2.1. Rethinking the conceptual and operational framework of critical infrastructures

Losses due to natural and technological disasters have been increasing all over the world. Modern society has become a risk society in the sense that it is increasingly occupied with debating, preventing and managing threats that it has produced itself or been exposed to. Society has entered a condition of "reflexive modernization," in which the very industrial and technical developments that were initially put in the service of guaranteeing human welfare now generate new threats (Beck, 2002). The dominance of the modern concept of risk and calculability is challenged by and has to be distinguished from "manufactured uncertainties" (Beck, 2009).

Nowadays one of the major problems is that disruptions in critical infrastructure from natural disasters and man-made accidents can quickly propagate through a complex chain of connected networks to cause failures in other economic or social networks and even other parts of the world (Park et al, 2011). Being more and more the backbone of society, providing services that are essential for its functioning (Bruijne and van Eeten, 2007) the concept of critical infrastructures has become a key concept in recent discussions (Van der Bruggen, 2008; EC, 2008; Cohen, 2010). In spite of all the efforts toward understanding and definition, authors, such as Dunn (2005), claim that there is a 'conceptual sloppiness', meaning a careless use of terms with repercussions for how the issue is approached, analyzed, and ultimately how protection is planned. The critical infrastructure concept is in flux (Pursiainen, 2009) none of the proposed definitions have gathered full consensus (Moteff, 2003; Popescu and Simion, 2012). The issue is that too many definitions could be a hindrance to professional practice and/or intellectual discourse (Aven, 2011); thus there is the need to have a good, common, conceptual schema and common criteria for critical infrastructure assessment, which can support better and faster decisions and a more coordinated critical infrastructure management (Dunn, 2005; Fekete, 2011). Reaching consensus on conceptualization is not an end in itself, but can provide a basis for determining a modus operandi for emergency response. Based on this knowledge it is possible to evaluate response capabilities, allocate resources more effectively and clarify roles and responsibilities of critical infrastructure managers. If an infrastructure is identified as being important for emergency response more resources will be used taking into account that infrastructure's characteristics. Despite the progress that has been made concerning conceptualization, the identification and modeling of the emergency response sector as a critical infrastructure has not become focused. So this work intends to contribute to the consolidation of critical infrastructure concept, with particular relevance for emergency management.

In an emergency scenario infrastructures can play a dual role. An infrastructure can be a critical element at one moment but then at another, a vulnerable infrastructure. In other words, at one moment it is part of the solution while it can be part of the problem at another moment. As much as possible, this work aims to position infrastructures as part of the solution. So it is a goal to identify the different characteristics and needs of critical infrastructures in the moments of emergency management, with particular relevance for the moment of response, when the threat is set in motion and time is precious. Response encompasses all activities carried out in order to save lives and reduce damage from the event and includes providing emergency assistance to victims, completing emergency repairs critical to infrastructure, and ensuring the continuity of critical services (Fagel, 2011). The actions carried out in the first moments after the disaster impact play a very important role concerning disaster consequences, and may even prevent the event from spiraling out of control. Extreme and catastrophic events pose challenges for normative models of risk management decision making (Cox, 2012). This work intends to show the importance of taking into account the different times and spaces involved in critical infrastructure management.

In spite of the importance of emergency response, in the analysis of critical infrastructures according to different perspectives (institutions, governments and academia) it is also possible to identify a strong focus on prevention. Because critical infrastructure is still a concept in flux and because for many decades the emergency response was based on command-and-control methods, the institutional emergency response structures are not organized taking into account the change in the characteristics of critical infrastructures. Since ‘liberalisation’ and privatisation began to take effect in the 1980s and 1990s, infrastructure systems have no longer been governed by a single actor alone but by structures of multiple actors (Orwat et al, 2010). Traditionally, infrastructural risks were managed by rather isolated monopolies and regulated by single governments, but the present situation requires collective efforts by the concerned actors (Sajeva and Masera, 2006). One of the challenges is how to manage an institutionally fragmented environment (Bruijne and Van Eaten, 2007) in an emergency response scenario. A clear assessment of critical infrastructure framework allows a better articulation among the several stakeholders involved in critical infrastructure management.

Summing up, this part is focused on exploring the critical infrastructure concept consolidation and how they are managed by countries and institutions within these intrinsic frameworks. Moreover, the academic work developed thus far will also be analyzed. This phase is focused in the following questions: How can critical infrastructures are defined? What are their functions in emergency management?

2.1.1. Critical infrastructure concept setting in countries and institutions

The critical infrastructure term emerges in the 1990´s in the United States of America (USA) and in the early of the 21st Century in Europe (Lewis, 2006; Galland, 2010).

In the USA, in 1996, is established the President's Commission on Critical Infrastructure Protection formalized in the Executive Order 13010 - Critical Infrastructures Protection; where critical infrastructures are defined as those infrastructures that are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States. However, many things changed since 1996. After the September 2001 events, it was promulgated the Executive Order 13228 where the possibility of terrorists attacks were the main concern regarding critical infrastructure protection. In 2003 the USA government publishes *The National Strategy for the Physical Protection of Critical Infrastructures and*

Key Assets, which begins in the following way: *The September 11, 2001, attacks demonstrated the extent of our vulnerability to the terrorist threat. In the aftermath of these tragic events, we, as a Nation, have demonstrated firm resolve in protecting our critical infrastructures and key assets from further terrorist exploitation.* This document shows the position and their main focus concerning critical infrastructures, their main concern was terrorism. However the devastating effects of Hurricane Katrina in 2005 will drive to a change. The partial come-back of the all-hazard approach in the United States CIP strategy (or CI protection) came only after Hurricane Katrina in 2005 shifted the focus somewhat away from the one-sided emphasis on terrorism. The National Infrastructure Protection Plan, issued in 2006, advocates a multi-hazard approach, although the threat of terrorism still dominates (Pursiainen, 2007).

The terrorist attacks (September 2001 - New York, March 2004 - Madrid and July 2005 - London) are turning points in the way that critical infrastructures are seen. In 2005 in the Green Paper on a European Programme for a Critical Infrastructure Protection and in 2006 in the Memo/06/477 the European Council stated that the terrorist attacks in Madrid and London have highlighted the risk of terrorist attacks against European infrastructure and in order to counteract these potential vulnerabilities the European Council requested in 2004 the development of a European Programme for Critical Infrastructure Protection. In 2004 it was published a major milestone - Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. This document, which was implemented in most of the European countries, recognizes a link between the assets constituting critical infrastructures and measures of prevention, preparedness and consequence management (Whalley, 2010). Critical Infrastructure Protection (CIP) has become a new field of European integration; however that carries out many challenges, related with issues such as European level of responsibility, decision making procedures and the creation of a common ground taking into account the different characteristics of European countries (Pursiainen, 2007).

The European Commission has developed several efforts in order to create a common policy concerning the protection of European Critical Infrastructures, common methodologies may be developed for the identification and classification of risks, threats and vulnerabilities to infrastructure assets (Directive 2008/114/EC). The European Union (EU), typically associated with economic cooperation, has become increasingly involved with protecting the security and safety of European citizens (Fritzon *et al* 2007; Boin and Ekengren, 2009). Nevertheless, defining critical infrastructures and distinguishing them from other infrastructures is a key challenge for policy-makers, and one that has been addressed in different ways by national governments. The issue is that the definition of critical infrastructures is still a moving target (CEPS, 2010), which will have consequences in their management.

Table 2-1: Critical infrastructure definitions

Country/Institution	Definition
Australia	Critical infrastructures are physical facilities, supply chains, information technologies and communication networks that, if destroyed, degraded or rendered unavailable for an extended period, would significantly impact on the social or economic well-being of the nation or affect Australia's ability to conduct national defense and ensure national security.
Canada	Critical infrastructure (CI) consists of the physical and information technology facilities, networks, and assets essential to the health, safety, security, or economic well-being of Canadians, and the effective functioning of government.
European Union	Critical infrastructures consist of those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments in the Member States.
Finland	Vital functions: The vital functions encompass the indispensable intersectoral functional entities of society, the continued operation of which must be secured at all times.
Germany	Critical infrastructures are the organizations or facilities whose failure or impairment would cause a sustained storage of supplies, significant disruptions of public order, or other dramatic consequences for large parts of the population are defined as critical.

Japan	Critical infrastructures are formed by business entities providing highly irreplaceable services and are essential for people's social lives and economic activities. If an infrastructure's function is suspended, reduced or unavailable, people's social lives and economic activities will be greatly disrupted.
NATO	Critical infrastructures are those facilities and services that are vital to the basic operations of a given society, or those without which the functioning of a given society would be greatly impaired.
Norway	Critical infrastructures are those constructions and systems that are essential in order to uphold society's critical functions, which in time safeguard society's basic needs and the feeling of safety and security in the general public.
Portugal	Critical Infrastructure are components, system or part thereof located in territory that is essential for maintenance of vital functions in society, health, safety and economic welfare or social, and the disruption or destruction would have a significant impact, given the impossibility of continuing to ensure these functions.
Switzerland	Critical infrastructures are infrastructures whose disruption, failure, or destruction would have a serious impact on public health, public and political affairs, the environment, security, and social and economic well-being.
UK	Critical infrastructures are the key elements of the national infrastructure that are crucial to the continued delivery of essential services to the UK. Without these key elements, essential services could not be delivered and the UK could suffer serious consequences, including severe economic damage, grave social disruption, or even large-scale loss of life.
UN	Critical facilities: the primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency.
USA	Critical infrastructures are the systems and assets, whether physicalor virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, nationaleconomic security, national public health or safety, or any combination of thosematters.

Source: Brunner and Suter, adapt (2009)

In the analysis of the several definitions presented by several countries and institutions (Table 2-1) is possible to identify two trends: in one hand there are countries and organizations (Australia, United Kingdom, USA and NATO) that see critical infrastructures in a military perspective, taking as major focus the terrorist threat; on the other hand there are countries and organizations (Norway, Sweden, Switzerland and UN) where the critical infrastructures concept has as major goal the well-being of the population (CRN, 2008; CEPS, 2010). The nature of the threat plays a crucial role in the way a country or an institution define the concept of critical infrastructure and determine the strategies concerning critical infrastructure policy. In countries such as USA the main goal pursued by the institutional plans is to protect critical infrastructures; however in countries such as Sweden and Finland the main goal is work in order that critical infrastructures can be more and more resilient. In the first case an attack to an infrastructure can affect the national moral, thus the focus is on the infrastructures; in the second case the main focus is on the functions rather than the infrastructures that support them.

Despite of all the differences and all ambiguities involving the definition of critical infrastructure, there is a strong focus on prevention; countries and institutions such as Australia, European Union, Japan and USA the focus are infrastructures which are critical for daily life whose function can be disturbed or interrupted. However there are infrastructures that are only critical during stressful moments such as fire stations; institutions and countries such as UN and Finland take into account the different times; for instance UN mentioned critical facilities both in routine circumstances and in the extreme circumstances of an emergency. Still, in almost cases policy has as main goal critical infrastructures protection, which is often understood as a “hardening” of critical infrastructure against threats and attacks (Lewis, 2006). Critical infrastructure protection is prominently concerned with objects that appear as indispensable for the functioning of social and political daily life. However, there are infrastructures which are not critical for the daily life but are critical infrastructure in an emergency response scenario.

2.1.2. Critical infrastructure concept in scientific academics

The terrorist attacks changed the way the world see critical infrastructures, and the academics were no exception (Pursiainen, 2009). In the XX Century the works developed concerning critical infrastructures were mostly related with engineering research field.

However, during the first decade of XXI Century, social sciences rise as a relevant area in the design of better strategies. The normal functioning of critical infrastructures is no more focused just on the machinery, related with engineering area, to be more and more focused in the external component, which comprehends the link between the infrastructures and society. Authors such as Dunn (2005), Pursiaineen (2007), Burgess (2007) and Grubesic and Matisziw (2011) brought a new perspective to critical infrastructures knowledge defending that a group of infrastructures are critical because they have value for society and for a culture; criticality emerges as a symbolic concept. The growing importance of the role played by social sciences increases the complexity concerning critical infrastructure research. In one hand there are authors such as Apostolakis and Lemon (2005) Kröger (2007), Utne (2011) who define critical infrastructures as technological networks; in another hand there are authors such as Maliszewski and Horner (2010) who define critical infrastructures as entities deemed to be necessary for society to function correctly and thus require protection. Besides these two perspectives, authors such as Bouwmans et al (2006) and Chai et al (2008) developed efforts in order to establish a bridge between engineering area and social sciences, describing critical infrastructures as socio-technical systems which means that critical infrastructures operates not only according to technical specifications but also according to constraints imposed by the social environment. These infrastructures are complex networks, geographically dispersed and can be defined as non-linear systems that interact both among themselves, and with their human owners, operators and users (Amin, 2002). This diversity of perspectives bring some problems concerning the communication between the several actors involved in critical infrastructure management, which have consequences in issues such as the establishment of priorities regarding questions such as: What to protect? Who must protect? From who/what must be protected?

Regarding these questions there aren't consensual answers, in Table 2-2 and Table 2-3 is possible to verify how different the sectors of activity that are focused and the purposes of the work can be. In Table 2-2 is possible to verify that most of the authors focused only one or two sectors; among those the electricity is the most frequently focused sector, followed by the telecommunications sector. The infrastructures focused by the authors are not directly comparable because they have quite different technical and organizational properties. However, in the analyses that were carried out they have in common a particular moment – infrastructures that are important for the daily life, which normal functioning is interrupted by a disturbing event. Analyzing the survey of the sectors focused by the authors is evident that the focus is on prevention; thus, none of the authors choose the emergency response as sector. Under logic of preparedness, complex, uncertain and threatening events are not acted upon in advance of their occurrence (Adey and Anderson, 2012). The definition of critical infrastructure is focused in the role of things in society and their functioning in daily life. The emergency response sector follows different rules concerning space and time than the sectors critical for the daily life as well as challenges regarding skills of pattern recognition and scenario formulation involved by a high level of uncertainty. Technologies of intervening upon the future are always failing; their failure is however part of governmentality, the very motor of the continuous requirement for new technologies and more knowledge (Aradau and Van Muster, 2007).

Table 2-2: Sectors focused by the authors

Authors	**Sector**								
	Electricity	Natural	Fuels	Water Drinking	Sewage, Wastewater	Industry	Telecommunication	Railway	Road network
Argonne Labs and Peerenboom,2010	X	X							
Argonne Labs and Conzelmann, 2008	X						X		
Australian and CSIRO, 2008	X	X	X				X		
Baiard et al., 2007							X		
Beyeler and Brown, 2004									
Beyeler et al., 2002	X						X		
Broadwater, 2006	X					X			
CCN Criptologia, 2010							X		
CCN-CERT, 2011; CNPIC,2010; Zielstra, 2010						X	X		
COSO, 2004; ERM Initiative, 2010; PMI, 2004	X	X	X	X	X	X	X	X	X

Authors	Sector								
	Electricity	Natural	Fuels	Water Drinking	Sewage, Wastewater	Industry	Telecommunication	Railway	Road network
Coursaget and (SGDSN), 2010									
Dodrill et al., 2007									
Donzelli e Setola, 2007	X			X		X			
Drabble et al., 2009	X	X	X	X	X	X	X	X	X
ENEA et al., 2010	X						X		
ERA, 2010; Pragma, 2010									
Ezell e Wiese, 2000				X	X				
Ferigato e Masera, 2007									
Ghorbani e Marsh, 2004					X				
Idaho e Dudenhoeffer, 2006	X					X			
IntePoint e Armstrong, 2010	X						X	X	X
ISOGRAPH Inc, 2008	X	X	X			X	X		
ISOGRAPH Inc, 2010						X	X		
Jenelius, 2006									X
Johansson e Hassel 2010								X	
Johansson, 2010	X							X	X
Lee et al, 2005	X					X	X		
Lee, 2001				X	X				
Li et al., 2007								X	X
Los Alamos Labs and Holland, 2008				X	X				
Los Alamos Labs e Flaim, 2006							X		
Los Alamos Labs e Michelsen, 2008				X	X		X		X
Los Alamos Labs e Smith, 1999									
Los Alamos Labs et al., 2006	X	X		X	X				
Mañas, 2007							X		
McManus et al., 2004	X						X		
Milulak, 2004						X	X		
National Infrastructure Institute and Peimer, 2010									
Newman et al., 2005	X								
Oak Ridge et al., 2003				X	X		X	X	X
OGC, 2002									
Panzieri et al., 2005	X				X	X			
Peggion et al., 2008									
Portante et al., 2007		X	X						
Pruyt e Wijnmalen, 2010	X		X	X				X	

Authors	**Sector**								
	Electricity	Natural	Fuels	Water Drinking	Sewage, Wastewater	Industry	Telecommunication	Railway	Road network
Quarles e Haimes,2007	X			X			X		X
Sandia Labs e Brown, 2005a	X	X			X			X	
Sandia Labs et al., 2004	X						X		
Sandia Labs e Brown, 2005b	X						X		
SPARTA Inc et al., 2005	X	X	X					X	
USACE et al., 2010	X	X	X	X	X	X	X	X	X
Total	27	12	9	15	14	14	25	12	11

Source: Yusta et al, 2011 adapt. and extended

In the analysis of the main purposes of the studies developed on critical infrastructures area (Table 2-3) one of the key words is vulnerability that is related with the susceptibility of people, places and infrastructures to disruptive events (Grubesic and Matisziw, 2011). In Table 2-3 is possible to identify a significant number of authors more focused on interdependency identification and modeling as a vulnerability coefficient (Rinaldi et al, 2001; Chai et al, 2008; Johansson and Hassel, 2010). Errors in one system can easily cause failures in other system, triggering new failures and eventually leading to systematic failures in both infrastructures (Bouwmans et al, 2006). These trends are related with the need of establishing priorities (Apostolakis and Lemon, 2005; Latora and Marchiori, 2005) and to critical infrastructure protection defined as the strategies, policies, and preparedness needed to protect, prevent, and when necessary, respond to attacks on these sectors and key assets (Lewis, 2006). Given that resources are limited and that the mitigation of the impact of hazards is not the sole objective of public policy or resource allocation, there is a need to determine which mitigation strategies to pursue from among the viable options (Murphy and Gardoni, 2007). Authors such as Schintler *et al* (2007) defend a moving from protection to resiliency because most infrastructures providers do not have financial resources to protect their infrastructures from low probability events like tsunamis. Therefore, a critical infrastructure resiliency policy may be a way to link private and public sector, because resiliency represents the ability to resist, absorb, recover or adapt to the consequences set in motion when a threat event is successful (Fisher and Norman, 2010; Suter, 2011).

Table 2-3: Purpose of the studies developed concerning critical infrastructures

Author	**Purpose of the study**			
	Conceptual analysis	Vulnerability analysis	Resilience analysis	(Inter)dependency analysis
Apostolakis and Lemon (2005)		X		
Boin and McConnell (2007)			X	
Brown *et al* (2006)			X	
Chai et al (2008)				X
Chang et al (2007)				X
Crucitti et al (2004)		X		X
De Bruijne and Van Eeten (2007)	X			
Egan, M. (2007)	X			
Eusgeld et al (2009)		X		
Ezell (2007)		X		
Fekete (2011)	X			
Grubesic and Matisziw (2011)		X		
Hellström (2007)		X		
Johansson and Hassel (2010)		X		X
Little (2003)			X	
Moteff and Parfomak (2004)	X			
Murray et al (2007)				X
Oliva et al (2010)				X
Ouyang et al (2009)				X
Peerenboom and Fisher (2007)				X
Porcellinis et al (2008)				X
Rahman *et al* (2009)				X
Rinaldi *et al* (2001)	X			X
Robert and Morabito (2010)				X
Santella et al (2009)				X
Setola et al (2009)				X
Simpson et al (2005)			X	X
Tagarev and Pavlov (2007)	X			
Theoharidou et al (2010)	X			
Tolone et al, (2004)				X
Trucco et al (2012)				X
Utne et al (2011)				X
Zio and Kröger (2009)	X			

Promoting resilience strategies in preparation for critical infrastructure breakdowns is a tough call (Boin and McConnel, 2007), because the critical infrastructure breakdown is a possibility, and systems resilience is built on that system's ability to alter non-essential attributes, to be able to adapt to the circumstances (Manyena, 2006) without affecting the infrastructure functioning.

There are authors (Aven, 2009; Kröger and Zio, 2011) who consider resilience as part of vulnerability. However, some communities may be very vulnerable to the impact and the consequences of a hazard, while showing high levels of resilience in the response phase (Menoni *et al*, 2012). This work considers that vulnerability and resilience belong to different moments a potentially harmful event, vulnerability is related with engineering techniques, mitigation issues, but resilience is related with capacity of adaptation (Figure 2-2). Also Francis and Bekera (2014) consider vulnerability and resilience as concepts that belong to different moments in risk management; vulnerability analysis at regular intervals is a key to recognizing disruptive events in advance and continuously self-evaluating and learning from incidents; on other hand the ultimate goal of resilience is the continuity of normal system function after a disruption. Thus, before the disruption event the focus should be on the definition of mitigation strategies and after the disruption event the focus should be on the definition of recovery strategies. Precursor resilience allows operators and infrastructures to cope with stress and unexpected difficulties while still maintaining a robust service to customers and other infrastructures (Roe and Shulman, 2012).

Resilience could be viewed as the intrinsic capacity of a system predisposed to a shock or stress to adapt and survive by changing its non-essential attributes and rebuilding itself (Manyena, 2006). Between the transition vulnerability and resilience there is the threat - capability to adversely affect (cause harm or damage to) the system by adversely changing its states (Haimes, 2006).Beyond vulnerability and resilience, in a third moment is introduced the concept criticality, related with the post- harmful event moment and that represents the severity of the consequences to the facility, the system and the community (Fisher and Norman, 2010; Fekete, 2011). Relating to the critical infrastructure management of a community is relevant to take into account the relations among vulnerability, resiliency and criticality, and then identify the levels of each one in the community concerned. It enables assessing the likelihood and severity of temporal and spatial consequences, facilitates timely and effective planning for operation, ultimately ensures effective execution of the preparedness phase, and, when needed, the subsequent timely organized response and recovery phases (Haimes, 2012).

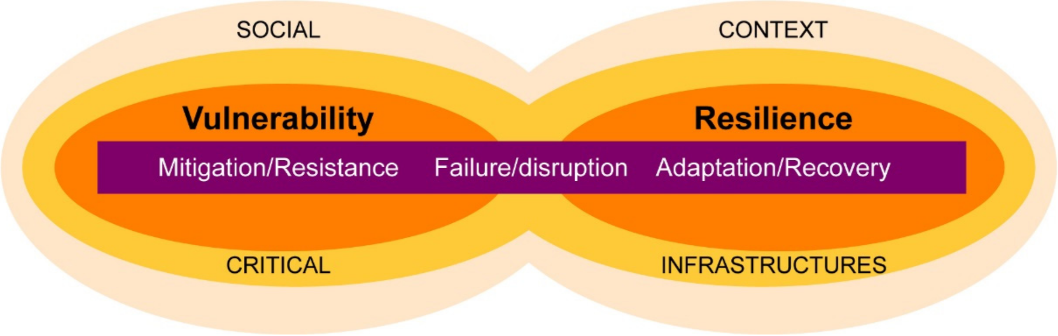

Figure 2-2: Critical infrastructures in the social context

2.1.3. Critical infrastructures in emergency response

It is often argued whether it is best to invest more in risk prevention or more in emergency response. A good risk prevention policy is important in order to decrease the chance and magnitude of a possible incident. One could argue that it is better to invest in risk prevention to ensure that accidents do not take place at all. However, in spite of this, a ‘zero risk’ situation cannot be achieved (Neuvel and Zlatanova, 2006). If in prevention phase the institutions have months, even years; in emergency response phase institutions have, in the best cases, hours to decide what needs to be done and to implement the decisions.

In spite of emergency response importance, it was not until well into the twentieth century that the intrinsic value of comprehensive emergency management was recognized on a global scale, and risk reduction and more formalized emergency planning emerged (Coppola, 2011). Concerning critical infrastructure in emergency response different strategies are adopted; on the one hand, there are countries such Australia and USA who have developed critical infrastructures resilience strategies, but emergency response is not classified a sector important in the achievement of higher levels of resilience; on the other hand, United Kingdom in the Resilience Plan for Critical

Infrastructure classifies emergency services as a critical infrastructure sector. However, it is only considered as belonging to the emergency services the Police, Ambulance, Fire and Rescue, and Maritime and Coastguard Agency[1]. The organization for emergency response in European countries is also marked by a vertical structure of command. Civil defence is on the base of civil protection emerging - the former has military or paramilitary origins and was created in order to protect civilian populations against armed aggression by a foreign power; civil protection, which evolved 40-50 years later than civil defence, was devised to protect citizens against natural and technological disasters (Alexander, 2007; Bremberg and Britz, 2009). This evolution continues to mark emergency response structure most fire brigades are organized partly along military lines, though they are usually amenable to civilian command techniques (Alexander, 2002). Further developments are needed in what critical infrastructure in emergency response concerns; the question is what strategies can be adopted to consolidate the role of critical infrastructure in emergency response.

In an emergency scenario the first priority is to minimize the loss of people and protect the survivals, in a secondary plan there is the need to minimize property and environment damage caused by the disaster. Thus, the urgent relief services are very diverse and urgent. Emergency management requires the delivery of food, medicine, tents, sanitation equipment, tools and other necessities to the people in distress, often for considerable periods of time (Whybark, 2007). However, there are other institutions that should also be considered. In this kind of scenarios there are in one hand the critical infrastructure that can provide help and in another hand critical infrastructures that have problems and, possibly, spaces and people who are in need. At this point there are questions such: Who is responsible for what? Who needs to do what?

The responsibility for disaster control primarily lies with the mayor of the municipality where the disaster situation occurs (OECD, 2010), that can be a good principle the problem is how to put it into practice, how to coordinate different resources.

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[1] Source : http://www.cabinetoffice.gov.uk/sites/default/files/resources/Sector-Summary-Emergency-Services.pdf

Critical infrastructures have undergone massive institutional restructuring under the headings of privatization, deregulation and liberalization, which bring new challenges concerning critical infrastructures management in an institutionally fragmented environment (Bruijne and Van Eaten, 2007). Until one or two decades ago, most critical infrastructures in Europe were still operated as public monopolies with direct or indirect government control, but now there is a changing composition of the multi-actor network involved. Thus, in one hand there is the conventional paradigm which is marked by the full vertical integration of activities in the infrastructure value chain and in other hand there is the new paradigm (Figure 2-3) that does not deny the existence of natural monopolies in infrastructures, but rejects the conclusion that infrastructure sectors should therefore be considered monopolies in their entirety (Bouwmans *et al*, 2006). Even when the responsibility for setting goals rests primarily with the government, but the implementation of steps to reduce the vulnerability of privately owned and corporate assets depends primarily on private-sector knowledge and action (Auerswald, 2005). Critical infrastructure management in an emergency response context is less and less an exclusive responsibility of the government. Emergencies are increasingly involving the necessity to coordinate activities and responses by a much broader host of organizations involving the private sector, non-profits and volunteer organizations (Jennex, 2007). Thus, a new approach to government referred to as governance has emerged from combining the practices of traditional government with market-driven approaches of the private sector and the resourcefulness of non-profit organizations (Agranoff, 2004). The problem that stands is how to coordinate, command and control all these institutions, boosting the strengths, diminishing the weaknesses and taking into account their needs. When a crisis happens usually there is a flood of potential responders to the scene, which can harm more than help to resolve the situation. Good organization and coordination between emergency teams is just as critical in saving lives and protecting property after a disaster happens (Neuvel and Zlatanova, 2006). Therefore is important to have a previous plan where is laid who is in charge, who intervenes first.

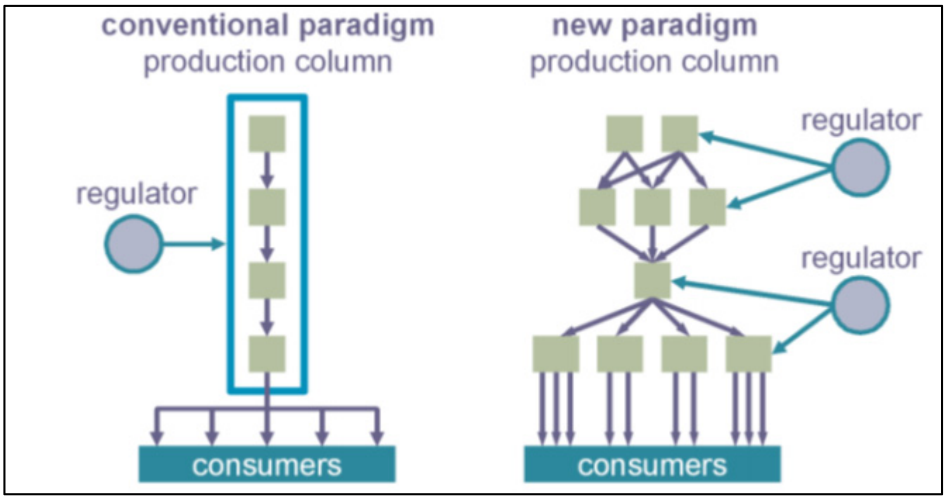


Figure 2-3: Conventional and new infrastructure paradigm
Source: Bouwmans *et al*, 2006

Contingency plans can be a very useful tool once that based on accidents scenarios that may jeopardize the normal system functioning, set operational procedures for response aiming at the reestablishment of social and economic functions, in the shortest time (Tavares, 2013). Effective operational procedures (i.e. availability of emergency supplies and synchronization among personnel) can reduce emergency reaction time, decrease natural disaster-related damage, and improve emergency plan efficiency (Tseng et al, 2011). However, the implementation of the contingency plans have been facing new challenges such the increasing presence of the private sector in emergency response, which is a trend that is likely to continue (Egan, 2010), also partnerships between private sector companies and relief organizations are also becoming increasingly common (Balcik et al, 2010). These changes have led to an alteration of paradigms analyzed by Bouwmans *et al* (2006); the conventional paradigm is marked by the full vertical integration of activities in the infrastructure value chain; the new paradigm rejects the conclusion that infrastructure sectors should therefore be considered monopolies in their entirety, i.e. there is more than one institution per sector and there is more than one regulator in the system.

Critical infrastructure risk management is complex; each critical infrastructure has a very specific operating mode and is guided by specific rules. Thus, traditional management styles of one or two people in charge of word making all the decisions must be changed to a framework where the person in charge more often defers to the expertise of the members of the problem-solving group during the analysis part of the response effort (Turoff et al, 2010).

In emergency response is also important take into account the issues that can contribute to the delay in emergency response. From this point of view is possible to distinguish and measure two response times: supportive response time - time spent seeking information, decision making, communicating and coordinating tasks, the length of supportive response time can increase due to less amount of information, lower decision quality, less communication and poor coordination; effective response time – time spent on performing response tasks as an immediate remedy to an emergency, effective response includes “putting out fire” and “giving medical treatment” (Chen, 2005). A previous accurate definition of institutions, roles and responsibilities contributes for the decrease of supportive response time.

This kind of approach demands flexible ways of planning and a constant effort of databases updates. Nevertheless, it is more feasible and less expensive that institutions belonging to the same sector know the resources available by each partner than a governmental institution be aware of all the resources available in all the institutions involved in emergency response. The adoption of support functions for the sectorial management of resources and abundant use of information and communications technology obviate the need for complex chains of command (Alexander, 2010). There are cases such as the Marmata Earthquake, Turkey on 1999, and L’Aquila Earthquake, Italy on 2009, where the non-governmental institutions had success where the governmental institutions had failed (Özerdem and Jacoby, 2006; Alexander, 2010). Still there are cases such the Katrina Hurricane, USA on 2005, where the enormous scope of the disaster led to a response network so diverse that there was a failure to fully comprehend which actors were actually part of the network (partly because of a large voluntary component), the skills they offered, and how to use these capacities (House Report, 2006).

2.1.4. Summing up…

Critical infrastructure in risk management and emergency response is an understudied research issue. The analyses indicate that concerning critical infrastructure risk management there is a strong focus in prevention over response, either by the academics either by institutions and governments. However, the previous analysis shows that critical infrastructure plays a fundamental role in risk management. An infrastructure can be a critical infrastructure in one moment and in other moment a vulnerable infrastructure, in other words, in one moment is part of the solution in other moment can be part of the problem. Critical infrastructure is an important problem, as it impacts life and property in the affected area (Chen et al, 2008). In this work the concept of critical infrastructure should be read in a risk management context and consist of those physical and information technology facilities, networks, services and assets vital to the well-being of citizens and which main priority, in an emergency response scenario, is to minimize the loss of people and protect the survivals, as well as to minimize property and environment damage caused by disasters. The definition proposed shares points in common with other critical infrastructures definitions; the work doesn’t propose a break with what has been done, but to provide a different point of view that takes into account critical infrastructure in risk management context emerges as more and more necessary.

2.2. Problem formulation

Network infrastructures, such as transport networks, are becoming extremely important in public policy considerations, not only in terms of evaluating the possible (dis)equilibrium (demand vs. supply) points, but also in preventing intentional attacks, disasters and accidents (Reggiani, 2013). However, as society cannot afford the costs associated with absolute protection, it is necessary to identify and prioritise vulnerabilities in infrastructures (Apostolakis and Lemon, 2005). It may not be feasible to address all needs, so certain needs must be rejected or postponed until future funding becomes available (Lambert and Turley, 2005). Individuals, organisations, and societies often need to establish priorities in order to address the myriad risks to their health, safety, and environment (Long and Fischoff, 2000), and the road transport system has proved to be one of the most critical infrastructures (Lambert et al, 2013). Accessible roads are vital for social services, businesses and the welfare of people (Ayyub et al, 2007).

In Figure 2-4 there is an example of a real-world case, located in the Coimbra - Portugal, where is possible to identify a set of critical infrastructure such Hospital, Health Centre, Pharmacy, as well as school. They are all connected thanks to the road network - an important critical infrastructure in the normal functioning for society, connecting people, businesses and services separated in space (Jenelius, 2010; CEPS, 2010).

Given the importance of the transport networks for journeys to work, for production logistics, and for business travel, the reliability of transport networks is a key interest from the point of view of transport system users and hence planners at all levels, both in the public and private sectors (Jenelius et al, 2006).

The problem is that road network interruptions caused by natural disasters are becoming more frequent and their consequences are becoming of a wider range (EM-DAT, 2013). There is a wide range of disruptive events such as partial flooding, reduced visibility, poor traction due to weather hazards, and deterioration of road surfaces may occur on a daily basis (Sullivan et al. 2012).

The main question is how to identify the roads, which interruption can have higher impact in the normal functioning of society. This research proposes a new methodology for identifying the most vulnerable links in a road network, defined as the key links where loss is most significant.

The dominant approach to prevention of loss due to critical infrastructure failure is risk analysis and risk management. However, in spite of the maturity reached by many of the methods used in risk assessment and risk management, it hasn't already been established a consensual platform on fundamental concepts and principles (Aven, 2012).

Figure 2-4: Critical infrastructure example from Coimbra city, Portugal

For several decades the conventional risk management approaches were based on failure reporting and risk assessment calculating historical data-based probabilities; still there are new types of threats and expect that hazard events take place to illuminate the infrastructure's vulnerabilities has costs. The consequences of an event in the normal functioning of a network are involved in great uncertainty. Indeed, according with authors such Johannsson (2011), the notion of scenario is central to the risk definition, if it is known for certain that there will be an explosion in a factory, there is no reason to talk about that explosion as a risk.

Aven (2012) presents the following classification system for the risk definitions:

1) Risk=Expected value (loss) (R=E)

a) Risk equals the expected loss.

b) Risk equals the product of the probability and utility of some future event.

c) Risk equals the expected disutility.

2) Risk=Probability of an (undesirable) event (R=P)

a) Risk is the chance of damage or loss.

b) Risk equals the probability of an undesirable event.

c) Risk means the likelihood of a specific effect originating from a certain hazard occurring within a specified period or in specified circumstances.

3) Risk=Objective Uncertainty (R=OU)

a) Risk is the objective correlative of the subjective uncertainty; uncertainty considered as embodied in the course of events in the external world.

b) Risk is measurable uncertainty, i.e., uncertainty where the distribution of the outcome in a group of instances is known (either through calculation a priori or from statistics of past experience).

4) Risk=Uncertainty (R=U)

a) in regard to cost, loss or damage.

b) about a loss.

c) of the happening of an unfavourable contingency.

d) of outcome, of actions and events.

5) Risk=Potential/possibility of a loss (R=PO)

a) Risk is the possibility of an unfortunate occurrence.

b) Risk is the possibility of an unfavourable deviation from expectations.

c) Risk is the potential for realisation of unwanted, negative consequences of an event.

6) Risk=Probability and scenarios/Consequences/severity of consequences (R=P&C)

a) Risk is a combination of hazards measured by probability; a state of the world rather than a state of mind.

b) Risk is a measure of the probability and severity of adverse effects.

c) Risk is equal to the triplet (s_i, p_i, c_i), where s_i is the ith scenario, p_i is the probability of that scenario, and c_i is the consequence of the ith scenario, i=1, 2 … N; i.e. risk captures: What can happen? How likely is that to happen? If it does happen, what are the consequences?

d) Risk is the combination of probability and extent of consequences.

7) Risk=Event or consequence (R=C)

a) Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain.

b) Risk is an uncertain consequence of an event or an activity with respect to something that human value.

8) Risk=Consequences/damage/severity of these + Uncertainty (R=C&U)

a) Risk=Uncertainty + Damage.

b) Risk is equal to the two-dimensional combination of events/ consequences (of an activity) and associated uncertainties.

c) Risk is uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value.

d) Risk is the deviations from a reference level (ideal states, planned values, expected values, objectives) and associated uncertainties.

9) Risk is the effect of uncertainty on objectives (R=ISO).

In the analysis of this classification there three elements to be highlighted: events, consequences and uncertainty. In one hand there is the definition in Group 1 related with risk perception, and in other hand there is Group 7 and Group 8 express a state of the system that is independent of the risk perception.

The choice of the fit definition of risk depends of the goals set for this work; the main goal is to identify the most vulnerable roads in the network; the level of vulnerability of a road depends on the consequences of its interruption in the normal functioning of the territorial system. In view of this the risk definitions point in Group 7 appear as the most suitable risk definition, according with:

Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain (Rosa, 1998 and Rosa, 2003).

Also IRGC (2005) recommends a similar risk definition *Risk refers to uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value.* Both definitions perspectives risk as state of the world; it is the conjoint of possibility, uncertainty of outcome, and human stakes in the outcome, regardless the human perceptions or level of risk awareness.

The uncertainty can be due to the randomness because of the inherent variability in the system and imprecision because of the lack of knowledge and information on the system. Uncertainty is thus an unavoidable component affecting the behaviour of system; in spite of how much dedicated effort is put into improving the understanding of systems, components and processes through the collection of representative data, the appropriate characterization, representation, propagation and interpretation of uncertainty remains a fundamental element of the risk analysis of any system (Aven and Zio, 2011).

At this point, the Rosa (2003) and IRGC (2005) definitions are suitable for a risk characterization, however does not answer to questions such the severity of the consequences; thereby to reduce the uncertainty. A method of bounding those uncertainties is through scenarios' formulation. Thus, in the following phase the notion of risk of the previous phase is complemented by a notion expressed in Group 6 the set triplets (Kaplan and Garrick, 1981; Johansson, 2011; Jenelius and Mattsson, 2014):

1. What can happen?
2. How likely is it that will happen?
3. If it does happen, what are the consequences?

If all of these questions can be answered, the risk of a system can be appropriately defined. This leads to the definition of risk as a function of the probability of an unwanted event and the severity of consequences of that event (Kaplan et al, 1981):

$$R = \{< S_{i,} L_{i,} X_{i,} >\} \tag{1}$$

where S_i denotes the *i:* the risk scenario, L_i denotes the likelihood of that scenario, and X_i denotes the resulting consequences. The notion of scenario is central to the risk definition. A scenario is seen as the possible way a system can go from one point to a future other point, taking always into account the of the main goals of the model - support to decision-making, to a more informed, strategic action. Regarding scenario analysis, one of the first concerns is that only few scenarios can be evaluated. However, in this work scenario-based analysis will be used as a supporting feature of other analyses, with different approaches, thereby the quantification of the resulting consequences will be different.

Based on the Rosa (2003), IRGC (2005) definitions as well as on the Kaplan and Garrick (1981) approach, this work it will be focused on a vulnerability characterization applied to the road network - identify the roads which interruption would have more impact in the normal functioning of society, i.e. would generate more losses, taking into account uncertainties, which will be addressed in scenario based analysis.

Thus, the next question to be answered is how to characterize the risk of road network? Although many efforts have been made in network analysis in early transport research, the absence of a systematic theoretical scheme is still a prominent problem to be addressed (Lin and Ban, 2013). The following section will be focused on how to answer that question and what has been done to solve the problem.

2.3. Main concepts and recent developments

This chapter begins with some viewpoints and an overview of the research that has been developed is given, to either support or discuss the methodological choices of this thesis. The road network can be seen through two perspectives: structure and function (Figure 2-5). The structure can be described by set of links and nodes; however it is important always to take into account the function of road network: connect persons and activities.

The question thus become: how is possible to identify the roads which interruption would have larger consequences? This broad question arises several other questions. The structure of the network is assessed based on network’s connectivity; the function of the network connecting activities and persons is assessed based on the road network as a source of more or less accessibility.

Transportation networks are embedded in real space, which means that nodes and edges are real physical connections; transportation networks are more than just nodes and edges (Erath, 2009). The topology-based methods mainly capture the topological features critical infrastructures, identify the critical components and provide suggestions on robustness improvements concerning the topological perspective. Hence, topology-based methods cannot be used alone to inform decision-making for real-world critical infrastructure and call for integrating other modelling approaches in a uniform analysis framework for overall decision support (Ouyang, 2014). Human behaviours are too complicated to be fully captured through a topological structure (Lin and Ban, 2013). Hence the proposed model will include the accessibility component, defined as the potential to reach spatially distributed opportunities from a set of origins (Paez *et al.* 2012) – a definition which emphasises the combined results of the transport network and the geographical distribution of activities.

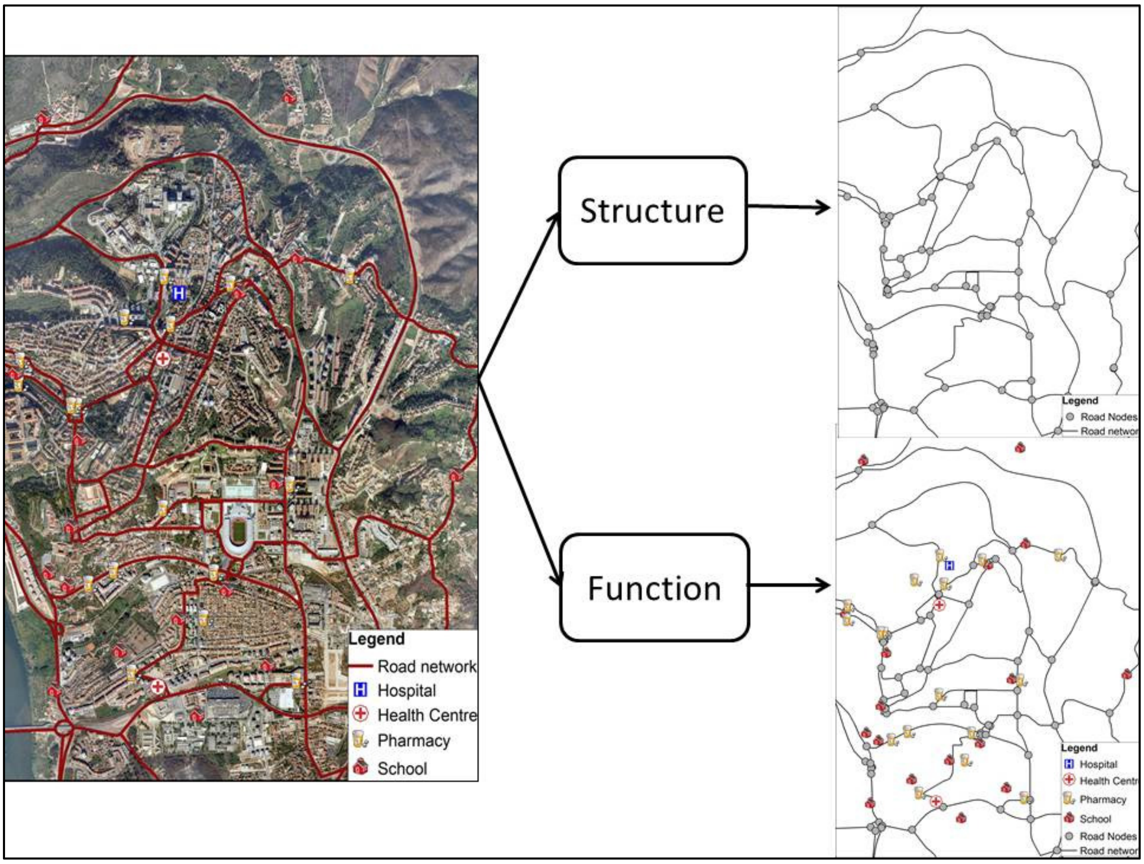


Figure 2-5: Structure and function components' of the territory (example from Coimbra city, Portugal).

In this work road network is perspective as element of connectivity between people and assets and as element of connectivity among critical infrastructures; therefore vulnerability, connectivity and accessibility are key words.

One of the motivations of this work is to show that road network is more than nodes and links; each road network shapes and is shaped by the territorial dynamics. The question here is the extent to which one shapes and is shaped by the other.

2.3.1. Road network's connectivity

At this point the question is: will the most vulnerable links in the road network correspond to the ones with higher connectivity? The concept of network vulnerability relates to the consequences of failure of some component of the network such as a link, irrespective of the probability of failure (Taylor and Susilawti, 2012). The operational consequences of an interruption are the increase of amount of distance between the points (Jenelius *et al*, 2006).

The main function of the road network is to ensure the connectivity between points; connectivity can be defined as the presence of an available or functional path between an origin-destination (O-D) pair (Matiziw *et al*, 2009). Network measures can be applied widely in transportation practice to identify critical nodes and links in a system, which can provide necessary warning for potential attacks or faults. The identification of highly connected links and poorly connected links can aid in helping decision makers plan for service that better connects lower connectivity areas with lower connectivity resources without the cost of restructuring the system or providing new routes (Mishra *et al,* 2012). However, they are lacking important properties that would make them more capable of providing realistic representations of complex systems (Berdica, 2002; Lewis, 2006; Solano, 2010; Murray and Grubesic, 2012, Jenelius, 2014).

Centrality measures have been widely used in the relevant literature to identify the most important roads. However, they seem to lack important properties that would make them more robust tools capable of providing realistic representations of complex systems (Berdica, 2002; Lewis, 2006; Solano, 2010; Murray and Grubesic, 2012).

Jiang and Claramunt (2004) propose a topological analysis where nodes represent named streets and edges represent street intersections. The importance of measures such as street connectivity, average path length and clustering coefficients in the road network structure are discussed in their analysis. The approach was applied to the road networks in the district of Sätra and Gävle in Sweden.

Crucitti et al (2006) compared five different measures of centrality: degree, closeness, betweenness, straightness and information. The approach was applied to 18 1-square-mile samples of different cities. It was analysed the influence of centrality measures in the urban structure, taking into account variables such as if the city was planned or self-organized.

A generalisation model named Intersection Continuity Negotiation is proposed by Porta *et al* (2006); the model recognises the continuity of streets over a plurality of edges. Regarding the topological properties there was focused: degree and degree distribution; degree correlations; characteristic path length; clustering coefficient; global and local efficiency and small-world networks. The model was applied to six cases of urban street network with 1-square mile each.

Xie and Levinson (2007) reviewed the existing measures of heterogeneity, connectivity, accessibility and interconnectivity; also proposed measures of entropy, connection patterns and continuity. The proposed measures were applied to 16 test networks. Some of the proposed measures were later applied by Erath et al (2009) to characterise the growth of the Swiss road network between 1950 and 2000.

Levinson (2012) focused on questions of how network scale and connectivity vary with city size. This model predicts that road networks will be more connected, less circuitous, and less tree like according to the degree of greater accessibility a new link creates.

Novak and Sullivan (2014) propose a Critical Closeness Accessibility (CCA) that quantifies the relative importance of each link in a roadway network with respect to its system-wide contribution to emergency accessibility and is based on the network science/graph theory concept of closeness. The concept of centrality closeness is viewed as relevant to the CCA measure because CCA is designed to be used with non-connected graphs resulting from various disruption scenarios where links may be completely removed from the network. The model was applied to the Vermont state road network.

The problem is that most of these works are focused on exploring the road network properties, without taking into account that each topological measure play different roles and have different importance for the normal network flow. Moreover, there are attributes that are traditionally used, such as degree and betweenness (Barthélemy, 2011; Mishra et al, 2012). However, there are other topological measures that can be useful in the assessment of the road network structure. Some the works use clustering techniques in order to identify patterns in the road networks. In this work the identification of the connectivity patterns is based on the biclustering technique, which application to spatial data is underdeveloped. Most of the recent applications of biclustering are used in biological data analysis (Cheng and Church, 2000; Madeira and Oliveira, 2004; França, 2013), although the technique has also been applied to the analysis of consumer opinions of films (Yang et al, 2003), text mining (Dhillon, 2001), analysis of political opinions (Hartigan, 1972) financial risk analysis (Ribeiro and Chen, 2012), and more recently natural risk analysis (Freiria *et al*, 2014a).

Biclustering is a technique that includes samples and attributes in specific biclusters. Traditional clustering methods only focus on one dimension at a time. Biclustering methods, on the other hand, perform clustering in two dimensions simultaneously (Madeira and Oliveira, 2004). The main goal of the biclustering technique, developed by Cheng and Church (2000), is to identify subgroups of samples and subgroups of attributes through the simultaneous clustering of both rows and columns of the expression matrix, instead of clustering these two dimensions separately. Other clustering techniques, such as hierarchical clustering, group entire columns or rows even though most of the time not all the objects in the column (or row) form part of the bicluster. Using the biclustering technique, each attribute in a bicluster is selected from a subset of samples and each sample is selected using a subset of attributes. Usually spatial clustering is defined as the process of grouping a set of spatial objects into clusters so that the objects within a cluster are very similar to each other, but dissimilar in relation to objects from other clusters (Shekhar et al, 2011) i.e. each object belongs to only one class. Traditional clustering aims to find global patterns by maximising the similarity within a class and minimising the similarity between classes (Ribeiro and Chen, 2012). However, reality is too complex to be split into closed classes. The biclustering technique enables objects that belong to more than one class to be identified and therefore emerges as a suitable methodology.

In most road network analyses the basis is a matrix composed of a set of roads (in the rows) and their corresponding attributes (in the columns). When biclustering algorithms are used in a matrix composed of roads and attributes, each road in a bicluster is selected using only a subset of the attributes, and each attribute in a bicluster is selected using only a subset of the roads. This sub matrix is called a bicluster. The goal of biclustering techniques is therefore to identify subgroups of roads and subgroups of attributes by performing simultaneous clustering of both the rows and columns in the road expression matrix, instead of clustering these two dimensions separately (Madeira and Oliveira, 2004). Thus, clustering methods offer a global perspective, whereas biclustering methods offer a more specific perspective. So far biclustering technique didn't allowed ranking the biclusters according with its importance; however this work intends to overcome that barrier. Several approaches have been also developed to establish priorities in critical infrastructures in order to contribute towards better risk management.

Haimes *et al* (2002) presents a methodological framework to identify, prioritise, assess and manage risk scenarios in large-scale systems. This risk prioritisation methodology considers multiple quantitative factors such as reliability estimates, as well as qualitative factors such as expert rankings. The overall aim of the case study was to ensure that the deployment of U.S. forces abroad for operations other than war would be effective and successful, with minimal casualties, losses or surprises.

Apostolakis and Lemon (2005) propose identifying the minimal cut set (mcs), defining cut set as the set of events (usually failures) that lead to interruptions in service. A *mcs* is a cut set that cannot be reduced, i.e. the removal of one of its elements will not lead to the interruption of service. The case study selects the electricity supply, water (for domestic use and fire protection) and natural gas, as well as the interactions between them. In terms of threats to the system, it focuses on malevolent acts that may lead to the disruption of services.

Rocco and Ramirez-Marquez (2011) identify sets of network elements that are critical to the connectivity of a network and its communities. Specifically, the paper defines a vulnerability set and value for each of the communities in a complex network. In addition, a relative vulnerability value is identified for each community, taking the remaining communities into account.

In the studies that have been developed, one commonly used technique in the literature for identifying important links is the full network scan approach (Chen et al, 2012; Berdica and Mattsson, 2007; Jenelius et al, 2006; Santos et al, 2010). In this approach, each link is iteratively removed from the network and the consequences of its closure are measured in terms of the reduced network performance. The critical links are then identified by evaluating all possible link closures (Jenelius, 2010). There is no doubt that this process is computationally expensive, even for simple and symmetrical grid street networks (Chandra and Quadrifoglio, 2013) and therefore almost impossible to apply to large networks. The biclustering technique offers improvements with regard to computation time, which is a significant barrier to applying models to real-world problems. In its traditional form biclustering technique does not allow ranking the different biclusters, a new approach of the biclusters ranking will be proposed based on homogeneity parameters and a ranking algorithm. This new approach will be compared with a more traditional approach – full network scan approach.

Scale is not only relevant to the unit of analysis used in research but also to its compatibility with decision-making (Eakin and Luers, 2006; Adger, 2006). Therefore based on the local-regional analysis this study presents a new model named the LRSRM (Local Regional Scale Risk Model), which can be defined as an integrated data model whose main goal is to identify the most important roads from a multiscale prespective. LRSRM represents a step forward, since it focuses on the interaction between identifying the most important roads in the network which connect people and health services, the specificity of the natural hazards which threaten the normal functioning of network, taking into account the consequences of a road interruption.

The work here proposed goes beyond the works that have been developed once it presents a methodology that allows identifying connectivity patterns in the network and discusses the role of the links' attributes in the normal functioning of the network and a new ranking system is presented. Furthermore presents a different approach, focusing on the importance of the road network as both a critical infrastructure and a connecting element between different critical infrastructures.

2.3.2. Road network providing accessibility

SFRM allows identifying the most important roads based on an integrated approach of the structural and functional component. So, once outlined what has been done concerning connectivity assessment (structural component), the following step is to review what has been done regarding accessibility perspective (functional component). Accessibility is considered, by planners and other stakeholders, a key variable for territorial development and planning; development and planning policies are defined with the purpose of promoting an equity and better distribution of people and activities in the territory (Julião, 1999).

In this study accessibility is defined as the potential to reach spatially distributed opportunities from a set of origins (Paez et al. 2012) – a definition which emphasises the combined results of the transport network and the geographical distribution of activities. Road accessibility is fundamental not only for the normal functioning of the territorial system, but also for actions such rescue operations. In this phase the main goal is to identify the roads which provide highest accessibility; i.e. to identify the links which provide higher levels of access to critical infrastructures in a network, such as hospitals; it is also a goal to identify parishes with lower levels of access to critical infrastructures. Identifying the populations that are inherently disadvantaged in terms of accessing activities and services is also useful in prioritising maintenance projects and defining emergency route planning. This phase is based on the assumption that the highest the level of accessibility of a road the biggest would be the consequences of its interruption.

Although accessibility is a well-known concept, there is no consensus on how it should be measured or defined (Vandenbulcke et al. 2009; Novak and Sullivan 2014). Numerous geographical studies have analysed the distances between residential locations and the location of facilities in an effort to identify risks, gaps, shortages and disparities (Boscoe et al. 2012). The models have focused on issues such as minimal travel time (Jäppinen et al. 2013; Vandenbulcke et al. 2009; McGrail and Humphreys 2009), the costs involved (Koopmans et al. 2013; Condeço-Melhorado et al. 2011), maximum service coverage (Teixeira and Antunes 2008; Guagliardo 2004), individual travel behaviour (Church and Marston 2003; Blumenberg 2008; Morency et al. 2011) or a combination of these approaches. According to Paez et al. (2012), accessibility measures typically comprise two basic components; the quality/quantity of opportunities and the cost of travel (determined by the transport conditions or communications network on the one hand, and the spatial distribution of travellers and opportunities). While it is not difficult to find a research devoted to accessibility in general, the number of research devoted to exploring the potential impact of road interruptions in accessibility and on territory normal functioning is smaller. Furthermore while many studies define and measure the geographic accessibility of facilities, it hasn’t been explained why the accessibility is high or low, except to conjecture that it has to do with the number of facilities or the locations of these facilities (Burkey 2012).

Sullivan et al (2010) employ different link-based capacity-disruption values for identifying and ranking the most critical links and quantifying network robustness in a transportation network, defined as the degree to which the transportation network can function in the presence of various capacity disruptions on component links.

To offer an alternative method to define the urban accessibility landscape in the aftermath of earthquake damage, Bono and Gutiérrez (2011) combine graph theory concepts and GIS-based spatial analysis to assess how the urban space accessibility decreases when the road network is damaged.

Nakanishi et al (2013) focuses on the recovery phase – and constructs conceptual and operational demand and supply models for the recovery phase to help seek options for more sustainable outcome.

There are also authors (Berdica and Eliasson, 2004; Taylor and D'Este, 2004; Jenelius et al, 2006) which relate vulnerability and accessibility in degraded networks; however in those cases the consequences are mostly seen as the increase of the amount of time spent in the journey.

The accessibility model proposed in this work is a step forward because it proposes an integrated approach of the characteristics of the population at the point of origin (demand), the characteristics of destination point (offer), and the physical constraints of the segment that unites these two points. The explanation of the variables, understanding why the accessibility can be low or high can play a relevant role in the definition of risk management strategies. The accessibility will be assessed in a risk-based perspective; firstly the roads will be rank according with the levels of accessibility, at this phase the higher the level of accessibility of a road the more vulnerable it will be to interruptions; afterwards a scenario-based approach will be also explored, in order to analyse the consequences of road interruptions taking into account the different components of the accessibility model proposed. The model proposed can also be seen as a step forward because it can be a useful tool in the several phases of the risk management cycle. In the prevention phase can be an important contribute in the definition of resources allocation strategies; in the recovery phase can serve as a basis in the definition of paths that should be restored in first place.

2.3.3. Structural Functional Risk Model (SFRM)

Network measures can be applied widely in transportation practice to identify critical nodes and links in a system, which can provide necessary warning for potential attacks or faults. However, human behaviours are too complicated to be fully captured through a topological structure, exploring the relationship between the underlying topological structure of transportation systems and the human movements on them is a challenging task (Lin and Ban, 2013).

The main research contribution of this thesis is the Structural Functional Risk Model (SFRM) an integrated approach of the structural and functional components of the road network, which main output is the identification of the most vulnerable network.

Topological analysis has been recently applied in urban network assessment with interesting results; it is similar in some respects to accessibility but they have never been used jointly. There is the need of more research focusing the relationship between accessibility and centrality, particularly with a real case study (not a simplified graph) in order to investigate reciprocal correspondences and possible relationships (Rubulotta et al, 2012).

The work here presented is a step forward because presents an integrated approach of the structure (topological analysis) as well as the function (accessibility) of each road of the network. It can pointed as an example of the integrated approach importance that the consequences of the interruption of a dangle road in a topological perspective represents a small setback, still in that same dangle road can be located a critical infrastructure, such a Hospital. Thus the dangle road may not as meaningless as it can seem if considered only the topological perspective. It also can be pointed examples of roads with low levels in terms of accessibility, which interruption can mean the network’s breakdown into two or more parts.

3. Methodology

At this phase the methods and tools used to build SFRM are presented and explained (Figure 3-1).The methodological schema is based on the risk conceptual framework previously explored – Risk = Event or consequence and severity of consequences = R = E&C. In one hand there is vulnerability - consequences of the link failure in the network flow - and in other hand there is uncertainty – uncertainty regarding the severity of the consequences.

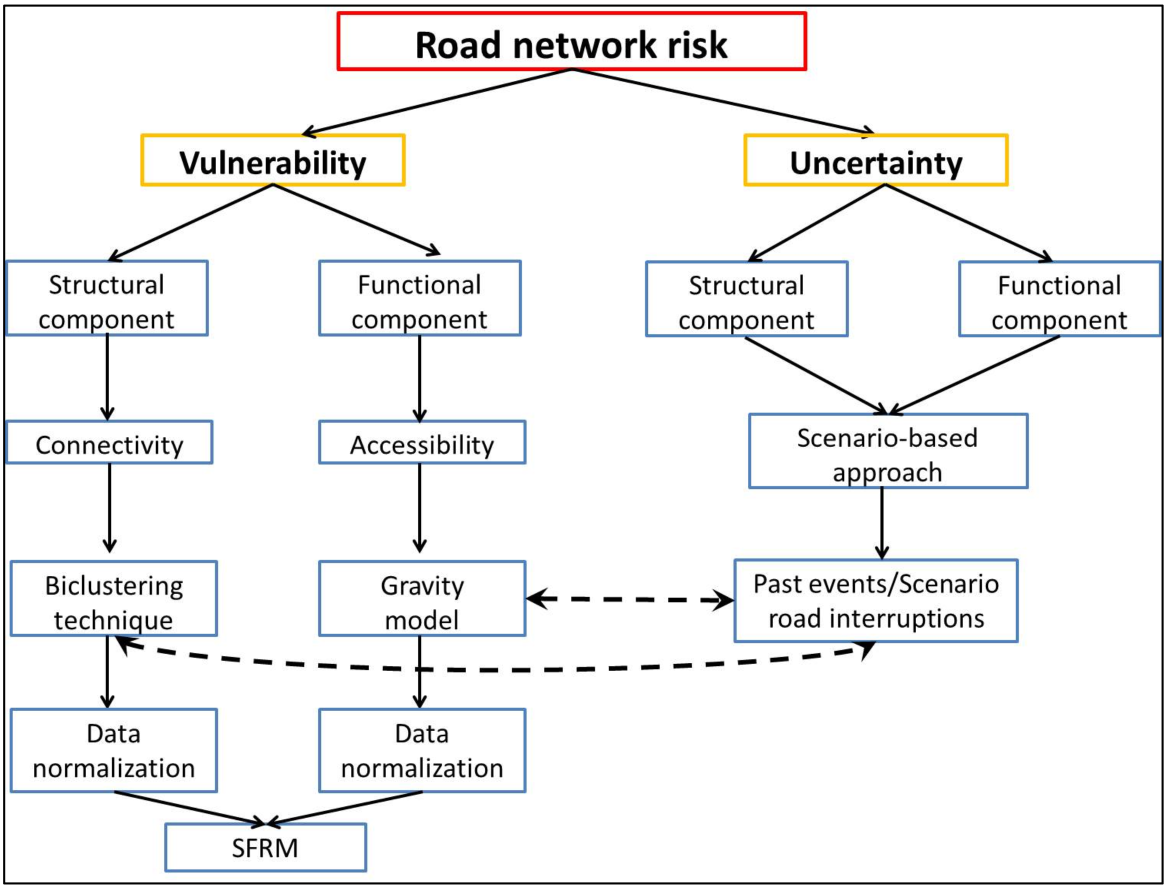


Figure 3-1: Methodological framework

The question is how to assess these two elements of the risk equation? Road vulnerability has two components: structural and functional, which will demand different methodologies. The structural component will be assessed based on the biclustering technique and the functional component will be assessed based on a modified gravity model. In both approaches it will be used multiple regression analysis for two reasons: firstly to test the results' reliability and secondly to analyse the results taking into account the territorial dynamics so they can be a support in decision-making process.

The uncertainty involved in this process will be evaluated based on a scenario-based approach taking into account the structural as well as the functional approach. The scenarios analysed will be plausible road interruptions, based on the results obtained concerning the vulnerability of the structural and functional component, and past road interruptions.

The vulnerability and uncertainty won't be assessed in separated phases; this approach can be seen as a practical application of has been conceptualized by Nielsen and Aven (2003) and Aven (2010). Representations of uncertainty are added to the analysis from the limited knowledge of causal relations in the system, still expressions of uncertainty should not be seen as part of the model, since it must be ascribed to himself and not to the system represented. The main focus of the work is to assess the road network vulnerability.

3.1. Structural component

The assessment of the structural component of the road network, which main goal is to identify the links more vulnerable, is composed by a set of phases (Figure 3-2).

The first step is characterizing the structure of the road network, which allows selecting the more suitable variables to the identification of the most vulnerable roads. However, each variable gives different perspectives concerning the network vulnerability. Thus, is necessary to apply a technique identifying roads with similar characteristics concerning the road network connectivity. In this work is applied the biclustering technique that allows identifying road patterns as well as variables patterns. Since biclustering is an unsupervised learning technique, its output (a set of biclusters) does not contain any class information. However, based on an exploratory regression analysis is possible to test how well the variables correlated with the biclusters, identifying the variables more relevant in the biclusters connectivity patterns. Moreover, the regression analysis is also an opportunity to perform tests not only significance but also confidence on the results. The regression analysis results will be compared with a ranking algorithm, in order to identify the biclusters that integrate the most important roads.

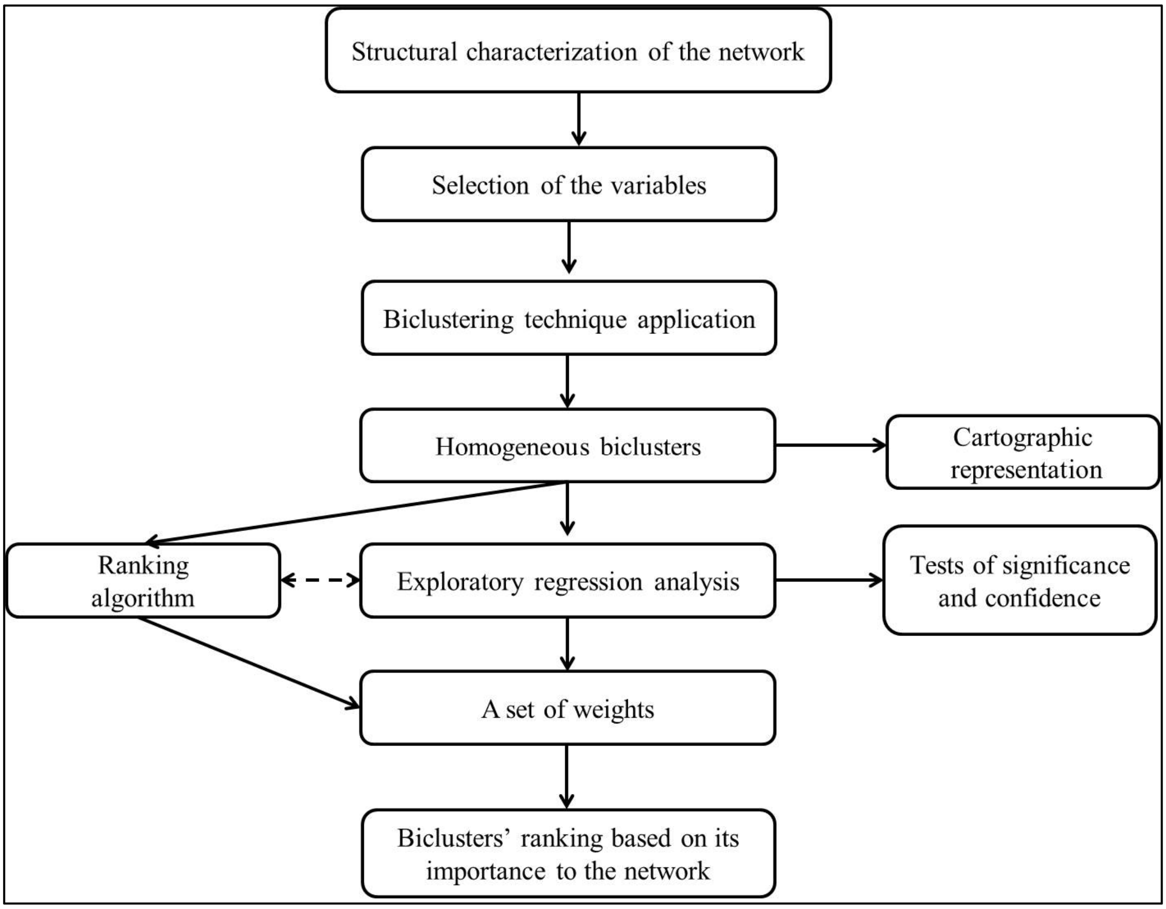


Figure 3-2: Structural characterization of the network

The final output of the structural component is a set of road patterns organized according with their importance to the normal road network functioning.

3.1.1. Structural characterization of roads on different scales

The first phase in the study is focused on identifying the variables relevant to determining the most important roads in the network. However, data quality and determining data proprieties are not the only obstacles to road network analysis in terms of real-world problems. Several authors (Berdica, 2002; Taylor and D'Este, 2004; Apostolakis and Lemon, 2005; Demsar, 2008; Jenelius, 2010; and Fekete, 2011) have developed road network analyses. However, issues such as data acquisition and the role played by each attribute have not been a focus of attention and not all road attributes have the same role and importance. The main issue remains the gap between research and strategic applications for solving the real-world problems of road networks. Xie and Levinson (2007) state that road network connection patterns have been understood poorly by urban planners and engineers. Characterising, describing, and extracting information from networks is nowadays one of the main goals of science, since the study of networks is currently an area of interest in several research fields, such as biology, economics, social science and computer science (Scardoni and Laudanna, 2012).

An urban street network is often perceived as a graph whose edges represent street segments and nodes represent segment intersections (or junctions), but it is not suitable for uncovering structures or patterns (Jiang, 2007).

The dual representation of spaces is recent (Jiang and Claremunt, 2002) however it has advantages to the present analysis in comparison with more traditional approaches. In the structural analysis of a road network the main focus are the streets, the risk of interruption is mainly in the segment, and less in the endpoints. The geometric network can be used for computing distances, routing, and tracking, whereas the network topology can uncover underlying structures or patterns (Jiang et al, 2013).

In the dual representation the first problem is to determine which street segments belong to the same unit. There are two known and often used approaches: the street name approach (Jiang and Claremunt, 2004) and the Intersection Continuity Negotiation (ICN) (Porta et al, 2006). In the street name approach the principle of continuity is based on the fact that two different arcs of the original street network are assigned the same street identity if they share the same street name. However, street names are not always reliable because at the regional level streets with the same names can exist in different locations. The ICN method, based on the principle that two spatially aligned street segments are likely to belong to the same road, works very well on grid-like street networks which typically reflect direct, top-down planning interventions. The ICN method, however, is often misleading when applied to cities exhibiting a complex geometry, which have evolved as a result of bottom-up actions, i.e. self-organizing cities (Masucci et al, 2014). In this work is used a similar approach to street name approach, however instead of the name each street has a unique ID.

The basic steps of a dual representation are as follows (Flow chart 1 and Figure 2): phase I entails to planarize the street lines, which means that new lines split at intersections will be created; then a unique ID is assigned to each line. In phase II the network is a set of edges and nodes where the edges intersect, each individual street that is transformed into an edge maintains the same ID assigned to it in the previous phase. In phase III the previous network is transformed into a graph consisting of nodes representing the individual streets and edges if the corresponding streets intersect. Each node will have the same ID of the individual streets from which it has been created.

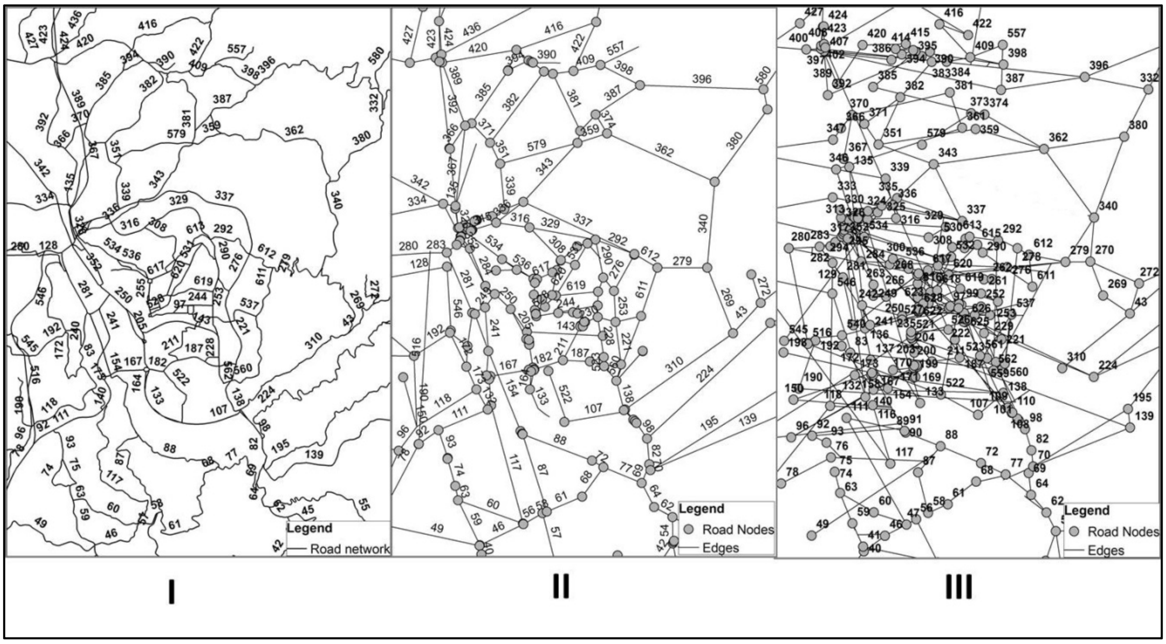


Figure 3-3. Steps of the dual approach (I) natural streets; (II) primal approach; (III) dual approach

This graph can be defined as an *adjacency matrix* **X** = $\{x_{ij}\}$ where

$$x_{ij} = \begin{cases} 1 \; if \; (i,j) \in \varepsilon \\ 0 \; if \; (i,j) \notin \varepsilon \end{cases} \tag{2}$$

One important issue is that each node plays a different role in the network and not all have the same importance. The following phase is focused in how to assess the role and importance of each node in the network.

The characterization of local structures is related to the identification of communities, which are identified by subgraphs where nodes are highly interconnected among themselves and poorly connected with nodes outside the subgraph. Different communities can be traced back with respect to varying levels of cohesiveness.

The main goal of this phase is how to attribute to the roads their share of accountability for the cohesion and connectivity of the network.

A central issue is network connectivity i.e. the possibility of going from one node to another following the connections given by the edges in the network. A graph is called fully connected if there is a path connecting any two nodes in the graph. The concept of "path" lies at the basis of the definition of distance among edges. A path that ends at the same node as it starts, i.e. v1 = vn is designated as a circuit; a circuit that consists of three edges is called a triangle. A circuit where only the first and the last nodes are the same is called an elementary circuit. A graph without any circuits is called a tree if it is connected, and a forest if it is not (Lewis, 2009). While graphs usually lack a metric, the natural distance measure between two edges is defined as the number of nodes traversed by the shortest connecting path (Barrat et al, 2008; Johansson and Hassel, 2010).

The identification of the roads with higher level of connectivity seems straightforward; however there are different kinds of network (Figure 3-4) and the level of connectivity of a road may depend of several parameters. Based on these assumptions there were selected seven indicators: the alpha index (α), betweenness, Bonacich Power (b power), cluster index, cut level, degree, fragmentation.

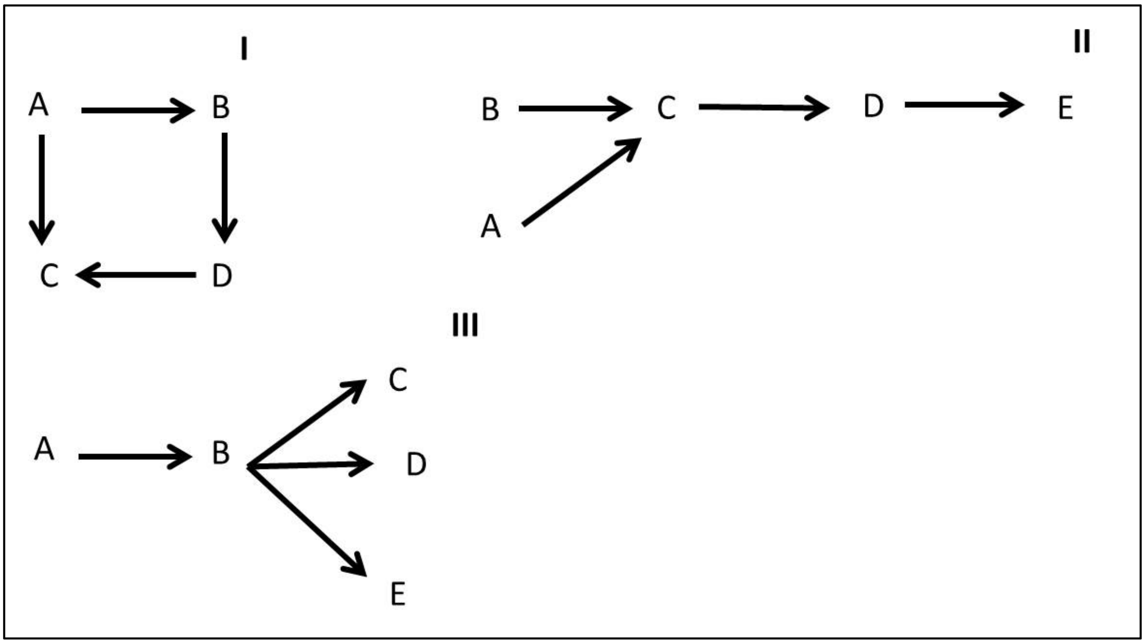


Figure 3-4: Different types of networks (I) grid pattern; (II) linear pattern; (III) tree-like pattern

Alpha Index (α): synonym of expansiveness and refers to the effect of each road's out-degree on the probability that will have ties with other roads. It reflects the number of closed circuits in a network, the higher the number of closed circuits the higher will be the α. It is a measure that represents the difference between the number of connected links and the potential number of fully connected links.

$$\alpha_i = \frac{number\ of\ circuits\ _i}{maximum\ possible\ number\ of\ circuits\ _i} = \frac{l-n+1}{2n-5} \tag{3}$$

α_i is equal to the number of circuits of node *i* divided by the maximum possible number of circuits involving node *i,* where *l* is the number of links and n is the number of nodes.

Betweenness: defined as the number of shortest paths passing through a node and is important for analysing the hierarchical structure of the network and ranking the links of the network. The road is viewed as being in a favoured position to the extent that the link falls on the geodesic paths between other pairs of links in the network.

$$\mathrm{C_B}\ (n_i) = \frac{\sum_{j<k} g_{jk}\ (n_i)}{\mathrm{g_{jk}}} \tag{4}$$

where g_{jk} is equal to the number of geodesics connecting *jk* and $g_{jk}(n_i)$ is the number that node *i* is on.

Bonacich Power (*b* Power): measure that evaluates the road's centrality as a function of how many connections one has, and how many connections the roads in the neighbourhood had. The more connections the roads in the neighbourhood have, the more central the road is.

$$BPi = \alpha\,(I - \beta R)^{-1}\,R1 \tag{3}$$

where α is a scaling vector, which is set to normalize the score; β reflects the extent to which you *weight* the centrality of people ego is tied to; R is the adjacency matrix (can be valued); I is the identity matrix (1s down the diagonal) 1 is a matrix of all ones.

Cluster Coefficient: measures a tendency towards dense local neighbourhoods. Cluster analysis is a natural method for exploring structural equivalence. The local clustering coefficient of the node v is the fraction of pairs of neighbours of v that are connected over all pairs of neighbours of v.

$$C = \frac{1}{n}\sum_{i\in V} C_i = \frac{1}{n}\sum_{i\in V}\frac{M_i}{k_i\,(k_i-1)/2} \tag{6}$$

In the example of equation 6 M_i is the number of edges that exist between the neighbours of node *i,* and k_i is the number of neighbours for node *i.* In general,, the clustering coefficient of a node ranges from 0 - when none of the node's connections are connected with each other- to 1 – when all of the node's connections are connected with each other.

Cutpoints: the node that if removed the network would have disconnected components; is an alternative approach to finding the key "weak" nodes in the network is to ask: if a point was removed, would the structure become divided into-unconnected parts? If there are such nodes they are called "cutpoints".

$$cut\ (A, B) = \sum_{i\ \in A, j \in B} w_{ij} \tag{7}$$

In this example there is component A and component B, node *i* belongs to the component A and *j* belongs to component B, the cut value will depend of the weight of the connections between *i* and *j.* One of the main problems with this measure is that it doesn't take into account the influence of each road.

Degree: counts the number of direct connections a node has to other nodes in the network. The degree centrality, *d*, of node *i* is defined as follows:

$$d(i) = \sum\nolimits_j m_{ij} \tag{8}$$

where m_{ij} = 1 if there is a link between the i and and j nodes and m_{ij} = 0 if there is no such link.

Fragmentation: can be defined as the proportion of pairs of nodes that cannot reach each other. Given a matrix R in which r_{ij} = 1 if i can reach j and r_{ij} = 0, so fragmentation can be defined as follows:

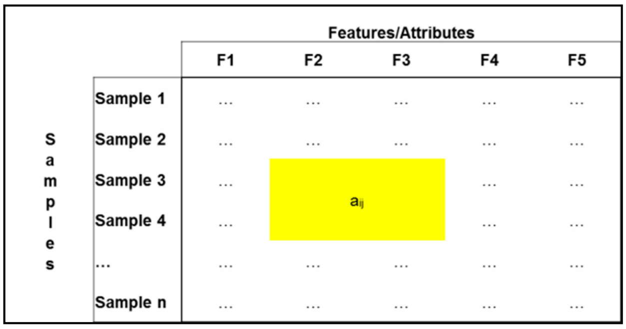
$$F_i = \frac{2 \sum_i \sum_{j<i} r_{ij}}{n(n-1)} \tag{7}$$

F_i is equal to the fragmentation of node i. Fragmentation centrality of a node *i* is the difference in the total score with the node *i* included in the network *n* and the score with the node removed from the network *n*.

Some examples can be given: degree is one of the most common measures of structural characteristics of a network; still the degree centrality does not account for the quality of the connection to other links, assuming that each connection is equally valuable. Variables such as betweenness and Bonacich Power rank roads according to their importance for the network, while betweenness focuses on the roads that are more central. However, there are roads that are important because they are connected to roads with a high level of centrality; this kind of data is provided by the Bonacich Power. Still, a road can have a high betweenness and a high value of Bonacich Power but there are alternative routes, which mean that the impact of an interruption to that road would be minor. The Alpha index is useful for measuring the level of the network's connectivity and the degree of alternative routes present.

3.1.2. Application of biclustering technique

After the structural characterization of the network, this phase focuses on the application of the biclustering technique, which consists of the simultaneous partitioning of the set of roads (the rows data matrix) and road attributes (the columns data matrix) into subsets (classes/biclusters) (Ribeiro and Chen, 2012). The database is a matrix with n rows and m columns in which n is the number of roads and m is the number of attributes. A bicluster is a subset of rows which exhibit coherent patterns across a subset of columns (Figure 3-5).



		Features/Attributes				
		F1	F2	F3	F4	F5
Samples	Sample 1	…	…	…	…	…
	Sample 2	…	…	…	…	…
	Sample 3	…	a_{ij}		…	…
	Sample 4	…			…	…
	…	…	…	…	…	…
	Sample n	…	…	…	…	…

Figure 3-5: Bicluster's example

There are two general types of biclusters, namely additive-related and multiplicative-related biclusters (Madeira and Oliveira, 2004). In this work an additive model is used: each pair of rows has the same difference in all the related columns or each pair of columns has the same difference in all the related rows.

Suppose there is n roads described by m topological measures (attributes). It was given a matrix $X \in {}^{n*m}$, where each element is represented by x_{ij}, $i \in 1 \ldots n$ is the row index and $j \in 1 \cdots m$ is the column index. We denote $R = \{1 \cdots n\}$ and $C = \{1 \cdots m\}$ the sets of rows and columns of matrix X. If we have $I \subseteq R$ and $J \subseteq C$ we denote $X(I, J)$ as the sub-matrix of X containing only the elements x_{ij} with indexes within the sets i and j.

The bicluster algorithm needs four free parameters: *(i)* noise threshold ε, *(ii)* minimum number of rows in percentage N_r *(iii)* minimum number of columns N_c and *(iv)* maximum bicluster overlap in percentage P_o. The noise threshold ε parameter specifies the noise tolerance as well as the homogeneity in the biclusters identified (Cheng et al, 2008). The maximum overlap allowed specifies the maximum percentage of overlap allowed in rows and columns between two detected biclusters. For example a 510 x 7 size road data X matrix, the value of this parameter is set to 10%, which means that the greatest number of rows and columns in which two biclusters overlap are $1\ (7 \text{ x } 0.1 = 0.7)$ and $51\ (510 \text{ x } 0.1 = 51)$ respectively. The noise threshold ε and the minimum number of rows should contain low values, since the lower they are, the more homogenous the bicluster will be.

The dataset of roads and indicators was set up and hosted using *Bivisu* (Cheng et al, 2008) developed in *Matlab*. In the first experiment the parameter values were based on the work developed by authors such as Cheng and Church (2000), and Madeira and Oliveira (2004). Nearly 200 runs were then carried out in order to find the biclusters, in order to find the biclusters with better values according with the quality standards which will be explained in the next subsection (Table 3-1).

Table 3-1: Tests run: Phase II – parameter settings

Parameter	Parameter settings
Noise threshold	5;4;3;2;1.5;1;0.5
Minimum number of columns	6;5;4;3
Minimum number of rows in percentage	15;10;5
Maximum bicluster overlap in percentage	25;20;10

Finally, a round of tests was carried out based on the results obtained in the previous phase. The best configuration setup may not correspond to the parameters shown in Table 3-1, which were used in the previous phase. Taking this possibility into account, extra experiments can be carried out.

The quality of the biclusters is assessed using three criteria: MSRS (Mean Square

Residue Score) endorsed by Cheng and Church (2000); ACV (Average Correlation Measure) endorsed by Teng & Chan (2006); and Parallel Coordinate (PC) Plots. Due to the uncertainty of its role, bicluster size cannot be considered as a criterion, although it cannot be totally disregarded and will be taken into account.

From the definitions above, the biclustering problem can be formulated as: given the m*n matrix x find a set of biclusters $B_r = (I_r, J_r)$ with $r = 1,\dots, t$ where each bicluster B_r satisfies any condition of homogeneity. There are two main metrics to evaluate how good the clusters are so far. For the homogeneity aspect, one is the mean square residue score (MSRS) in Cheng (2000) and Ribeiro and Chen (2012) defined by

$$MSRS = \frac{1}{nm}\sum_{i \in R\, j \in C}\left(x_{ij} - x_{iC} - x_{Rj} + x_{RC}\right)^2 \tag{11}$$

where $x_{iC} = \frac{1}{m}\sum_{j \in C} x_{ij}$, $x_{Rj} = \frac{1}{n}\sum_{i \in R} x_{ij}$ and $x_{RC} = \frac{1}{nm}\sum_{i \in R, j \in C} x_{ij}$.

denote respectively X_{iC} a cluster of columns; X_{Rj} a cluster of rows; X_{RC} a cluster of rows and columns.

Given a homogeneity threshold δ, which defines the maximum allowable dissimilarity, a valid bicluster can be determined if MSRS ≤ε.

The second metric is the average correlation value (ACV) Teng (2006) is computed by

$$ACV = \max\left\{ \frac{\sum_{i,j \in R} |CorR_{ij}| - m}{n^2 - n}, \frac{\sum_{k,l \in C} |CorC_{kl}| - n}{m^2 - m} \right\} \tag{12}$$

where $CorR_{ij}$ and $CorC_{kl}$ are, respectively, the correlation coefficients between rows *i* and *j*, and columns *k* and *l*.

A bicluster with high homogeneity in the attributes should have a low MSRS and a high ACV. Thus the former represents the error in the algorithm and the latter the accuracy achieved. ACV is widely used to measure the degree of coherence of the bicluster; it can be defined as quality measure for correlation between roads and attributes. The higher the level of correlation the higher the ACV value will be.

At this stage there will be a set of biclusters, as the ones of Figure 3-6, each one integrating roads with similar characteristics. Still, is important to mention that the methodology will be applied to real-world networks, thus the biclusters may not be as homogeneous as would be in artificial networks. Also, it must be noted that the example in Figure 3-6 are just graphical, in a real-world case the roads would be spatially dispersed; i.e. it can exist a grid pattern block at North of the case study and other grid pattern block in the South. In this phase the question is how to rank the biclusters according with its importance to the networks flow. Taking as example figure the question is how to know if the roads that integrate Bicluster 1 are more important than the roads that integrate Bicluster 2, or vice-versa. The answer to this question can be to identify the variables more relevant in the biclusters' connectivity patterns. This approach is only possible because each bicluster is defined by a specific subset of roads and attributes, thus it is possible to extract information from them.

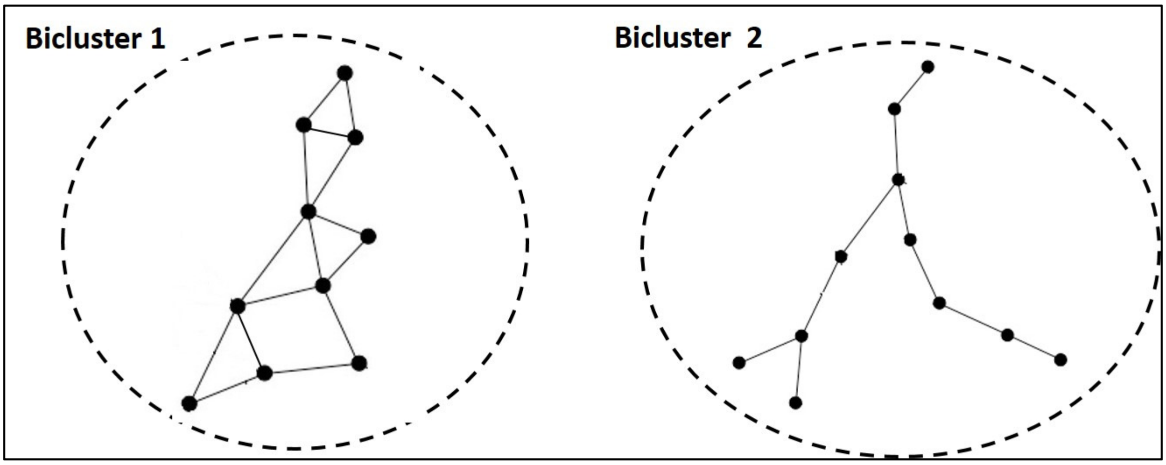


Figure 3-6: Graphical example of biclusters

In this work an approach similar to the one used by Goia et al (2010) is used; each bicluster is given sequentially a value, which at this phase is defined as y. Afterwards, a multiple regression model is applied to each bicluster, which has the advantage of rejecting the variables that do not contribute to the relevant information and assess the importance of each attribute in the connectivity pattern of each bicluster, based on multiple regression analysis, which can be expressed as follows:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \tag{13}$$

y represent the Biclusters' Connectivity Index and x represent the explanatory variables; β are unknown variables estimated from data, based on the least-squares method, which make the sum of squares of the residual as small as possible; the difference between the observed value of y and the straight line ($\beta_o + \beta_1 x_1$) be an error ε.

Based on the assumption that the biclusters' with highest mean values concerning the explanatory variables and respective coefficients will correspond to the biclusters with highest connectivity level, the regression analysis results – the predicted y- will correspond to a ranking.

One of the most common methods to assess the fitness of the model is the R^2, which measures the proportion of the variation in y that is explained by the variation in x. The values of R^2 range between 0 (no linear relationship between x and y) and 1 (perfect match between x and y).

$$R^2 = \frac{SSR}{\sum (y_i - \bar{y})^2} \tag{14}$$

where *SSR* is the proportion of the variation in *y* that is explained by the variation in *x.*

In multiple regression problems it is expected to find dependencies between the dependent variable and the explanatory variables. However, there are situation where there are also dependencies among the regressor variables; the situations where these dependencies are strong are designated as multicollinearity. The Variance Inflation Factors (VIF) are very useful measures of multicollinearity. The larger the variance inflation factor, the more severe the multicollinearity. Because no formal cutoff value or method exists to determine when a VIF is too large, typical suggestions for a cutoff point are 5 or 10 (Craney and Surles, 2002, O'Brien, 2007, Dormann et al, 2013). Biclustering methods perform clustering in ‘two dimensions’ simultaneously (attributes and samples), which means that only subgroups of attributes are in a given bicluster. This property automatically filters out attributes highly correlated. One of the basic rules in the selection of the attributes is that each one would give a different contribution; still some correlation may occur. This issue was examined for the seven indicators; it was found out that road biclusters were filtering out the correlated features. Therefore, is considered that the most important is the level of correlation between the most significant variables in the bicluster patterns connectivity.

One of the research hypothesis is that based on ACV is possible to rank the biclusters. ACV is widely used to measure the degree of coherence of the bicluster. The attributes more significant in the biclusters patterns connectivity will be compared with a ranking algorithm, based on ACV and MSRS values, as follows in Algorithm 1. The ACV values will be compared with the explanatory variables, in order to test the accuracy of the results.

```
RANKING ALGORITHM
CHECKING ACV & MSRS

N= 6 %Number of Biclusters

For all biclusters I = 1,N
    Check MAX (ACV (I) --> Accuracy (%)
    Rank  1<- MAX(ACV(I)
    If ACV(I) = ACV(I+1)
        Check error of biclusters (MSRS)
        Assign higher rank to the bicluster with less error
        Rank = Rank +1
    End if

End for all
```

Algorithm 1: Ranking algorithm

3.1.3. Network scan

The traditional way to measure link importance is to calculate the overall change of some performance measure (such the total increase in vehicle travel time) when the link is closed, in relation to if it would remain open (Jenelius, 2010).

The first step of the network scan is to calculate for each node the minimum cost path between that specific node and the remaining network nodes; the next step is to remove each node and assess the consequences of those failures. The importance of each node for the network is measured by analysing variations on geodesic distance. In this analysis rode nodes are interactively interrupted in the network which leads to an increase in geodesic distance because of the need to use paths that are not the shortest (Figure 3-7). The network analyses have been computed in ArcGis-ArcINFO 10.1 and, as in the application of the biclustering technique phase, also in this phase was used a dual approach.

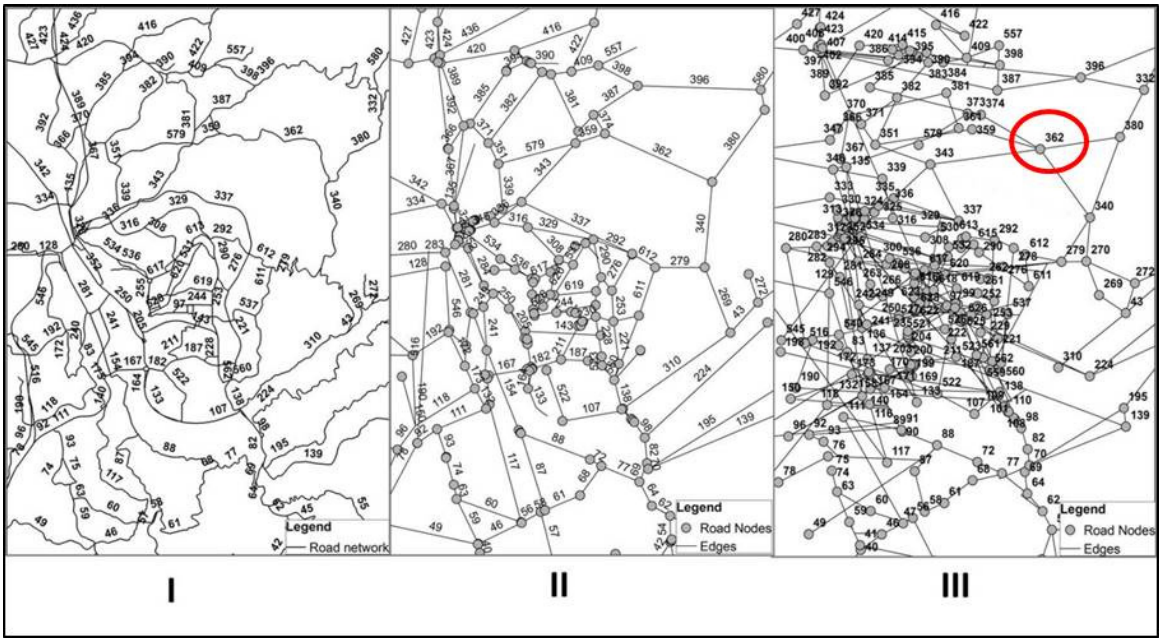


Figure 3-7: Dual approach phases – example (I) natural streets; (II) primal approach; (III) dual approach – 362 node – example

In GIS language point is the synonym of node in topological language. In ArcGis the first step is to generate a near table (Figure 3-8) (determines the distances from each feature in the input features to the closest feature in the near features), in the example of figure 14 the *input points* were all the points assembled in one feature and the *near points* were also all the point but point 362. The question is how the removal of point 362 affects the distance values among the other points of the network.

The points have been interactively removed from the *near points*. At the end of this phase there will as many near tables as point network, each table taking into account the removal of one point, plus a table simulating a normal situation with the presence of all the points.

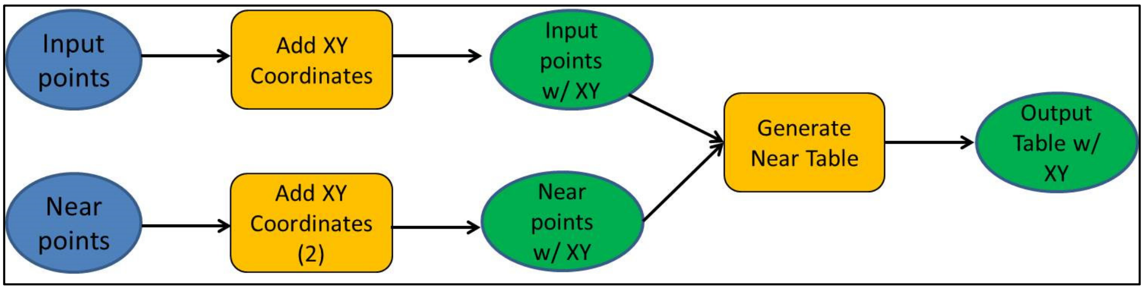


Figure 3-8: Generate Near Table process

In the following phase the tables are joined based on the common XY coordinates and ID and the mean geodesic distances are compared. The weighted mean geodesic distance was calculated as follows:

$$\overline{Gd_\iota} = \frac{\sum Gd_{ij} \quad F_{ij}}{F_j} \tag{15}$$

$\overline{Gd_\iota}$ is the average geodesic distance from node represented by *i*; Gd_{ij} is the sum of all the geodesic distances according to the shortest path with origin in node *i* as destination they are considered each node of the network represented by *j*, F_{ij} is the number of routes according to the shortest path with origin in node *i* and destination in each node of the network represented by *j*, F_j *is* the total number of routes generated from node *i* to node *j.*

The average overall geodesic distance in the original scenario ($\overline{Gd_0}$) was:

$$\overline{Gd_0} = \frac{\Sigma_i \Sigma_j \, Gd_{ij} \, F_{ij}}{\Sigma_i \Sigma_j F_{ij}} \tag{16}$$

The impact of disruption in each link was assessed through the average times without each link using

$$\overline{Gd_a} = \frac{\Sigma_i \Sigma_j \, Gd_{ij} \, F_{ija}}{\Sigma_i \Sigma_j F_{ij}} \tag{17}$$

where $\overline{Gd_a}$ is the overall geodesic distance according to the fastest detour when node *a* is removed.

In the following phase the average overall geodesic distance without node *a* were compared with the average geodesic distance in the original scenario based on the following equation:

$$\overline{N_a} = \overline{Gd_a} - \overline{Gd_0} \tag{18}$$

where $\overline{N_a}$ is the overall geodesic distance increase due to removal of node *a.* The process is repeated for each node level.

The N-1 criterion states that the system should tolerate the failure of any single component, regardless of the initiating event, and still maintain its function (Johansson, 2011). If there is no consequence for any of the scenarios, the system is not vulnerable to that particular component failure. In this case, the higher the geodesic distance increase due to removal of node *a* in comparison with an original scenario, the bigger the importance of node *a* in the network.

Each node has an ID that corresponds to a link in the road network; thus the final results are mapped at link level.

In the last phase the full network scan results are compared with the results of the biclustering technique results, through a regression analysis. This comparison allows testing the results of a new approach (biclustering technique) with the results of a traditional and widely used approach (full network scan). Moreover, the advantages and disadvantages of each approach will be also subject of comparison.

3.1.4. LRSRM – Scale dynamics in scenario-based approach

At this stage is presented the LRSRM (Local-Regional-Scale-Risk-Model), is defined as an integrated model whose main goal is to identify the most important roads from a multiscale perspective, analysing the consequences of a road interruption at regional and local scale.

There are cases, such as natural hazards, it is very important to protect critical infrastructures in order to keep disruption of services to a minimum, since many of these facilities, such health care, play a key role in disaster response and recovery (Novelo-Casanova and Suárez, 2012). However some areas are more susceptible to natural hazards than others and therefore, in addition to the different levels of road connectivity, the study also takes areas with a higher susceptibility to natural hazards, such as floods, forest fires and mass movements, into account.

In addition to the levels of connectivity of a road network and the areas with higher susceptibility to natural hazards, scale should also be considered. Depending on the scale on which simulations are carried out, roads present different geometries, details, attributes, and relationships to other features. Experience shows that the recognition and successful exploitation of cross-scale opportunities has been important in improving wellbeing in areas such as public health and education (Nyberg and Johansson, 2013). The scope of the data used should match the scale of analysis, in order to establish proximity between modelling and everyday decision-making. The planning and administrative authorities need simple methods to calculate vulnerability indicators on a national/regional level as well as a municipal level, as input for preventive work on risk management (Lambert et al, 2013). The model therefore includes an application for regional and local scales.

Once identified the most important roads at regional and local scale, based on the application of the biclustering technique, the following phase is focused on how 3 road interruption scenarios affect access to hospitals from parish centroids and how the network reorganises due to interruptions.

An O-D (Origin-Destination) matrix was created to identify the hospitals (D) closest to each parish centroid (O) in terms of the drive time between each OD pair. According to several authors (Alonso et al, 2013; Kwon and Varaiya, 2005), O-D matrices are an essential resource for managing and controlling a transport system. The drive time was calculated on the basis of the link length and actual speed limit established by the bodies with legal authority and jurisdiction over the respective roads. These limits are based on the road classification, land use in the surrounding areas and social or physical constraints, such as the proximity of a school or a steeply sloping area (Table 3-2). The speed limit in an urban municipal road network may therefore range from 10kph to 50kph, depending on the characteristics of the road.

The costs of the interruption were measured on the basis of the following parameters: the increase in the drive time needed to reach the nearest hospital in comparison with a normal scenario, and the number of parishes served by each hospital in the different scenarios, which is related to the number of routes (between the parish and the hospital) that each road can provide in the different scenarios.

Table 3-2: Speed limits

Designation	Function	Standard speed limits	Posted speed limits
Principal road network	Ensures connections between districts at national level	120	80-120
Complementary road network	Ensures connections between municipalities at district level	90	80-100
National road network	Ensures connections between municipalities at municipal and local level	90	50-90
Municipal road network	Ensures connections between rural settlements in the municipality and between these rural settlements and the city	50	30-50
Urban municipal road network	Ensures connections inside the city	50	10-50

3.2. Functional component

The aim of the functional analysis of the network is to identify the most important roads defined as the ones which provide higher levels of access to critical infrastructures in a network. At this phase the question is how to integrate in the same formula the characteristics of the critical infrastructure, streets and the population served (Figure 3-9). In this work a modified version of the gravity model is an answer to measure the levels of accessibility between the parish centroids and district hospitals in the Central Region in an integrated approach.

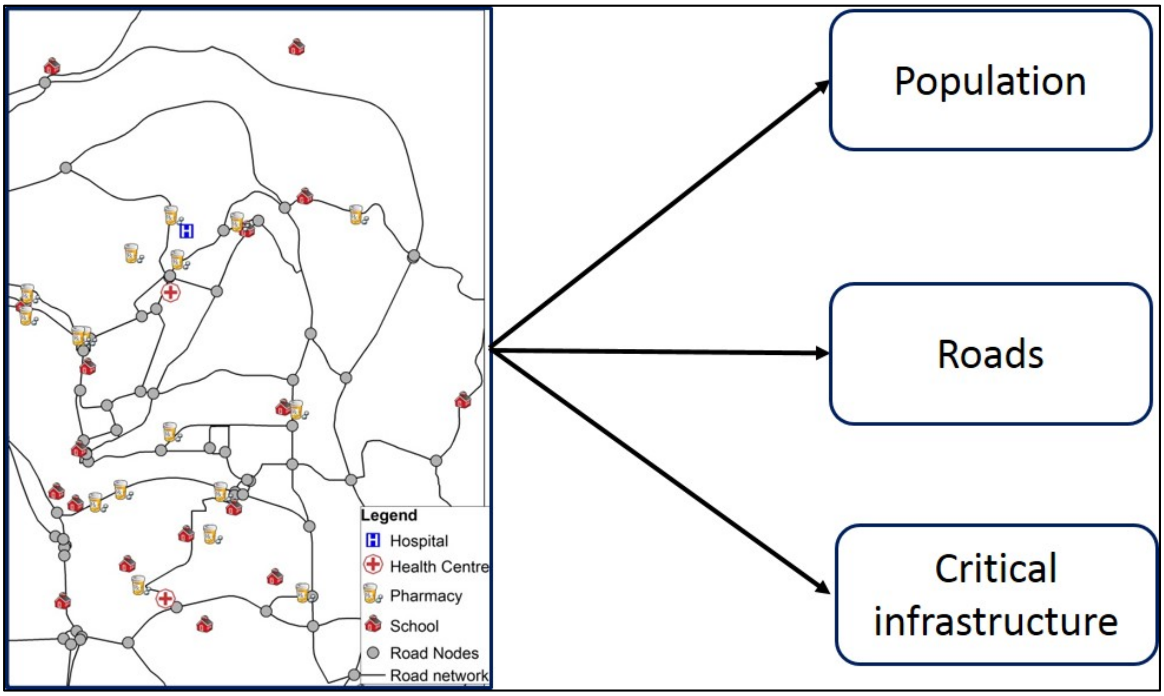


Figure 3-9: Functional component of the road network

3.2.1. Concepts

The gravity model is considered the most reliable measure of spatial access (Guagliardo 2004, Schuurman et al. 2010), and is one of the most common spatial interaction models (Martínez and Viegas 2013). Broekel et al. (2014), considering its pros and cons, classify the gravity model as the most suitable for combining geography and network structures. In this work a new approach to the gravity model is proposed where population is more than just a number, and the territorial physical constraints are taken into account in drive time assessment. The following phase is focused on the definition of the concepts used and the explanation of the methodological choices.

3.1.2.1 Mobility Index (*MI*)

The Mobility Index represents the population’s ease of travel taking into account its social vulnerability and is assessed on the basis of stepwise multiple regression analysis.

The question is to what extent does the population's social vulnerability influence the ease of travel? All the data used to build the Mobility Index (Table 3-3) is from the most recent Census carried out by Statistics Portugal in 2011 (INE, 2011), at parish level.

The multiple regression analysis can be written as follows:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \varepsilon = MI_{P_i} \tag{19}$$

In this case y, the dependent variable, is equal to the proportion of car use for daily travel; it is assumed that higher car use for daily travel equates with higher mobility. Lindell and Perry (2012) identified lack of access to a personal vehicle as one impediment to people's responses to environmental hazards and disasters. In addition, Comber et al. (2011) determined that non-car ownership is a significant predictor of difficulty in accessing hospitals and is even more significant than geographical distance. The explanatory variables, *x,* are the ones presented in Table 3-3. The index function was calibrated using a stepwise approach, which means that the decision of the regression variables that should be included in the model is conducted through parameter interface, i.e. testing whether parameters are significantly different from zero, which can lead to biases in parameters and incorrect significance tests (Whittingham et al, 2006).

Table 3-3 Initial explanatory variables

Variables
Activity rate
Children aged under 6 (%)
Couples with children (%)
Disabled people (%)
Family size
Ratio of dependent young people
Resident population (n)
Residents aged 65 or over (%)
Single parents (%)
Single-person households comprising one individual aged 65 or over
Total adult illiteracy rate

The statistical contribution was evaluated using the F-test – each independent variable is tested to determine whether it contributes significantly to the model, given that the other independent variables in the step are also included in the model. In this study, a variable was entered into the model if the significance level of its F value was less than the Entry value – 0. 05 - and it was removed if the significance level was greater than the removal value – 0.1.

The result of the regression analysis is represented by MI_{P_i} – Mobility Index per parish - that is the result indicating how the extent of the population's social vulnerability influences the ease of travel. The classes of the cartographic representation will be organized based on the Standard Deviation (S.D.) from the average values [-1, 5 S.D., -0,5 S.D.[; [-0,5 S.D. , 0,5 S.D. [; [0,5 S.D., 1,5 S.D. [;> 1,5 S.D.

A hospital-focused analysis was also carried out, based on the average values of the parishes connected to each hospital. The service area of each hospital is defined as a region that encompasses all accessible roads (that is, roads that are within a specified impedance). For instance, the 5-minute service area for a point on a network includes all the streets that can be reached within five minutes from that point.

$$\overline{MI_j} = \frac{\sum_{i \in j} MI_{P_i}}{|\boldsymbol{N}_j|} \qquad (20)$$

where hospitals are represented by *j* and parishes are represented by *i*; the $\overline{MI_j}$ is equal to the sum of all MI_{P_i} of each *j* dividing by number of elements in the set of parishes served by the hospital located in j, $\mathrm{N_j}$.

The main goal of the Mobility Index is to discover a population's ease of travel taking into account its social vulnerability. Thus, the average values of the explicative variables that are most significant at parish level per hospital service area will be assessed, as in equation 21 where the activity rate is used as an example:

$$\overline{AR_j} = \frac{\sum_{i \in j} AR_i}{|\boldsymbol{N}_j|} \qquad (21)$$

where $\overline{AR_j}$ is the activity rate average per hospital and is equal to the sum of all AR_i of each j dividing by number of elements in the set of parishes served by the hospital located in j, $\mathrm{N_j}$.

Public transport networks play a fundamental role for mobility in some urban areas as well as in the connection among municipalities. Therefore the results of the mobility Index will be analysed taking into account the offer in terms of roadway public transport.

The goal is to evaluate the role public transport plays in population mobility in the Central Region. In Portugal there are different types of public transport available (IMTT, 2014):

Urban public transport: this kind of transport is usually ensured by municipal public companies;

Service Public Connections: connections usually ensured by private companies that are awarded transport licence; these connections can be temporary or regular;

Express network: these routes shouldn't be less than 50km and the number of bus stops should be limited;

High quality connection: these connections should have a higher quality standard than an express network, the bus should have a hostess call and the routes shouldn't be less than 100km.

The comparison between the Mobility Index and the public transports will be particularly focused on the parishes with low mobility.

3.1.2.2 Service capacity (*Sj*)

Service capacity can be defined as the resources available in each critical infrastructure. Taking as an example of critical infrastructure the hospitals, the number of beds per hospital can be used to represent the service capacity.

Authors such as Luo and Wang (2003) calculate the physician-to-population ratio. On the other hand, Schuurman et al. (2010) and Rosenthal et al. (2005) consider the number of physicians in the centroid postal code area. A calculation of the number of physicians per hospital was not considered accurate in this case study, because some work in more than one hospital. Delamater (2013) considers that the number of beds may represent sets of opportunities in a particular area.

3.1.2.3 Distance friction factor (*d*)

The majority of studies define distance as a straight line between locations, using either Euclidean distance with projected coordinates or spherical distance with latitude and longitude coordinates (Boscoe et al., 2012). Still, geographic space is not homogeneous and its constituent elements are distributed in an uneven manner. Their quantities and qualities vary across sections of geographic space, across locations and regions (Halás et al, 2014). The friction factor can be defined as a mathematical factor that is used to assess the effort that is required to travel between two points. A frictionless territory would mean that space is equal everywhere. Thus, defining the friction factor is particularly troublesome since its value varies from place to place and also over time (Wang and Luo, 2005). In this work the friction factor will be considered in two parameters, related to the physical geography of the territory: slope and sinuosity. There are several authors that recognize the number of jobs or population (Abdel-Aal, 2014; Halás and Kladivo, 2014) as a friction factor. Also authors and institutions, such National Cooperative Highway Research Program (NCHRP, 2011), consider that the friction factor depends on the trip purpose, as such an HBW trip presents a lower friction factor than a HBNW trip because one will feel more motivated to travel in the first case than in the second (Table 3-4). Even though, this perspective can be suitable in some fields of knowledge, it does not apply to this work where the focus is the access of population to a critical infrastructure.

Table 3-4: Trip purpose and friction factor

Trip Purpose	**Friction Factor**
Home-based Work (HBW)	-0,02
Home-based Non-Work (HBNW)	-1,3
Non-Home-Based (NHB)	-1,35

In an emergency response context the focus is not on what distance may discourage a person from going from one place to another, but to know which characteristics of the territory can contribute to increase the travel time between two places. According to AASHTO (2011), sinuosity and slope are the two physical factors that most influence speed. In most situations slope and sinuosity are highly correlated; in this work the sinuosity index will be considered as a friction factor and assessed as follows:

$$s = \frac{c_{ij}}{sl_{ij}} \tag{22}$$

where s is the sinuosity index; ; c_{ij} is the length of the segment between i and j in kilometres and sl_{ij} is the straight-line distance between i and j in kilometres. The sinuosity index varies from 0 to 1. A straight feature has a sinuosity index of 1, but in the case of more indirect features the index will move closer to 0.

In the example of Figure 3-10 it is obvious that going from point *i* to point *j* in case A will be easier that going from point *i* to point *j* in case B. The question is how much easier? Is this premise applicable to a regional scale analysis?

Based on the work developed by Sohn (2006) also in this work the distance friction factor is obtained from the log-normalized regression of simple distance in minutes on the sinuosity values.

Figure 3-10: Sinuosity effects' on distance

The distance friction function is assessed in two phases: firstly is calculated the distance in minutes between points *i* and *j;* then the friction function is assessed based on the correlation between the distance in minutes and the territorial constraints. In a first approach, the distance in minutes will be calculated as follows:

$$d_{ij1} = \frac{c_{ij}}{v} * 60 \tag{23}$$

where d_{ij} is the drive time distance between points *i* and *j* in a first approach*;* and *v* represents the speed limits as defined in the Portuguese Highway Code (Table 3-2).

In the modified gravity model the distance will calculated as follows:

$$d_{ij1} = \frac{c_{ij}}{v_s} * 60 \tag{24}$$

where v_s is equal to velocity influenced by the sinuosity of the route.

3.1.2.4 Modified Gravity Model

In its most elementary form, the gravity model predicts that the flow or interaction intensity between two objects (e.g. origin and destination) is assumed to be directly correlated with the mass of the objects and inversely correlated with physical distance between the objects. More formally,

$$I_{ij} = K \frac{M_i^{\beta_1} M_j^{\beta_2}}{d_{ij}^{\beta_3}} \tag{25}$$

where I_{ij} is the interaction intensity between object *i* and *j, K* a proportionality constant, M_i the mass of the object *i* (e.g., origin), M_j the mass of object *j* (e.g., destination) and d_{ij} the physical distance between the two objects. β_1, β_2, and β_3 are parameters to be estimated. β_1 refers to the potential to generate flows, β_2 is related to the potential to attract flows, and β_3 is an impedance factor reflecting the rate of increase of the friction of physical distance (Broekel et al, 2014).

This work proposes a modified Gravity Index that promotes an integrated approach, giving emphasis to the residents' mobility capacities and to the territory's physical constraints; moreover the modified Gravity Index will be assessed in three different perspectives: link-based, critical infrastructure-based and parish-based. Each of these perspectives brings different inputs. A link-based analysis will allow ranking the different links according to their importance in the regional context, while the parish-based analysis is from the population's point of view. The issues under discussion are those like which populations are well-served in a health perspective. A hospital-based analysis will allow identification and ranking from the most important to the most vulnerable facility, which depend on factors such as the amount of resources available in each hospital versus the characteristics of the population served by that hospital.

The first step is to create an O-D (Origin-Destination) matrix, where the Origin (O) is the parish and the Destination (D) is the critical infrastructure, since in this work the hospitals will be used as an example of critical infrastructure. The level of importance of each link will depend on the characteristics of parishes and the connecting Hospital; each link can connect several parishes to several Hospitals.

Summing up, this analysis is focused on the link that connects each parish to a Hospital, which means that each Hospital will be connected to several parishes. Therefore, the link-based and the hospital-based analyses require the calculus of averages and aggregations, respectively.

The first step is to calculate the Gravity Index per parish, as follows:

$$GI\_P_i = \frac{MI_i * S_j}{{d_{ij}}^{\beta}} \tag{26}$$

where GI_P_i indicates the Gravity Index of each parish centroid, represented by *i*; MI_i is the Mobility Index for each parish centroid; S_j is the service capacity of the hospital, represented by *j*; d_{ij} is the drive time distance between points *i* and *j*; and β is a calibration parameter, representing the propensity for travelling given the distance between points *i* and *j*.

The Gravity Index link-focused GI_L_l is based on the following framework: there a set of streets, composed by segments, which connect the parishes and the Hospitals. Each segment can connect one or more parishes to a hospital i.e. one or more routes (Figure

3-11). The Gravity Index (GI*l*) is equal to the sum of the gravity index values per parish that intersect each segment (*l*) in the network, as follows:

$$GI\_L_l = \sum_{i \in \boldsymbol{N}} GI\_P_i \times a_i^l \tag{27}$$

where $\boldsymbol{N}$ is the set of parishes in the study area and a_i^l is a binary variable equal to 1 if link *l* is part of the shortest path between the parish *i* and the closest hospital. GI_l indicates the attractive force of the route between each parish centroid, represented by *i.* The following example can be given: link y (*l*$_y$) connects 3 parishes to the Hospital that have the resulting standardized gravity index values: 0.5; 0.3 and 0.8. In this case the gravity index of link y would be:

$$GI\_L_l = 0.5 + 0.3 + 0.8 = 1.6 \tag{28}$$

The cartographic of results is based on the following classes, which take the standard deviation (S.D.) from the average into account: [-1, 5 S.D., -0, 5 S.D.[; [-0, 5 S.D., 0, 5 S.D.[; [0, 5 S.D., 1, 5 S.D.[; >1,5 S.D.

The next step is a hospital-focused analysis, based on the average Gravity Index values of the parishes served by each hospital.

The Gravity Index ($\overline{GI_j}$) of hospital *j* based proposed in this study is:

$$\overline{GI_j} = \frac{\sum_{i \in j} GI\_P_i}{\left|\boldsymbol{N}_j\right|} \tag{29}$$

where the $\overline{GI_j}$ is equal to the sum of all GI_P_i of each *j* dividing by number of elements in the set of parishes served by the hospital located in *j,* $\boldsymbol{N}_j$.

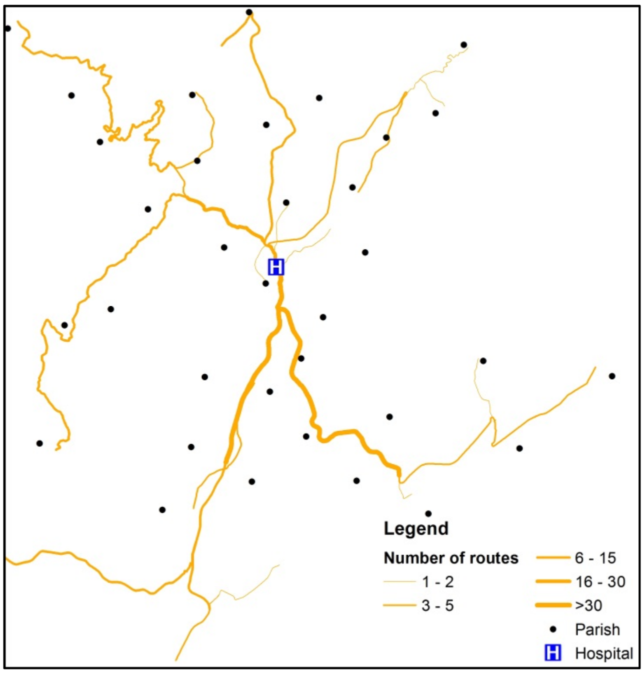


Figure 3-11: Number of routes per road segment

3.1.2.5 Interruption scenarios

In this work three scenarios are considered and in each, an individual link is interrupted, focusing the comparison of impacts across multiple criteria. The stated problems are: to discover if, in spite of the possible increase in terms of expenditure of time, there are other components that might minimize the consequences of the interruption; such as the possibility of the population in an interruption scenario being served by a hospital with better resources than they would normally have access to. Thus, the interruption scenario consequences will be evaluated in a hospital-focused perspective.

In an interruption scenario, an individual link, *a*, is completely removed; thus the gravity index will be as follows:

$$\overline{GI}_{j|a} = \frac{\sum_{i \in j} GI\_P_{i|a}}{\left|\boldsymbol{N}_{j|a}\right|} \tag{30}$$

where the $\overline{GI}_{j|a}$ is the gravity index of hospital j in a scenario where link a is interrupted, which is equal to the sum of the gravity index of all parishes allocated to hospital j ($GI\_P_{i|a}$) divide by number of elements in the set of parishes served by the that hospital in the case link *a* is interrupted*,* $\boldsymbol{N}_{j|a}$

The impact, *I*, of the interruption is assessed based on a comparison between a normal situation, $\overline{GI}_j$, and an interruption scenario, $\overline{GI}_{j|a}$, to each hospital as follows:

$$I = \overline{GI}_{j|a} - \overline{GI}_j \tag{31}$$

The Gravity Index is a compound index so the consequences of an interruption scenario will have to take into account the three different components of the index.

3.3. Structural- Functional Road Model (SFRM)

SFRM is calculated based on a link-focused basis, and is as follows:

$$SFRM_l = S_{W1} + F_{W2} \tag{32}$$

$$w1 = \frac{1}{\sum R} * (R_1 * ACV_1) \tag{33}$$

where $SFRM_l$ represents the Structural-Functional Road Model of the link represented by *l;* S is the results of the road structure assessment, based on the biclustering technique application; F_{W2} is the normalized results of the road functional assessment, based on the gravity model; R is the sum of the ranking algorithms; $w1$ is the weighting score of each bicluster; in equation 33 is shown the example for Bicluster 1 where R_1 is the value of the ranking algorithm of Bicluster 1; ACV_1 is the ACV value for Bicluster 1. The formula presented in equation 33 will be repeated for each bicluster.

Once the biclusters will be as homogeneous as possible, in the SFRM the roads that integrate the same bicluster will have the same weight.

The structural and functional component will be aggregated based on sum equation, which means that if, for instance, road *c* presents a null value concerning the functional component that won't mean that road *c* would be excluded from SFRM. In a normal scenario, road *c* presents a null value because is not part of any shortest path between any parish centroid and a Hospital, but can be an option in an interruption scenario of another road.

As in the previous phases, the classes will be organized based on the Standard Deviation (S.D.) from the average values [-1, 5 S.D., -0,5 S.D.[; [-0,5 S.D. , 0,5 S.D. [; [0,5 S.D., 1,5 S.D. [;> 1,5 S.D.

4. Case study

SFRM model is applied to the Central Region of Portugal and the municipality of Coimbra in a multiscale perspective (Figure 4-1). In this work the road network vulnerabilities are assessed based on an integrated approach of the structural and functional perspectives; despite being held together in an integrated approach, the structural and functional perspectives are different and separately evaluated based on different tools and methodologies. The presentation of the case study will be consistent with the methodological framework previously set up in this work. So, this chapter is organized in the following ways: firstly an overall characterization of the case study is presented; then the case study is presented in a structural and functional perspective.

Figure 4-1: Location of the case study area

The main goal of applying the model to real-world cases is to show its applicability and how it can be implemented. Still, there are several reasons that point Central Region of Portugal and the municipality of Coimbra as interesting case studies. Central Region of Portugal is an area marked by various asymmetries, which gives the chance to test the model as well as to identify areas that may need intervention.

The Central Region with 23 673 Km^2 and 78 municipalities; is an area full of contrasts, bordered by the Atlantic Ocean on one side and Spain on the other - the overland link to all other European countries. Throughout the work the name of the district capitals, such Aveiro or Coimbra, will frequently appear on the maps as a geographic reference. For several decades they have played an intermediate role between the national and local scale. This Region is also characterised by morphological contrasts in terms of lithological diversity, climate variability and extreme weather events. In addition, the demographic and socio-economic dynamics are differentiated by the heterogeneous nature of urban concentration and the varying potential of agricultural and forestry production, which determines the environmental framework (CCDRC, 2010).

The road network in the Central Region of Portugal is 4,573 km long (Figure 4-2). On the basis of a functional division (Table 4-1), both the municipal and urban municipal road networks were not considered on a regional scale. In the central region, the urban system is dominated by a small number of cities and an analysis of these in Figure 4-2 shows the importance of the municipality of Coimbra in this region. Furthermore, it is possible to identify differences in road network density between the Western and Eastern areas, which is certainly not the ideal solution for regions looking for a well-balanced road network capable of providing regional cohesion (Fernandes and Viegas, 1999).

The road network of the Central Region has two main functions: firstly to connect the North and South of Portugal and to connect the country with Spain and the European continent. Secondly, to establish regional connections based on an urban system, mainly concentrated in the Western zone. The road network used in this study (Figure 4-2) comes at regional scale from the Portuguese National Road Plan. In the road network spatial analysis the MAUP (Modifiable Area Unit Problem) is an ongoing issue; the arbitrariness in the definition of areal units can affect the results of a number of statistical analyses. MAUP has been recognized in the geographical literature (Openshaw, 1984) and consists of two closely related aspects: the scale problem and the zoning problem. The scale problem concerns changes in the results of spatial analysis with changing scale (usually grain size), whereas the zoning problem results from the variation of the results of spatial analysis due to different zoning systems or spatial configurations of areal units at the same scale (Wu et al, 2000). In this work to minimize MAUP some of the roads extend beyond the boundaries, as they are connected a few kilometres outside the boundaries of the case study.

Figure 4-2: Road hierarchy in Central Region

At local scale the road network used comes from the Cartography - scale 1. 10 000 - that was published by the Portuguese Geographic Institute and is used by the City Council for spatial planning purposes (Figure 4-3).

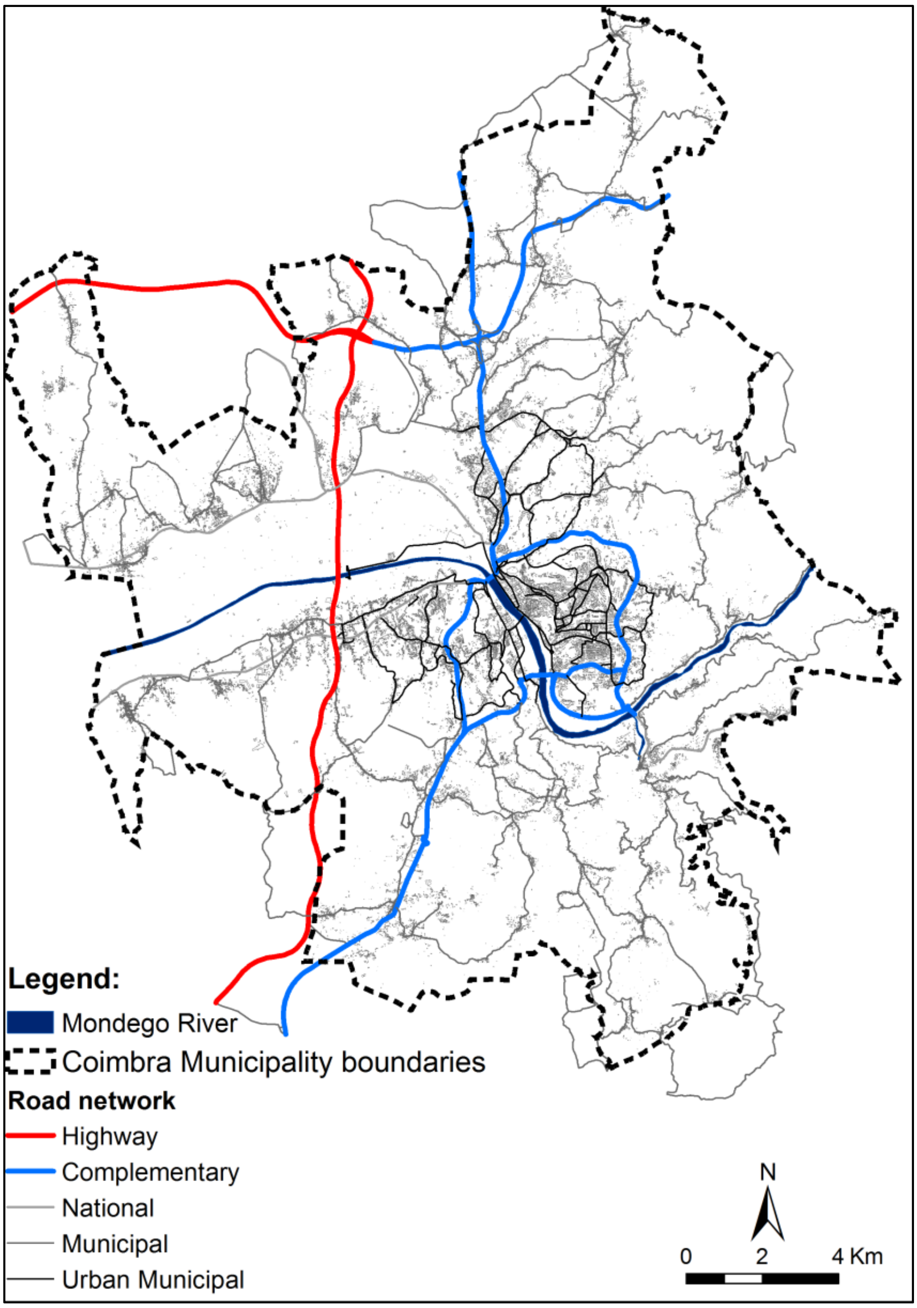


Figure 4-3: Road hierarchy in the Coimbra Municipality

The road network in the municipality of Coimbra is 509 km long and is mainly supported by the municipal road network (79%), whilst the remaining network is part of what may be classified as through traffic (Table 4-1). It therefore includes roads that operate on a regional and eventually a national level, but are connected and depend on local dynamics.

The scope of the data used and the scale of analysis should match, in order to establish proximity between the models and everyday decision-making. Still, multi-scale comparisons, disaggregating techniques and top–down versus bottom–up discussions are hard to imagine without a conceptual notion related to hierarchy (Fekete, 2010). This work recognizes the administrative hierarchies and the road hierarchies; both hierarchies are used by Portuguese institutions such as the Portuguese Geographic Institute and the Roads of Portugal. The roads are structured according to function: in the same network there are roads whose main function is to ensure connections between rural settlements within the district, as well as those whose main function is to ensure connections between the main cities in the country. Thus at regional scale only the roads that have a function at that scale are included, and the same principle is applied to the local scale. So, on the basis of these methodological premises, it was established that the municipal and urban municipal road networks should not be included in the regional analysis.

Table 4-1: Road hierarchy in percentage

Designation	Function	Regional		Municipal	
		Length (km)	%	Length (km)	%
Principal road network	Ensures connections between districts at national level	931	20	33	6
Complementary road network	Ensures connections between municipalities at district level	544	12	55	9
National road network	Ensures connections between municipalities at municipal and local level	3096	68	36	6
Municipal road network	Ensures connections between rural settlements in the municipality and between these rural settlements and the city			225	60
Urban municipal road network	Ensures connections inside the city			180	19

The main goal of distinct facilities is to provide highly differentiated services to a region. However, these facilities affect, and are affected by, local dynamics. Thus, throughout the work situations will appear where the regional scale will be compared to the local scale. The municipality of Coimbra, located in the Central Region of Portugal, fulfils the conditions for being a suitable case study, since it provides not one, but multiple health and education services to the entire region (CCDRC, 2010). Moreover, based on the analysis of Figure 4-2 and Figure 4-4, Coimbra is one of the most densely populated municipalities of the Region and plays an important regional role concerning the principal and secondary road network.

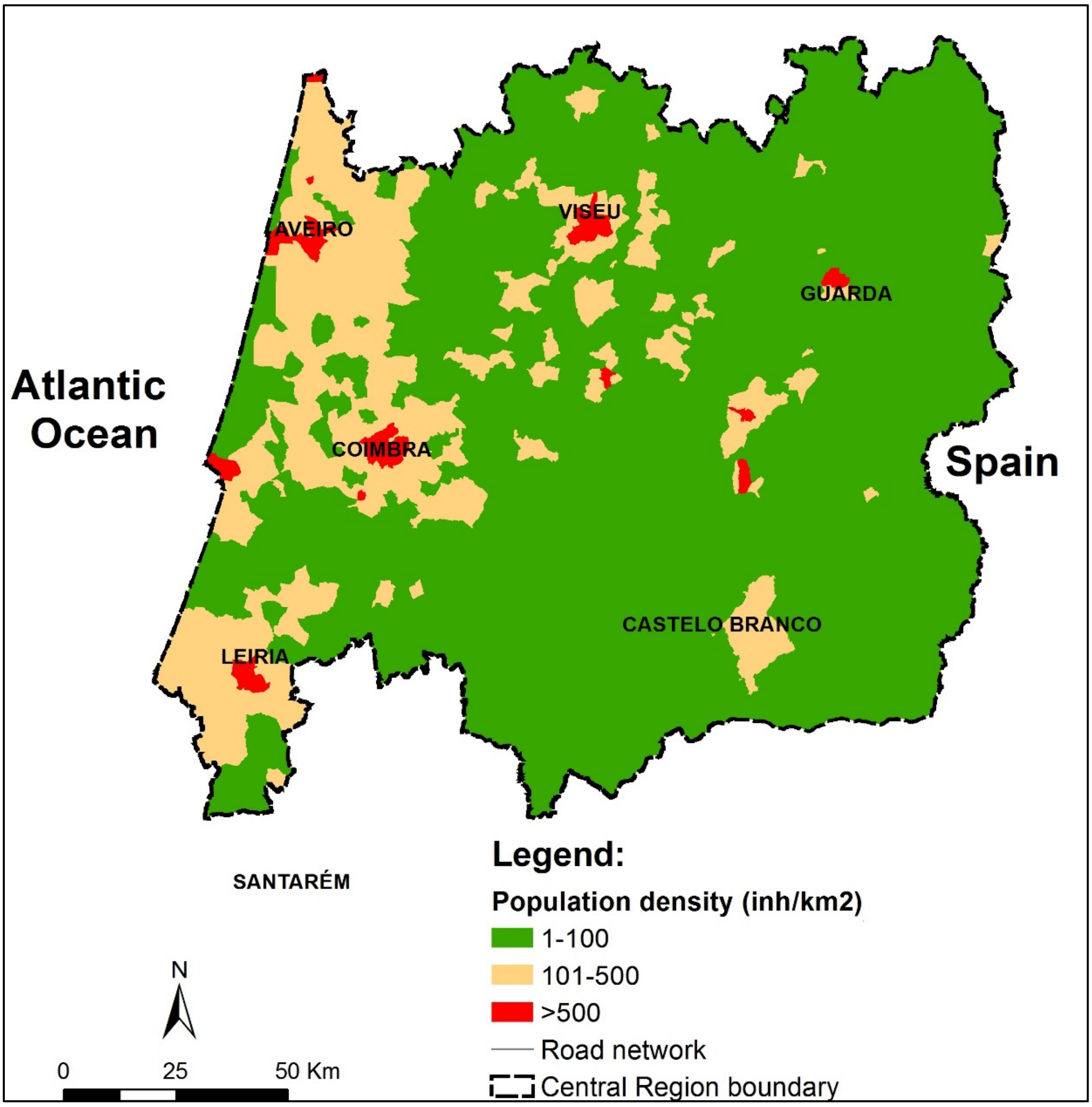


Figure 4-4: Population density in Central Region

In critical infrastructure management one of the most important criteria is the distribution of the population served by those infrastructures. The criteria used to analyse population density at parish level accords to the National Institute of Statistics terminology[2]: urban parish - a parish with a population density higher than 500 inhabitants per km^2 (inh /km^2); semi-urban parish – a parish with a population density between 500 inh/km^2 and 100 inh/km^2; a mainly rural parish – a parish with population density lower than 100 inhb /km^2. In the Central Region 80% of the area, which corresponds to 72% of the total number of the parishes, has a population density lower than 100 inhb /km^2; on the other hand only 1.4% of the area, which corresponds to 4% of the total number of the parishes, has a population density higher than 500 inhabitants per km^2.

From Figure 4-4 one can see that the urban parishes are essentially concentrated in the Western areas. The Eastern areas are dominated by mainly rural parishes. The results point to territorial inequalities in an area dominated by a low density population with only a small number of parishes presenting high population density. Based on the physical and human territorial characteristics such as the ones that were previously presented and on the NUTS (Nomenclature of Territorial Units for Statistics), CCDR (2011) has divided the Central Region into a set of territorial units (Figure 4-5).

The Coastal zone is the unit that which CCDRC (2011) points to as presenting a higher level of homogeneity in comparison to the rest of the Central Regional territorial units. It is also the larger unit in terms of area, population and has higher population density (Table 4-2). In a road network context the Coastal zone plays a very important role in the liaison between the two main Portuguese cities – Lisbon and Oporto.

Beira Alta is a geographical unity of rolling country: a line of hills with lower altitude parallel to the coast - Montemuro, Gralheira, Caramulo - and a second limited by Serra da Estrela. The North, Beira Alta is a corridor between the mountains Gralheira and Caramulo that, through the valley of the Vouga, establishes a connection to the coast. In

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[2] Source: www.ine.pt

the South, the contours of the Mondego Valley define the configuration of Estrada da Beira, the connection to Coimbra and the Beira Alta line.

The Central Rise referred to by CCDRC (2011) is the most important geographical feature in central Portugal and is composed of Serra da Estrela, Açor and Lousã; 48% of its area presents a slope of above 25%. In spite of these physical constraints, 16% of the total population of the Central Region lives in Central Rise (Table 4-2).

Figure 4-5: Territorial units of Central Region.
Source: CCDRC (2011)

Regardless of perceptive (human or physical) the Central Region is a territory marked by heterogeneities. Still, the most important issue is how those heterogeneities affect the population´s accessibility to critical infrastructure. The basic principle is that all the residents should have equal access to critical infrastructures; the stated question here is whether it is possible in an area with considerable asymmetries such as the Central Region. This issue is even more prominent in the current situation where the need of optimization of services provided by public funds is leading to the reduction of the number of units in critical infrastructures.

Table 4-2: Territorial units' characteristics

Designation	Area (km)	Population		
		Total (n)	Total (%)	Population density (n/km2)
Beira Alta	3489	307844	17,3	73,6
Beira Baixa	5123	157572	8,9	22,6
Beira Transmontana	4063	116267	6,5	23,4
Central Rise	5389	286113	16,1	37,2
Coastal zone	5610	909485	51,2	125,6

4.1. Case study – structural perspective

In the structural perspective each road network is transformed in an undirected graph consisting of nodes representing the individual streets and edges if the corresponding streets intersect. The road network of the Central Region is composed of 374 nodes and 766 edges. The road network of the municipality of Coimbra is composed of 504 nodes and 1,070 edges. The network at local and regional scale is characterized based on the following attributes, previously defined and explained: α, betweenness, *B* power, cluster index, cut point, degree and fragmentation.

On the basis of a matrix composed of a set of roads (in the rows) and their corresponding attributes (in the columns) the road network of the Central Region and, afterwards the municipality of Coimbra, are grouped in biclusters.

Once identified the most important biclusters at regional and local scale, the following phase is focused on how three different past events - road interruptions due to a flood, a forest fire, and a mass movement - affect access to hospitals from parish centroids and how the network reorganises in comparison to a normal scenario (Figure 4-6). The risk management framework the Central Region is problematic. According to the Regional Plan for Spatial Planning (CCDRC, 2010) there are zones in the region which have a high or very high level of susceptibility to natural hazards: floods – 3%; mass movement – 4%; forest fire – 40%. Indeed, the Central Region lies in an area which has experienced countless road interruptions over the years due to forest fires in summer and floods and mass movements in winter (PNPOT, 2007).

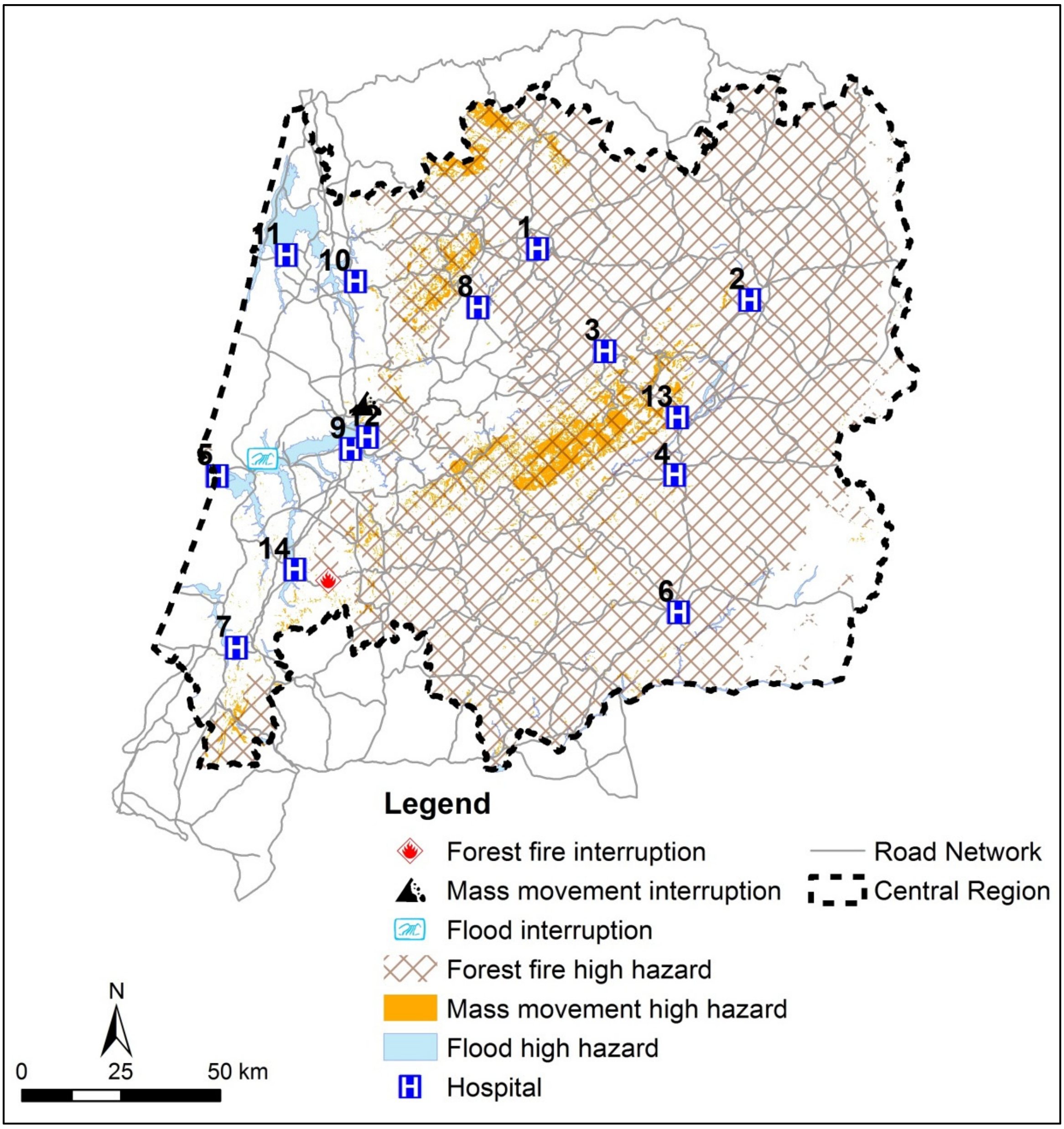

Figure 4-6: Roads' interruption and natural hazards

The scenarios analysed in this work were selected on the basis of a collection of news reports of interruptions due to natural hazards: one of the interruption scenarios was caused by a forest fire in 2012, the second by a mass movement in 2009, and the third by a flood that occurred in 2001 in an area highly susceptible to flooding (Figure 4-6). The interruptions that occurred in 2012 and 2009 were both located in areas that are highly susceptible to mass movements and forest fires. In neither case was this first time the roads had been disrupted due to events caused by natural hazards. In all cases, the main function of the roads that were disrupted was to ensure connections at national and district level, which means that they operate on a regional level.

In this phase the key point is how the road network reorganises on a regional and local scale in an interruption scenario, which involves assessing how road interruptions affect access between the parish centroids and the district hospitals. Factors such as an ageing population which requires more health care services and affects the accessibility of health care, are featuring increasingly in the public agenda.

4.2. Case study - functional perspective

The aim of the functional analysis of the network is to identify the most important roads defined as the ones which provide higher levels of access to critical infrastructures in a network. The problem focuses on the road links between parish centroids and district hospitals, of growing concern in the public agenda, due to factors such as ageing populations which require more health services, which in turn affect access to health care. The proposed model was applied to the 1,129 parishes – each one will represent a point of origin - and 14 district hospitals – each one will represent a point of destination - located in the Central Region (Figure 4-7). The parishes are the lowest administrative level in Portugal and therefore the closest to the needs of the population. According to the Portuguese Directorate General of Health, district hospitals are defined as medical facilities that provide basic services, although they may also offer intermediate, specific and, in exceptional situations, highly specialised services. These medical services have responsibilities within the sub-region where they operate. In the case study in a functional perspective road sections beyond the case study boundaries are not considered, unlike what happens in the case study from a structural perspective. This can be considered an example of how spatial data should match the purpose of analysis; in the structural perspective the focus is on issues such as the network’s cohesion.

Functional perspective is different from structural perspective. In the former there is a specific Origin (Parish) and Destination (Hospital) all within the case study and even after carrying out some tests, it was concluded that there was no need to include in the model road sections outside the case study. Based on this problem simulated scenarios of road interruption and the consequences of those interruptions for the accessibility to hospitals will be analysed.

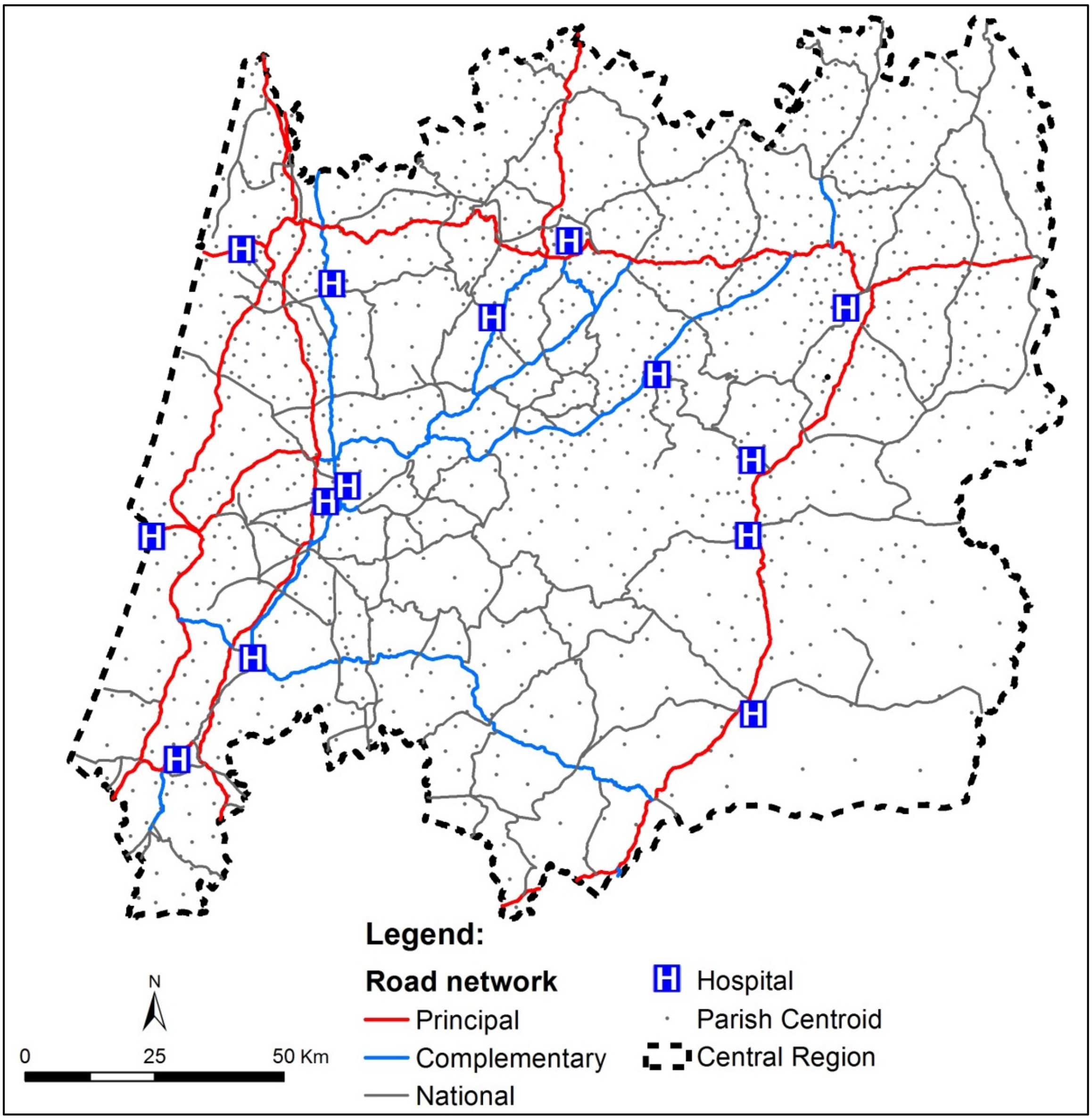

Figure 4-7: Case study – functional perspective

The Central Region is also an interesting case study from the point of view of its physical characteristics, 5% of the total road network presents a sinuosity index higher than 0.5 and 55% of the area presents a slope of over 10% (Figure 4-8), so the sinuosity index values were evinced as a suitable indicator to classify the impedance factor. Along with sinuosity, slopes are an important variable in accessibility and physical constraints (Table 4-3). In the Central Region 25% of the area presents a slope below 2%, 55% of the area presents a slope above 10% (in that area 8% presents a slope above 45%). Analysis of Figure 4-8 clear shows a contrast between the Coastal zones dominated by slopes below 2% and the Central Rise dominated by slopes above 10%.

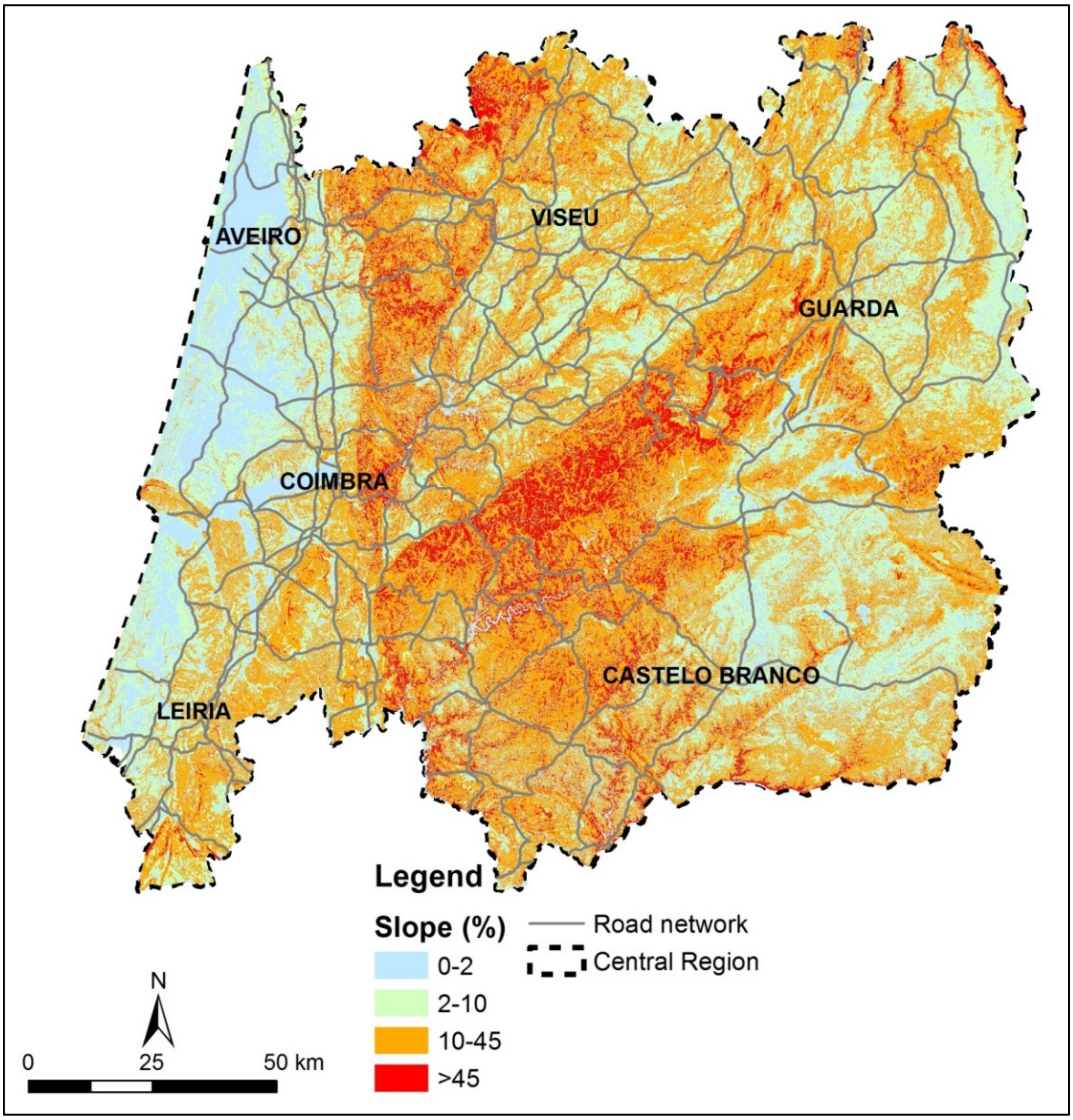

Figure 4-8: Slope in Central Regional

One of the questions is how important are these values for the road network. In a first approach, comparing the intersection of the slope values with the road distribution, it was verified that 47% of the roads' length is located in areas where the average slope is above 10%.

Table 4-3: Slopes in Central Region

Classification (%)	Area (km)	%
0-2	5 955	25
2-10	4 789	20
10-45	11 408	47
>45	1 889	8

5. Results

The purpose of this research is to propose a model, Structural Functional Risk Model - SFRM, which allows identifying the most vulnerable roads in the road network. The road network of the Central Region and of the Municipality of Coimbra in a multiscale perspective is used to demonstrate the application of the model. This exercise demonstrates its application of the model as outlined in the flow chart for its implementation as previously shown in the Methodology chapter of this work; this exercise also demonstrate how SFRM can be a useful tool for critical infrastructure risk management.

5.1. Structural component

This chapter is focused on presenting the results of the road network risk concerning the structural component (Figure 5-1).

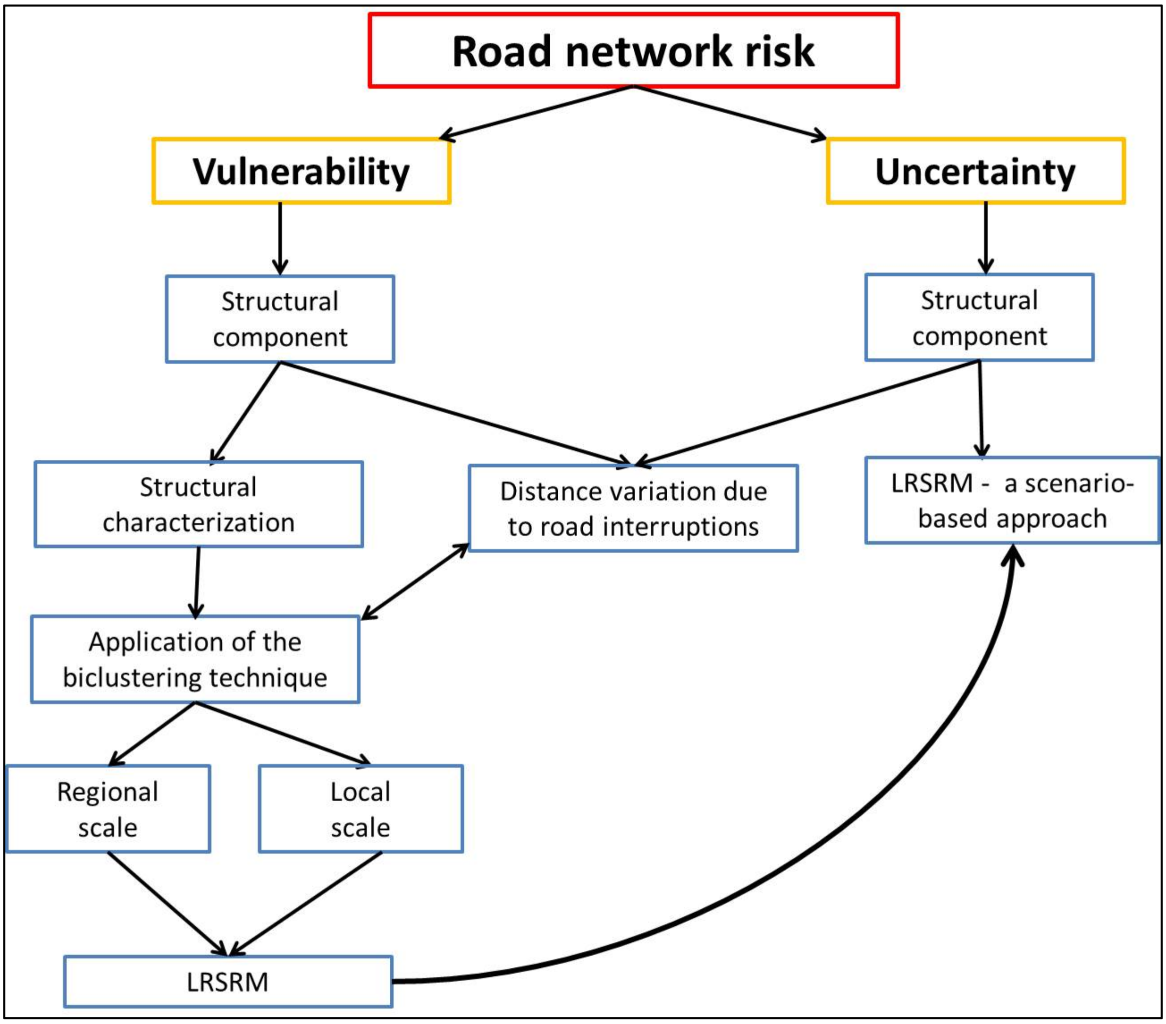

Figure 5-1: Structural component – results' framework

The main focus will be in the assessment of the road network vulnerabilities at regional and local scale based on the application of the biclustering technique, which results will be compared with the network scan results. The uncertainty component will be addressed in a scenario-based approach. The vulnerability and uncertainty component are interconnected; the network scan will be useful in vulnerability and uncertainty analysis and also LRSRM results will be useful addressing a scenario-based approach.

The results obtained at this phase allow showing that a good road network vulnerability assessment can contribute to diminish the uncertainty levels involved in the consequences of harmful events.

5.1.1. Structural characterization of the network

In the analysis of the results of the network structural characterization, it is important to have in mind the following network analysis principles set by Wasserman and Faust (1994):

- Roads are interdependent rather than independent, autonomous units;
- Relational ties (linkages) between actors are channels for transfer of flow;
- Network models focusing on individuals view the network structural environment as providing opportunities for or constraints on network flow;
- Network models conceptualize structure as lasting patterns of relations among actors.

The starting point for the structural characterization of the network was an adjacency matrix. Table 5-1 shows a small example extracted from adjacency matrix of the Central Region road network, where each road has an ID and whenever each pair of roads are connected the result will be 1. In the example Road 1 is the road with more connections, which means that has a higher degree value than roads such Road 8. Still, that does not mean that Road 1 is the most important of the eight roads, there are more variables that must be considered, as it will demonstrated in the next phase.

Table 5-1: Adjacency matrix- example extracted from adjacency matrix of the Central Region road network

	ID	Roads							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Roads	**1**	0	0	1	1	1	0	1	0
	2	0	0	1	0	0	0	0	0
	3	1	1	0	1	0	0	0	0
	4	1	0	1	0	0	0	0	1
	5	1	0	0	0	0	0	1	0
	6	0	0	0	0	0	0	0	0
	7	1	0	0	0	1	0	0	0
	8	0	0	0	1	0	0	0	0

In a first approach there were considered seven attributes, although the attributes that were appropriate for a regional scale were not the same as those appropriate for a local scale, and vice-versa. Attributes such as degree and *b* power are not redundant on a local scale but present a high level of redundancy on a regional scale (Figure 5-2). Thus, *b* power was excluded from the regional analysis. The magnitude of *b* power reflects the radius of power; small *b* values weight local structures, whereas larger values weight global structures. If the *b* power is positive, the ego has greater centrality when tied to roads that are central. Conversely, if the *b* power is negative, the ego has greater centrality when tied to roads that are *not* central. As *b* power approaches zero, it becomes the same as degree centrality (Borgatti, 2005). The level of redundancy between *b* power and degree is a good example of the importance of spatial extent analysis.

Degree centrality is based on the idea that important nodes have the largest number of adjacent nodes (Erath et al, 2009). In road network analysis this means that important roads have the largest number of adjacent roads. On a regional scale an interesting pattern emerges (Figure 5-3(A)), from which it is possible to distinguish between centralities (high values) and peripheries (low values). Degree was considered a useful variable to be in local and regional scale.

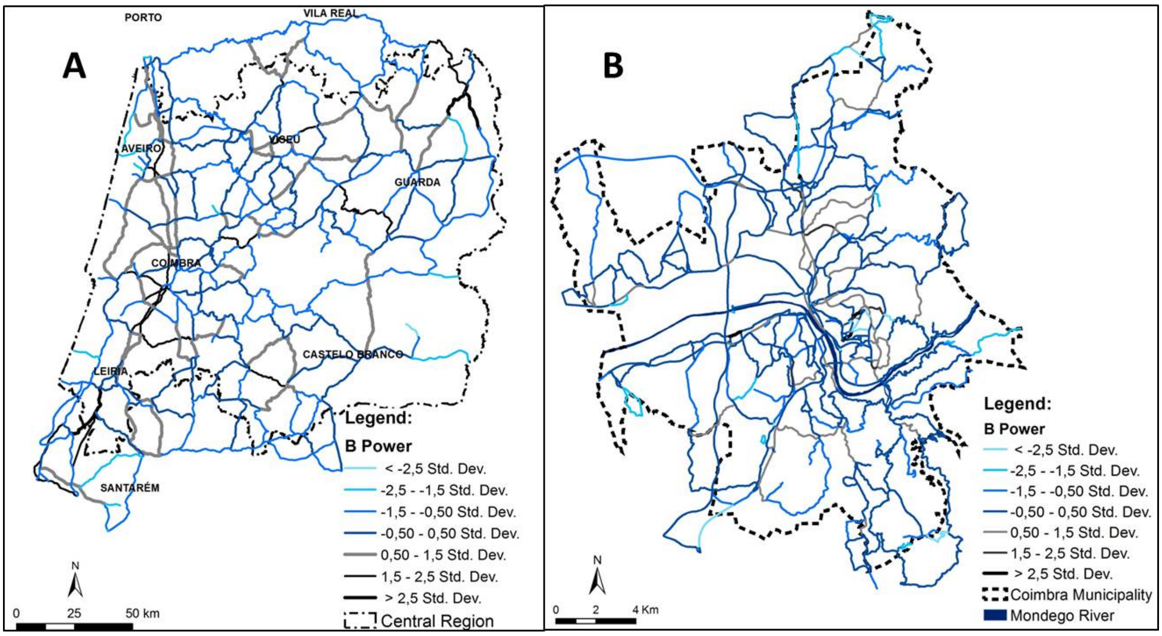

Figure 5-2: (A) B power at regional scale. (B) B power at local scale.

B power and degree are redundant at regional scale but can be complementary at local scale; road *d* can be pointed as an example of that complementarity at local scale, which presents a degree value above the local average and a *b* power value below the local average (Figure 5-4). Road *d* is connected to several roads; thus it presents a degree above the average, but the roads to which road *d* is connected have degree and *b* power below the local average, thus road *d* has a b power below the local average.

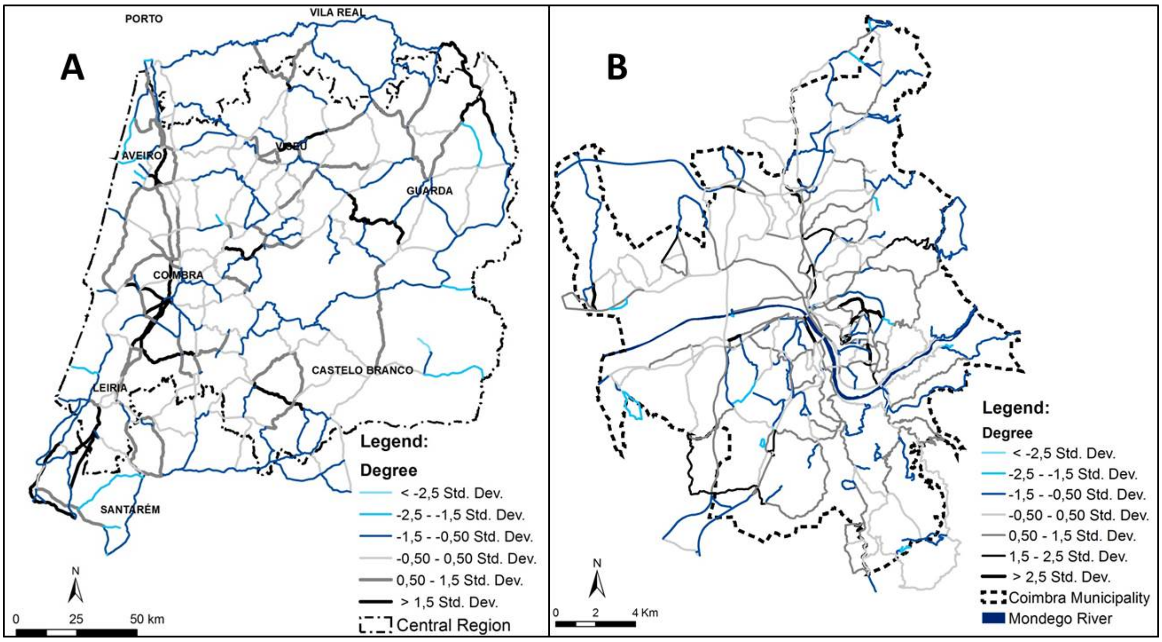

Figure 5-3: (A) Degree at regional scale. (B) Degree at local scale.

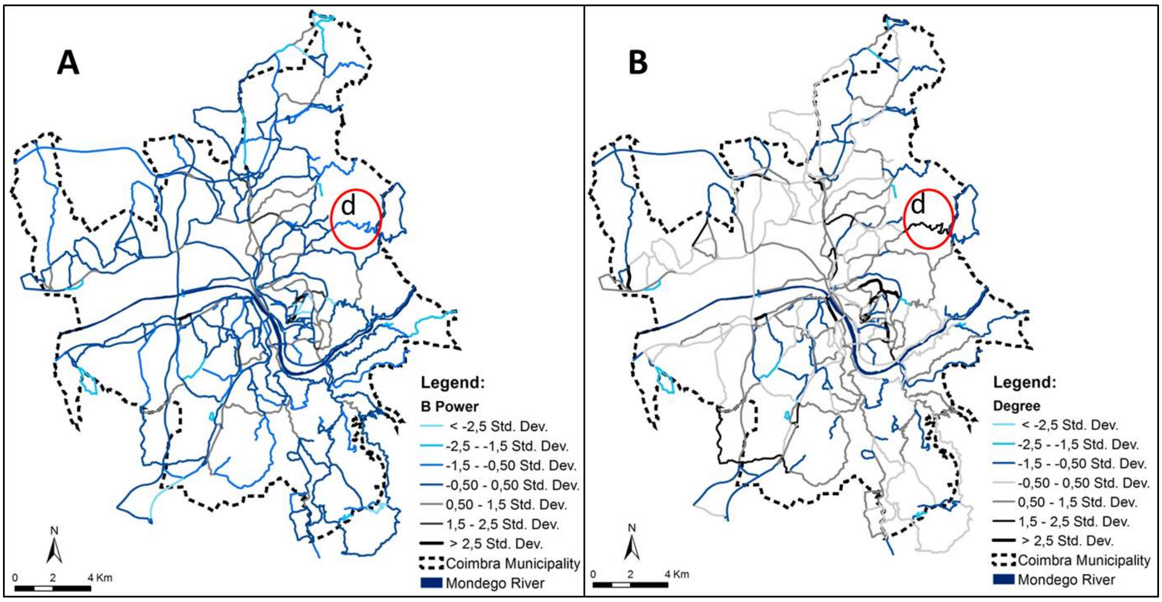

Figure 5-4: (A) *B* power at local scale. (B) Degree at local scale.

Betweenness, defined as the proportion of shortest paths between every pair of links that pass through a given link *l* towards all the shortest paths (Demsar et al, 2008), is an attribute that presents similar patterns, but not redundant, at local and regional scale. On a local scale (Figure 5-5 (B)) it identifies the main accesses to the city, whilst on a regional scale (Figure 5-5 (A)) it identifies the main accesses to 4 of the 6 major cities in the region; furthermore, 58% of the roads' length with 1.5 S.D. higher than the regional average is a highway or a complementary road. Analysing Figure 5-5 (A), it can be seen that the loads are concentrated in a small number of roads, and a division between the Eastern and Western sides of the region is evident.

Alpha (α) is based on the relation between the number of circuits that each road is part of and the maximum number of circuits. The higher the α values the higher the level of network optimization level. In Figure 5-6 (C) is shown an example of roads with α values above the average where is possible to identify closed circuits, there are roads that take part in more than one closed circuit. One of the questions is if the interruption of roads with high α values can cause bigger consequences in the network flow than the interruption of roads with low α values. In a first approach, α index appears a suitable variable to assess the network performance at regional Figure 5-6 (A) as well as at local scale Figure 5-6 (B).

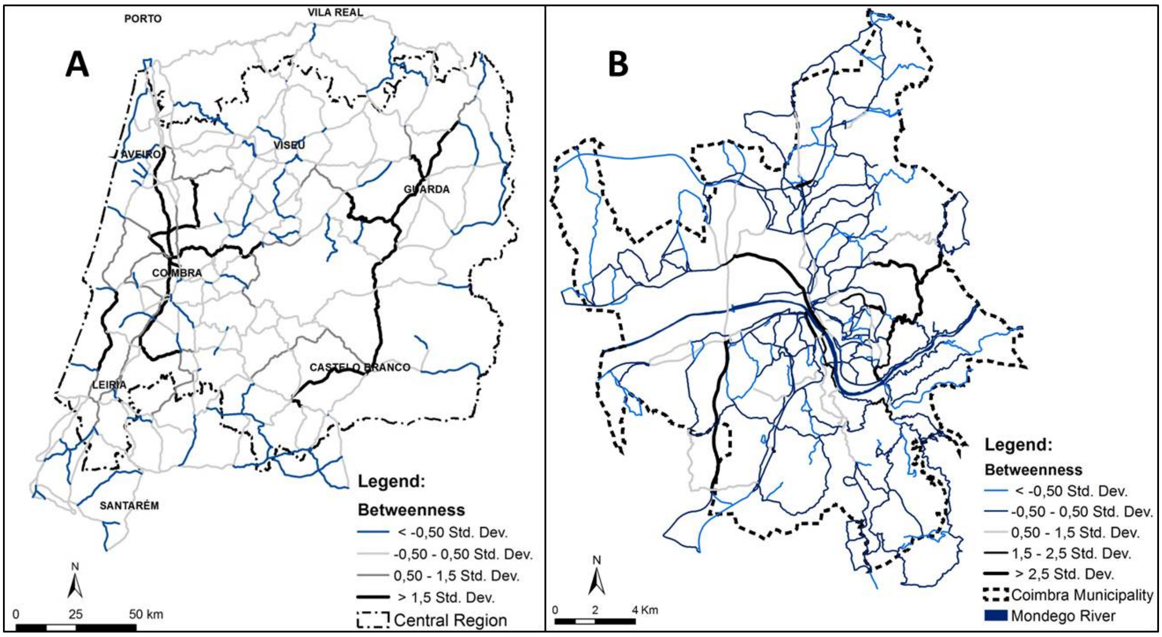

Figure 5-5: (A) Betweenness at regional scale. (B) Betweenness at local scale.

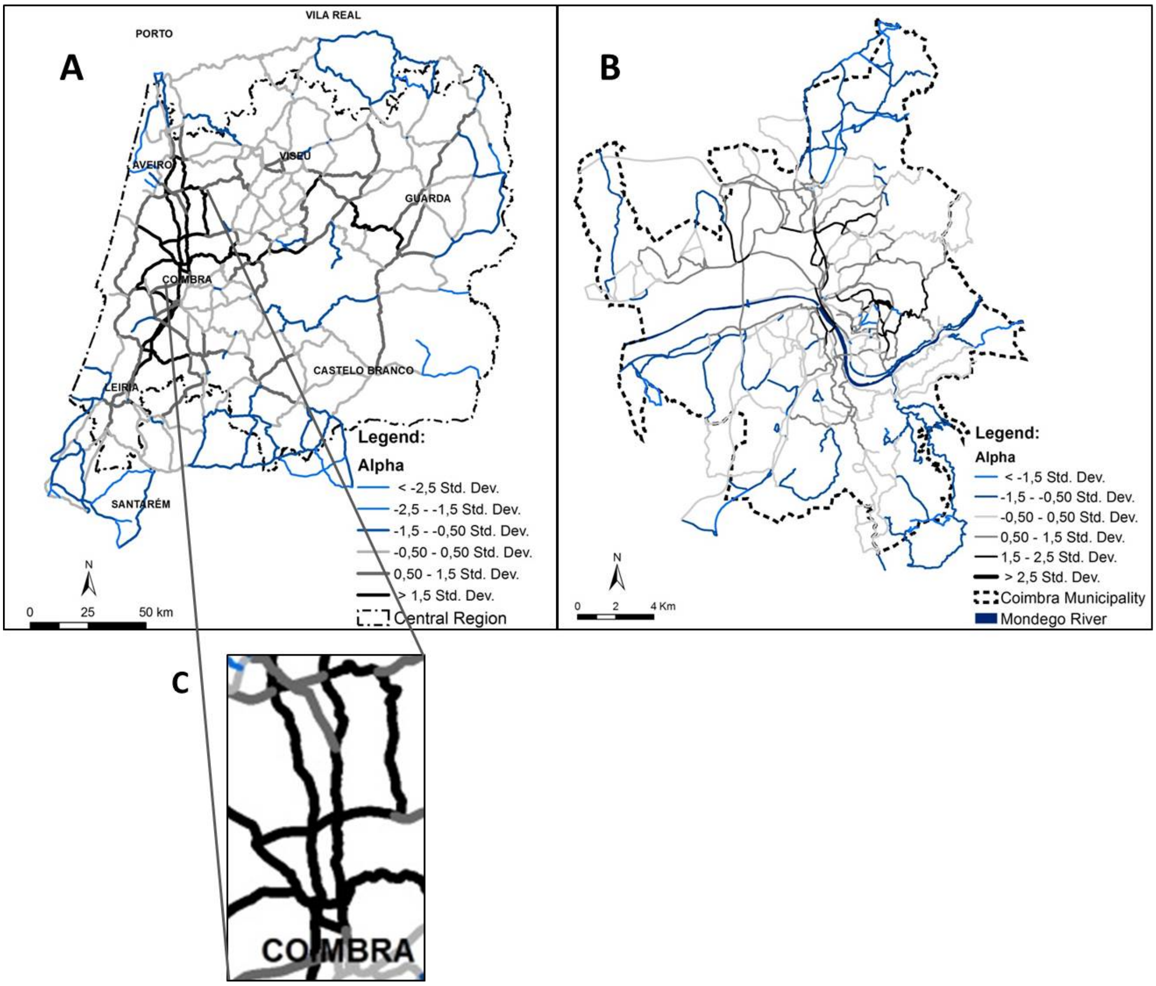

Figure 5-6: (A) Alpha at regional scale. (B) Alpha at local scale. (C) Alpha at regional scale – detail.

To sum up, each attribute may provide a different contribution. Degree can be useful in identifying areas with high levels of attractiveness, and betweenness can identify roads with higher loads and, on a regional scale, those which connect to cities with closer relations.

The results indicate that there must be compatibility between the purpose of the work and the variables used in the analysis. Each variable can provide a different perspective on the theme under discussion. If the purpose of the work is to evaluate network cohesion, attributes such as the clustering coefficient should probably be taken into account. Thus the same set of attributes cannot be used on local and regional scales. The regional network structure is guided by different rules in comparison to the local network structure, which demands different strategies in public policies such risk management or spatial planning.

5.1.2. Application of biclustering technique – regional scale

The biclustering technique was applied to a matrix of seven attributes (columns) and 374 roads (rows). A bicluster with high homogeneity in expression values should have a low MSRS and a high ACV. After running several experiments, the algorithm with the following parameters was selected: noise threshold - 1; minimum number of rows in percentage - 10; minimum number of columns - 5 and maximum bicluster overlap in percentage - 10. The application of this formula resulted in an average MSRS of 0.02 and an average ACV of 0.99, comprising 4 biclusters, despite extensive testing 9% of the roads remained unclassified (Table 5-2). A bicluster with high homogeneity in expression values should have a low MSRS and a high ACV; at the regional scale all the 4 biclusters present MSRS values quite low and ACV values very high. Still, to go further than the homogeneity values it is necessary to identify the most significant variables in the biclusters connectivity patterns.

In the exploratory regression analysis, the α index was significant in 100% of the test performed and the degree was significant in 64%. The correlation value of the model is $R^2 = 0.6$. The Collinearity statistics indicate that there is not multicollinearity among the variables, which means that are suitable for analysis (Table 5-3).

Table 5-2: Biclusters' characteristics- regional scale

Designation	Composition (roads*attributes)	Quality criteria		Length	
		MSRS	ACV	km	%
Bicluster 1	61*5	0.001	0.997	900	20
Bicluster 2	20*5	0.012	0.998	247	5
Bicluster 3	43*5	0.017	0.987	387	9
Bicluster 4	215*5	0.042	0.990	2625	57
Unclassified	-	-	-	414	9
Total	-	-	-	4573	100

Table 5-3: Collinearity Statistics at regional scale

Variables	**Collinearity Statistics**	
	Tolerance	**VIF**
Alpha (α)	0.599	1.67
Clustering Coefficient	0.908	1.10
Degree	0.632	1.58

Once identified the most relevant variables, the next phase will be focused in the analysis of each bicluster, in order to identify homogeneities in each bicluster and heterogeneities among the biclusters; taking into account that in this work an additive model is used: each pair of rows has the same difference in all the related columns or each pair of columns has the same difference in all the related rows. In Table 5-4 is possible to find perfect biclusters, the difference between C3-C5 and C3-C6 are equal. Regression analysis points degree, α and clustering coefficient as the most relevant variables in biclusters' connectivity patterns, so as expected, variables such betweenness are irrelevant. However, in real networks is not always possible to find perfect biclusters, thus it is necessary to include in the formula the error and a threshold, in this case, a value lower than the MSRS.

Assuming that the biclusters with the highest mean values concerning the most significant variables correspond to the bicluster with higher levels of connectivity, the question is which of them present the highest mean values and which present the lowest mean values. Analysing Table 5-5 there is Bicluster 1 and Bicluster 2 with highest mean values and in other hand there is Bicluster 3 with the lowest mean values concerning degree and α values. The highest mean values of degree and α correspond to the lowest mean values of clustering coefficient and vice-versa. Concerning the Connectivity Index Bicluster 2 presents the highest mean values and Bicluster 3 presents the lowest mean values.

Table 5-4: Bicluster's connectivity patterns example extracted from Bicluster 1

Road ID	C1 Degree	C2 Betweenness	C3 α	C4 Clustering coef.	C5 Cutpoint	C6 B Power	C1-C2	C1-C3	C2-C3	C3-C4	C3-C5	C3-C6
1	6	1024	8.0	0.1	0.0	6.0	-1018	-2.0	1016	7.9	2.0	2.0
14	6	580	10.6	0.4	0.0	6.0	-574	-4.6	569	10.2	4.6	4.6
23	6	1455	12.0	0.4	0.0	6.0	-1449	-6.0	1443	11.6	6.0	6.0
35	6	1889	10.6	0.5	0.0	6.0	-1883	-4.6	1878	10.1	4.6	4.6
56	6	986	10.1	0.3	0.0	6.0	-980	-4.1	976	9.8	4.1	4.1
69	6	7536	13.8	0.2	0.0	4.0	-7530	-7.8	7522	13.6	9.8	9.8
71	6	2935	12.0	0.3	0.0	5.0	-2929	-6.0	2923	11.7	7.0	7.0
80	6	2476	12.2	0.5	0.0	6.0	-2470	-6.2	2464	11.7	6.2	6.2
93	6	2275	14.2	0.5	0.0	6.0	-2269	-8.2	2260	13.7	8.2	8.2
95	6	1690	12.3	0.4	0.0	6.0	-1684	-6.3	1678	11.9	6.3	6.3
96	6	3423	13.5	0.5	0.0	6.0	-3417	-7.5	3410	13.0	7.5	7.5
97	6	631	13.9	0.5	0.0	6.0	-625	-7.9	618	13.4	7.9	7.9
99	6	362	12.3	0.5	0.0	6.0	-356	-6.3	350	11.9	6.3	6.3
133	6	10952	12.5	0.3	0.0	6.0	-10946	-6.5	10939	12.3	6.5	6.5
136	6	4341	16.3	0.4	0.0	6.0	-4335	-10.3	4325	15.9	10.3	10.3

Table 5-5: Significant variables in biclusters connectivity patterns – regional scale

Designation	Degree		α Index		Clustering coefficient		Connectivity Index	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Bicluster 1	6	0	12	1.8	0.4	0.4	2.9	0.03
Bicluster 2	7	0.4	12	2.5	0.5	0.1	3.5	0.27
Bicluster 3	3	0	8	1.4	0.7	0.3	1.1	0.09
Bicluster 4	5	0.5	10	1.8	0.4	0.3	2	0.3
Unclassified	4	2.3	8	3.2	0.7	0.1	-	-

The analysis of Table 5-2, Table 5-5 and Figure 5-7 show that there is a positive and high correlation between the variables more significant in the biclusters connectivity patterns and the ACV values, which indicate that the higher the ACV value of the bicluster, the higher the connectivity attributes of the roads that integrate that same bicluster will be. Thus Bicluster 1 and Bicluster 2 integrate the roads with highest level of connectivity and Bicluster 3 and Bicluster 4 integrate the roads with the lowest level of connectivity. Also the results of the ranking algorithm point Bicluster 2 as the one that integrates the roads with highest levels of connectivity and Bicluster 3 as the bicluster that integrates the roads with the lowest levels of connectivity (Table 5-6). Moreover, in Table 5-5 is evident that the unclassified group presents the highest standard deviation, which is an indicator of a high heterogeneity of this group and corroborates the assumption that this group cannot be used.

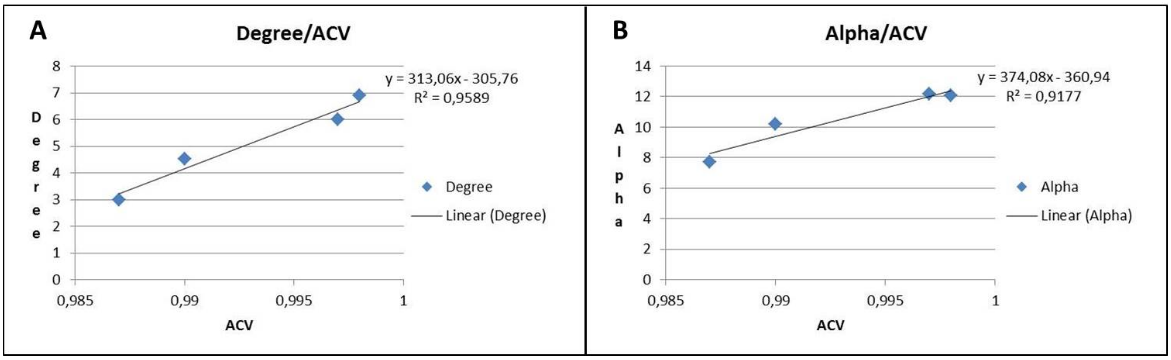

Figure 5-7: (A) Correlation between degree and ACV. (B) Correlation between Alpha and ACV.

Table 5-6: Ranking algorithm – results at regional scale

Designation	Ranking
Bicluster 1	2
Bicluster 2	1
Bicluster 3	4
Bicluster 4	3

The cartographic representation of the results allows confirming the results of the previous analysis; Bicluster 3 previously identified as the bicluster that integrates the roads with lowest level of connectivity corresponds in the Figure 5-8 to dangle roads, in several cases located in the most peripheral zones of the Region; on other hand there is Bicluster 2 where is possible to identify cases where the roads that integrate this Bicluster presents several connections.

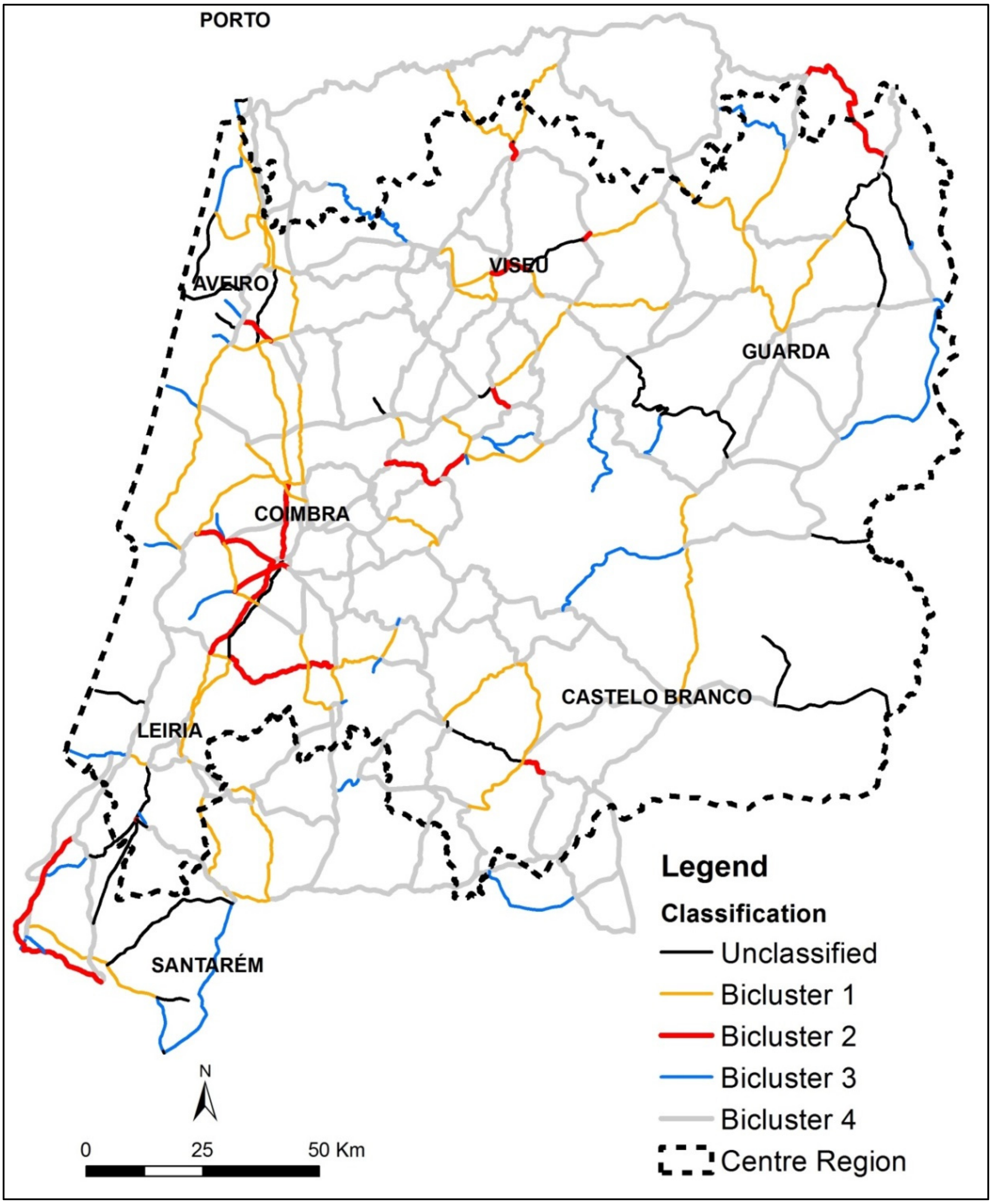

Figure 5-8: Cartographic representation of Biclusters – regional scale

Figure 5-8 and Table 5-7 show that the biclusters distribution is territorial. Analysing Table 5-11 shows that 61% of the roads' length of Bicluster 2 is located in the Coastal zone, on other hand 33% of the roads' length of Bicluster 3 is located in Beira Transmontana. Results point for a trend according to what the Biclusters with highest connectivity are mainly located in the Coastal zone and the Biclusters with lowest connectivity are located in inland zones such Beira Transmontana and Central Rise.

Table 5-7: Bicluster per territorial unit (roads' length percentage)

Designation	**Beira Alta**	**Beira Baixa**	**Beira Transmontana**	**Central Rise**	**Coastal zone**	**Total**
Bicluster 1	17.6	6.5	12.2	21.7	41.9	100
Bicluster 2	13.1	0.0	6.7	19.5	60.7	100
Bicluster 3	5.1	13.9	32.7	18.9	29.4	100
Bicluster 4	21.9	11.5	12.5	31.7	22.4	100

At this point one of the questions is if the functional road hierarchy influences or is influenced by the road connectivity, for instance do the national roads present a higher level of connectivity than the rest of the roads? Analysing the data in Table 5-8 it can be concluded that the roads that integrate Bicluster 3 are almost all national. Still, the results don't allow establishing clear relations between the level of connectivity of the bicluster and the functional hierarchy. In the case of Bicluster 2, the bicluster that integrates the roads with higher level of connectivity, 37% of its roads' length is highways and 40% are national roads; it is an example as it is not possible to establish relations the functional hierarchy and the connectivity. It will be interesting to explore these relations at local scale, once there are involved more functional hierarchies' and more significant contrast between rural and urban typologies.

Table 5-8: Percentage of the roads' length per hierarchical function – regional scale

Designation	**Percentage of the roads' length**			
	Highway	**Complementary**	**National**	**Total**
Bicluster 1	38	12	50	100
Bicluster 2	37	23	40	100
Bicluster 3	3	0	97	100
Bicluster 4	17	12	71	100

5.1.3. Application of biclustering technique – local scale

On a local scale after running several experiments the following parameters were considered best: noise threshold - 2; minimum number of rows in percentage - 5;

minimum number of columns – 5; maximum bicluster overlap in percentage – 15. The application of biclustering technique resulted in 6 biclusters (Table 5-9); despite extensive testing 24% of the roads remained as unclassified.

In Table 5-9 the MSRS values of Bicluster 1 and Bicluster 6 may seem high – MSRS = 0.29, however they also present high ACV values, 0.98 and 0.96, respectively. It is interesting to notice that smaller biclusters doesn't mean higher ACV values. Furthermore the percentage of roads' length that is integrated in each bicluster is very wide; in one hand there is Bicluster 1 with 30% and in other hand there is Bicluster 5 with 3%. Summing up, Bicluster 1 and Bicluster 4 presents the highest ACV values, on other hand Bicluster 3 and Bicluster 5 presents the lowest ACV values (Table 5-9).

On the basis of exploratory regression analysis it was possible to verify that α Index was significant in 100% of the tests performed, *b* Power and Degree were significant in 44% and 33% of the tests, respectively, α Index focus on the role played by each link in the number of closed circuits in the network and Degree focus the number of direct connections a links has to other links in the network. Neither α Index nor Degree indicates the strength of connectivity of road networks, *b* Power conquers this disadvantage. The Collinearity statistics indicate the inexistence of multicollinearity among the variables, all the VIF values are lower than 5 and the tolerance values are higher than 0.2 (Table 5-10).

Table 5-9: Biclusters' characteristics- local scale

Designation	Composition (roads*attributes)	Quality criteria		Length	
		MSRS	ACV	Km	%
Bicluster 1	179*7	0.29	0.98	179	30
Bicluster 2	82*7	0.26	0.96	117	20
Bicluster 3	29*7	0.18	0.92	44	8
Bicluster 4	35*7	0.23	0.98	26	5
Bicluster 5	20*7	0.17	0.92	15	3
Bicluster 6	29*5	0.29	0.96	56	10
Unclassified	-	-	-	137	24
Total	-	-	-	574	100

Table 5-10: Collinearity Statistics – local scale

Variables	**Collinearity Statistics**	
	Tolerance	**VIF**
Alpha (α)	0.59	1.68
Β Power	0.43	2.33
Degree	0.47	2.12

As in the regional scale, it is assumed that the biclusters with the highest mean values concerning the most significant variables correspond to the bicluster with higher levels of connectivity, the question is which biclusters present the highest mean values and which present the lowest mean values. Analysing Table 5-11 the Bicluster 4 appears as the bicluster with highest Connectivity Index; it presents the highest mean values in all the variables; Bicluster 5 is the bicluster with the lowest Connectivity Index.

Table 5-11: Significant variables in biclusters connectivity patterns – local scale

Designation	**Bonacich Power**		**Alpha Index**		**Degree**		**Connectivity Index**	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
Bicluster 1	3.8	0.7	8.4	1.3	4.2	0.7	6.5	1.0
Bicluster 2	3.8	0.8	5.6	1.1	4.4	0.6	4.4	0.8
Bicluster 3	2.1	0.7	4.1	0.8	2.2	0.8	3.2	0.7
Bicluster 4	4.4	0.7	10.2	1.1	5.5	0.6	7.8	0.8
Bicluster 5	2.8	0.6	2.9	0.5	3.5	0.6	2.3	0.4
Bicluster 6	2.8	0.9	5.2	1.1	4.1	1.9	4.1	0.8
Unclassified	3.3	1.8	7.6	4.3	4.2	2.2	-	-

Among the lowest values there is Bicluster 5 and Bicluster 3 which represent 11% of the network length (Table 5-9). Bicluster 4 corresponds to 5% of the road network length, only a small portion of the roads have the highest connectivity values of the network. The unclassified group, although presenting values close to the average connectivity values, cannot be considered because is very heterogeneous; in all cases the unclassified group presents the highest values concerning the standard deviation (Std. Dev.).

Figure 5-9 point a strong positive correlation between the variables more significant in the biclusters' connectivity patterns and the ACV values; which indicate that the higher the ACV value of the bicluster, the higher the connectivity attributes of the roads that integrate that same bicluster will be.

The results of the ranking algorithm (Table 5-12) are consistent with the results of Table 5-9 and Table 5-11. Summing up, results point Bicluster 4, followed by Bicluster 1, as the biclusters that integrate the roads with highest levels of connectivity and indicate Bicluster 5, followed by Bicluster 3, integrate the roads with the lowest levels of connectivity.

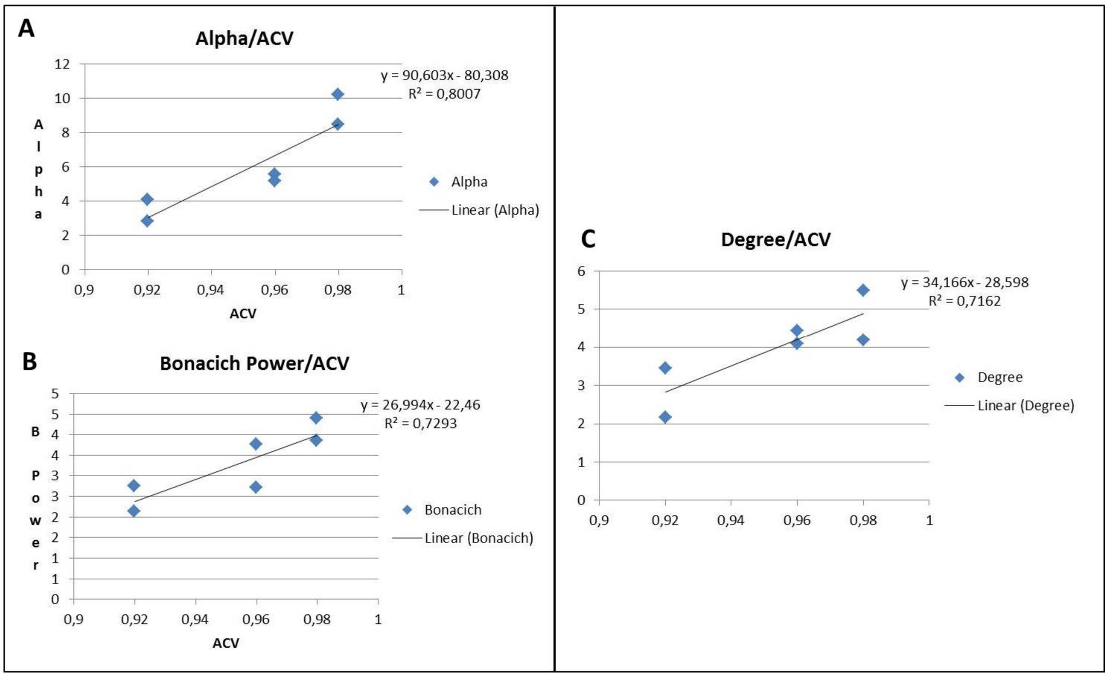

Figure 5-9: (A) Correlation between Alpha and ACV. (B) Correlation between Bonacich Power and ACV. (C) Correlation between Degree and ACV.

Table 5-12: Ranking algorithm – results at local scale

Designation	Ranking
Bicluster 1	2
Bicluster 2	3
Bicluster 3	5
Bicluster 4	1
Bicluster 5	6
Bicluster 6	4

The results of cartographic representation allow identifying the importance of the closed circuits with particular relevance for the roads located in the city and that integrate Bicluster 4. In Figure 5-10 the roads in Bicluster 3 are evinced as dangle roads or roads with a low level of connectivity. However, some of those dangle roads are caused by the segmentation of the links by the municipality's boundaries.

In local scale the MAUP (Modifiable Area Unit Problem) effect is stronger than in regional scale; it can be pointed as an example the road marked with an A in Figure 5-10, a road that is a highway that at regional scale presents a high level of connectivity, but a low level of connectivity at local scale where at West side it appears to be just a dangle road. It is an example that results analysis should take into account the scale.

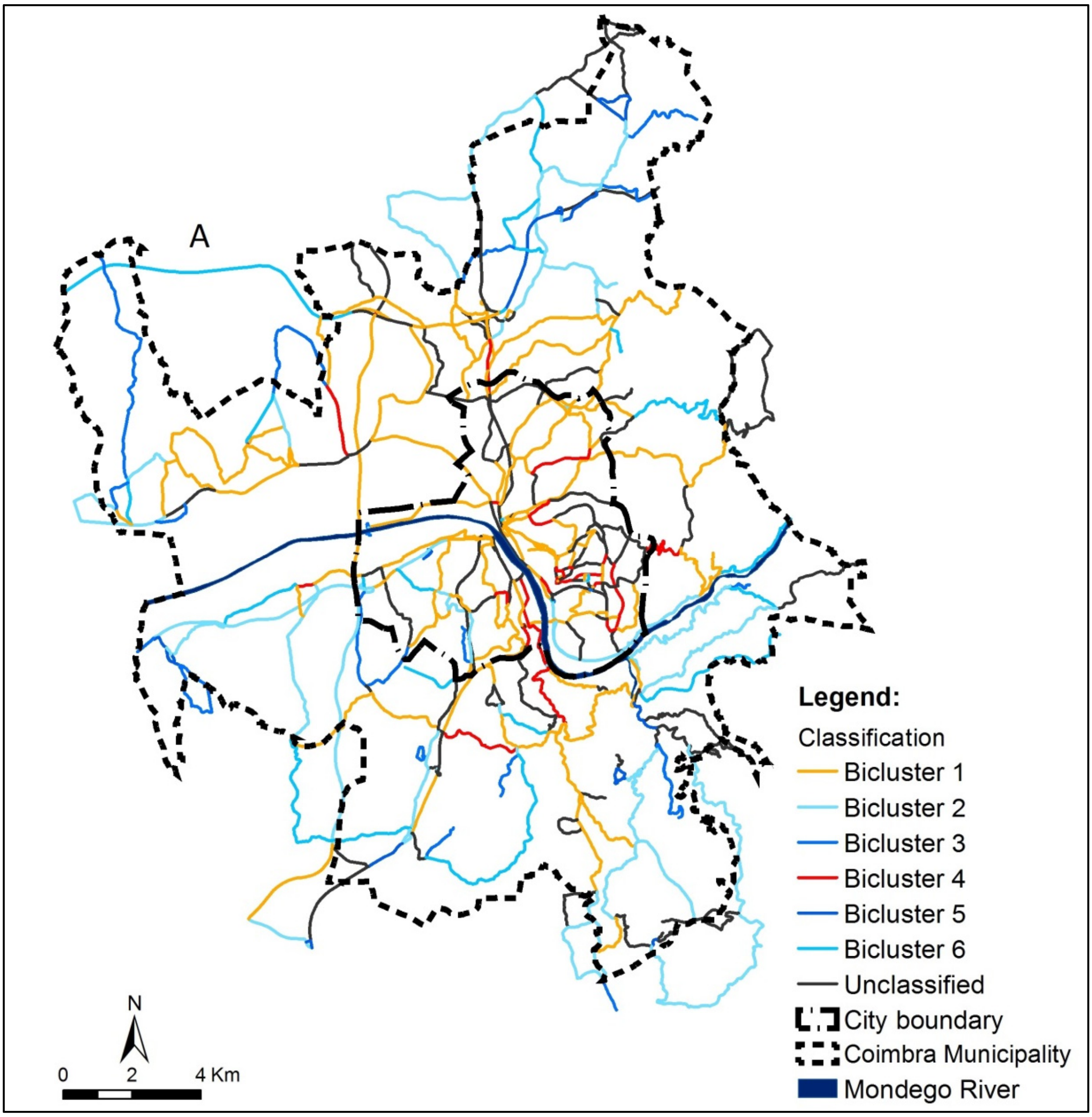

Figure 5-10: Biclusters' cartographic representation – local scale

In a first exploratory regression analysis α index was relevant in 100% of the tests performed; in figure it is possible to identify several cases in which the strength of the connectivity is related with the existence of more than on closed circuit.

As in regional scale analysis, also in local scale it is no possible to establish a clear connection between road functional hierarchies and level of connectivity (Table 5-13). Still Bicluster 3 and Bicluster 5, which aggregate the roads with the lowest levels of connectivity, correspond in most cases to municipal and urban municipal roads.

Regardless the explanatory variables of biclustering results at regional and local scale, what is under discussion is the presentation of a new methodology that allows the identification of the roads with higher connectivity which interruption would cause bigger consequences. The interruption of a road with high connectivity can even break the structure in two parts and the cartographic representation allows seeing that. One drawback of the biclustering technique it doesn’t quantify the consequences of a possible interruption, which, in most cases, demands a scenario-based approach. Still, once is not possible to cover all the scenarios, biclustering technique is useful because it allows identifying the bicluster of roads which interruption would cause bigger consequences in network dynamics.

Table 5-13: Percentage of the roads’ length per bicluster – local scale

Designation	**Percentage of the roads’ length**					
	Highway	**Complementary**	**National**	**Municipal**	**Urban Municipal**	**Total**
Bicluster 1	7	8	5	50	30	100
Bicluster 2	7	3	10	76	4	100
Bicluster 3	0	0	6	89	5	100
Bicluster 4	0	16	10	33	41	100
Bicluster 5	0	33	0	64	3	100
Bicluster 6	17	0	10	69	4	100

In the following phase the results of the biclustering technique will be compared with a methodology that consists of the evaluation of the mean geodesic distance variation due to link interruptions taking into account the consequences in terms of travel distance increase. This comparison will be useful in confirming the following research hypothesis: the higher the level of connectivity the more will the travel distance increase.

In spite of the importance of the road structure, it is always important to have in mind that the importance of the road network relies in the points that is responsible for connecting.

5.1.4. Network scan – regional scale

At this point there are two perspectives to be considered: firstly the comparison between the overall networks geodesic distances in a normal scenario and the biclustering technique results; then the comparison between the overall networks geodesic distance taking into account the consequences of each link interruption scenario.

Table 5-14 shows the average geodesic distance of the roads that integrate each bicluster. The data indicate that Bicluster 2, which in the previous phase presented the highest level of connectivity, corresponds to the roads with lowest values concerning average geodesic distance; on other hand there is Bicluster 3, which in the previous phase presented the lowest level of connectivity, in this phase corresponds to the roads with highest values concerning average geodesic distance. The highest the level of connectivity, the lowest will be the average geodesic distance.

Table 5-14: Average geodesic distance per bicluster – regional scale

Designation	Average geodesic distance (km)
Bicluster 1	37.2
Bicluster 2	23.8
Bicluster 3	56.5
Bicluster 4	42.3
Unclassified	54.0
Total (average)	42.7

The analysis of the average geodesic distance increase per bicluster indicates that the interruption of roads that integrate biclusters with higher connectivity would cause more geodesic distance increase than the interruption of the roads that integrate other biclusters (Table 5-15).

Table 5-15: Roads' interruption consequences – regional scale

Designation	Average geodesic distance increase (km)	Maximum accumulated geodesic distance increase (km)
Bicluster 1	5	46
Bicluster 2	4	43
Bicluster 3	-15	42
Bicluster 4	1	43

In the biclustering technique results Bicluster 2 was pointed as the bicluster with higher level of connectivity, followed by Bicluster 1; in the case of Table 5-15 Bicluster 1 presents the highest average geodesic increase in an interruption scenario followed by Bicluster 2. That difference, biclustering technique results point Bicluster 2 as being more important than Bicluster 1 but average geodesic distance results point Bicluster 1 as being more important than Bicluster 2. However in both phases the differences between Bicluster 1 and Bicluster 2 are not significant, being possible to put them in same level of importance. Moreover, the correlation values between the increase of the average geodesic distance caused by the interruption of each road and the values regarding α and Degree- are $R^2 = 0.9$ and $R^2 = 0.7$, respectively (Figure 5-11 (A), Figure 5-11 (B). Although lower than the previous values, also the correlation between the biclusters results and the increase of distance is high – $R^2 = 0.7$ (Figure 5-11 (C)).

Summing up, the results of Table 5-15 and Figure 5-11 indicate that the higher the level of connectivity of a road the higher will be the consequences of its interruption concerning the geodesic distance increase.

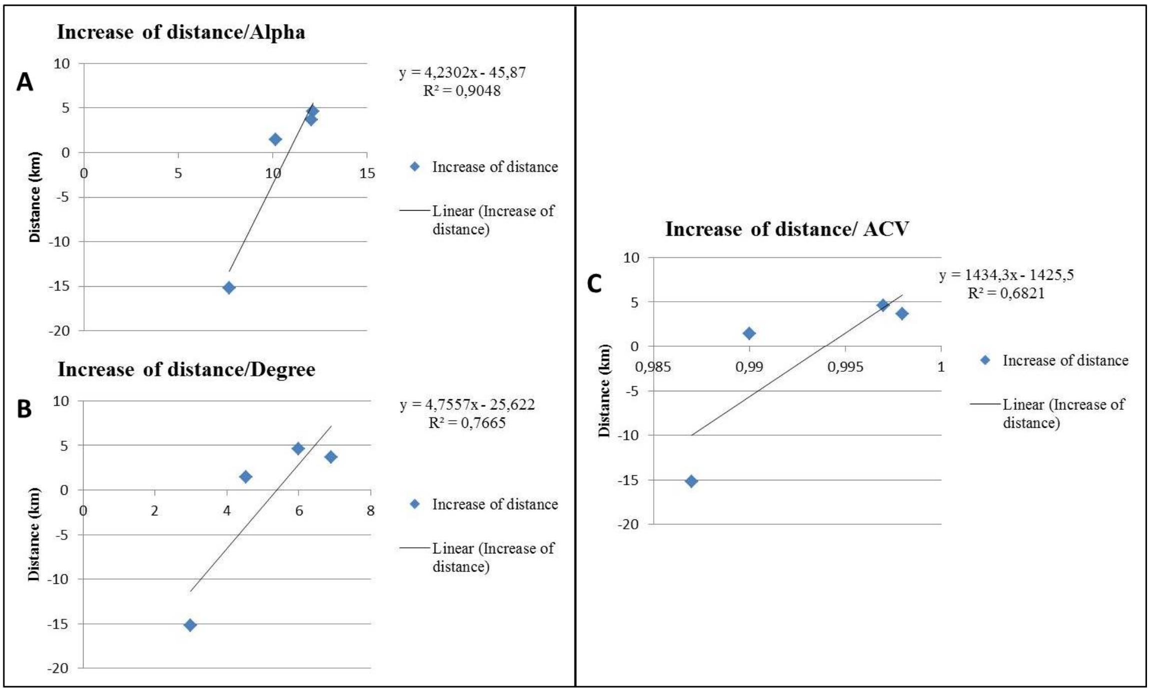

Figure 5-11: (A) Correlation between increase of distance and Alpha. (B) Correlation between increase of distance and Degree. (C) Correlation between increase of distance and ACV.

5.1.5. Network scan – local scale

This phase has as main goal to compare the mean geodesic distance variation and the biclustering technique at local scale. In Table 5-16 are summarized the average near distance of the links per bicluster and is interesting to see that Bicluster 4, which in the previous phase, presents the highest level of connectivity, corresponds to the lowest average geodesic distance; on other hand Bicluster 5, which in Table 5-10 presents the highest level of connectivity, presents the highest average geodesic distance.

Table 5-16: Average near geodesic distance among the links

Designation	**Average geodesic distance (km)**
Bicluster 1	7.5
Bicluster 2	9.5
Bicluster 3	9.6
Bicluster 4	7.1
Bicluster 5	11.4
Bicluster 6	9.0
Unclassified	8.2
Total (average)	8.3

The correlation between the biclustering results (Table 5-12) and the average near geodesic distance (Table 5-16) is R^2 = -0. 9 – the higher the level of connectivity, the lower is the mean geodesic distance.

The results (Table 5-17) indicate that the interruption of the roads that integrate Bicluster 4 will be the ones that will cause highest increase in terms of mean geodesic distance; in an interruption scenario each connection between two points would potentially increase 57 meters in average, one value that in the worst case scenario could be of 28 755 meters. Furthermore the mean geodesic distances of the values that integrate Bicluster 3 would decrease; in case of the interruption of some roads that integrate Bicluster 3 the network in analysis would become smaller, once some of those roads would become isolated or inexistent, such the dangle roads. The results are influenced by the modifiable areal unit problem (MAUP), thus it should be considered the possibility of the existence of some route alternatives, which can be beyond the case study boundaries.

Analysing the correlation values between the average geodesic distance increase and the road values of the variables statistically more significant in the biclusters' connectivity patterns high values are observed; α – R^2 = 0.7; *B* Power – R^2 = 0.8; Degree - R^2 = 0.9. (Figure 5-12 (A); Figure 5-12 (B); Figure 5-12 (C). Also the correlation between the ACV values and the distance increase is high: R^2 = 0.7 (Figure 5-12(D)).

Table 5-17: Mean geodesic distance variation by road network interruptions

Designation	**Average geodesic distance increase (meters)**	**Maximum accumulated geodesic distance increase (meters)**
Bicluster 1	34	17 252
Bicluster 2	33	16 573
Bicluster 3	-15	-7 795
Bicluster 4	57	28 755
Bicluster 5	4	2 020
Bicluster 6	28	14 144

The results indicate that the higher the levels of connectivity of the road, the higher will be the consequences of its interruption in terms of average geodesic distance increase.

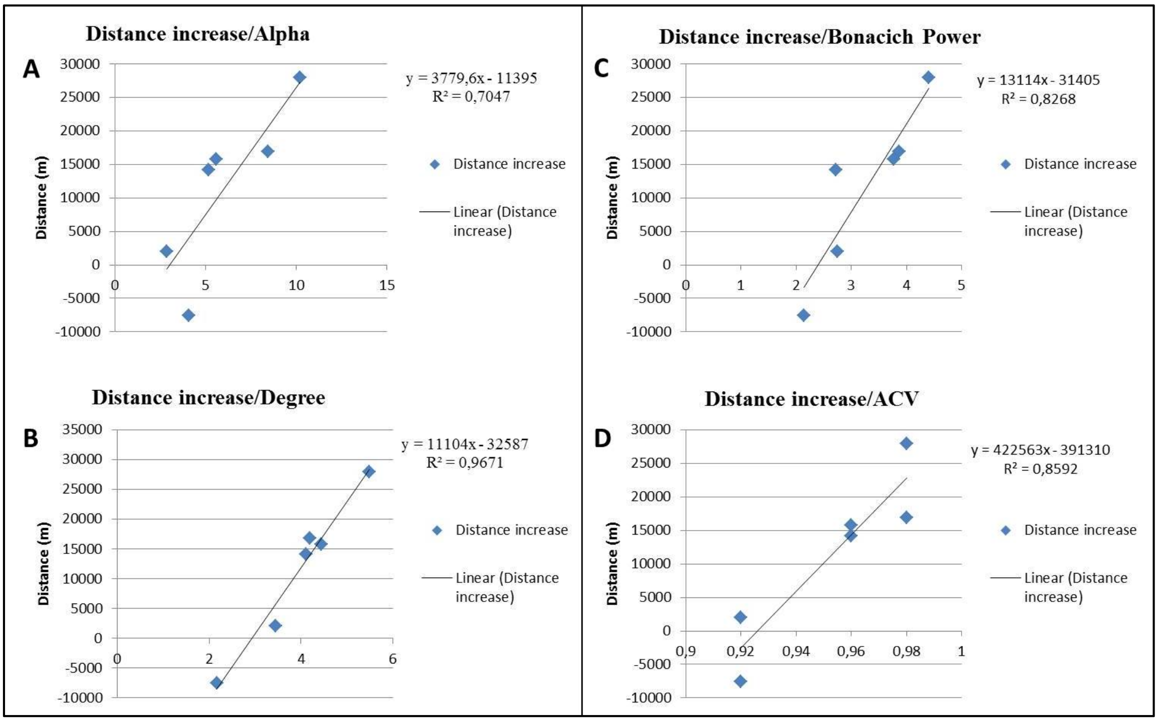

Figure 5-12: (A) Correlation between increase of distance and Alpha. (B) Correlation between increase of distance and Degree. (C) Correlation between increase of distance and Bonacich Power. (D) Correlation between increase of distance and ACV

5.1.6. LRSRM – Scale dynamics in scenario-based approach

This phase is focused on presenting the results of the LRSRM (Local-Regional-Scale-Risk-Model), defined as an integrated model whose main goal is, taking the most important roads from a multiscale perspective into account, to analyse the consequences of a road interruption at regional and local scale.

In this study, the differences between the regional and local scales began to emerge in the first phase, namely during the selection of variables. Initially the set of attributes was the same for both local and regional scales. Attributes such as degree and *B* Power were not redundant on a local scale but presented a high level of redundancy at regional scale.

There are cases in which a local municipality should be prepared to cope with the consequences of a natural hazard occurring in other municipalities in the region. This approach may therefore be seen as contributing towards a better understanding of local-regional links, such as determining which municipalities are affected in a set of natural hazard scenarios. This phase is focused on the application of the LRSRM to real-world problems, considering how the interruption of a road due to a hazardous event can affect network dynamics from a multiscale perspective. The LRSRM was applied on a regional and local scale and one of the aims was to help create greater proximity between the model and real-world problems associated with disruption affecting populations and critical infrastructures such as health facilities.

So, the following phase focuses on the results of applying the LRSRM model to the 3 road interruption scenarios (Table 5-18), assessing how the interruption of a road can affect the network structure and access between parishes and hospitals in the Central Region. Whereas the forest fire interruption took place on a spot on a road with a high level of connectivity, the mass movement interruption took place on a road with a low level of connectivity.

Table 5-18: Roads' interruption consequences

Hospitals	**Normal scenario**		**Flood Scenario (2001)**		**Mass movement scenario (2009)**		**Forest fire scenario (2012)**	
ID	Parishes served (n)	Average time (min)	Parishes served (variation)	Average time (variation)	Parishes served (variation)	Average time (variation)	Parishes served (variation)	Average time (variation)
1	168	29	0	0	0	0	0	0
2	222	32	0	0	0	0	0	0
3	83	30	0	0	0	0	0	0
4	50	35	0	0	0	0	0	0
5	36	18	-13	0	0	0	0	0
6	56	37	0	0	0	0	0	0
7	45	16	0	0	0	0	0	0
8	78	23	0	0	4	1	0	0
9	49	17	12	2	0	0	58	16
10	31	16	0	0	0	0	0	0
11	77	21	0	0	0	0	0	0
12	41	23	1	0	-4	0	1	0
13	32	21	0	0	0	0	0	0
14	78	36	0	0	0	0	-59	-23

Figure 5-13 to Figure 5-15 show the roads affected by the disruption scenarios: on the one hand there are roads with positive values – which means that they connect a higher number of parishes to the hospital that they would do in a normal scenario. On the other hand, there are also roads with negative values – which mean that they connect a lower number of parishes that they would do in a normal scenario.

In the forest fire interruption scenario, Hospital 9 is the facility most affected by the interruption because it is serving the parishes normally served by Hospital 14 (Figure 5-13). In a normal scenario Hospital 9 would serve 49 parishes, but in this case it would serve 107 (Table 5-18). An analysis of Figure 5-13 reveals a clear contrast between the roads that would serve fewer parishes in such a scenario and those that would serve more parishes than in a normal scenario.

Concerning the flood scenario, 13 parishes are affected by the interruption (Figure 5-14) although the variation in the average time for the routes between parishes and the nearest hospital seems to be almost insignificant (Table 5-18). A similar situation can be observed in the mass movement scenario: 4 parishes are affected by the interruption and the variations in the average time between parishes and hospitals, at regional level, are also insignificant (Figure 5-25). However, in such scenario the 4 parishes affected by the interruption would only be connected by the municipal road network. The flood scenario and the mass movement scenario both took place on roads with low connectivity values.

To sum up, the regional system would reorganise and find new equilibriums; in both the flood and the mass movement scenario the road interruptions would not incur significant costs, such as an increase in drive time to the nearest hospital.

The next question concerned how interruptions to the regional network may affect local dynamics, in this case the dynamics of the municipality of Coimbra. Although the average time for the routes on a regional scale in the flood and mass movement scenarios is insignificant, the same conclusions do not apply on a local level. Concerning the flood scenario, by applying a local scale analysis it is possible to find parishes in which the drive time to the nearest hospital increases by 20 minutes; in the forest fire scenario there is one parish in which it increases by 34 minutes.

An analysis of Figures 5-13 to Figure 5-15 shows that the increase in the number of connections between parishes and hospitals would be greater in the municipality of

Coimbra. On a local level, one of the most serious consequences is the number of parishes served and, as result, the role played by certain roads in different scenarios. Therefore at this point the connectivity analysis should be taken into account on a local scale.

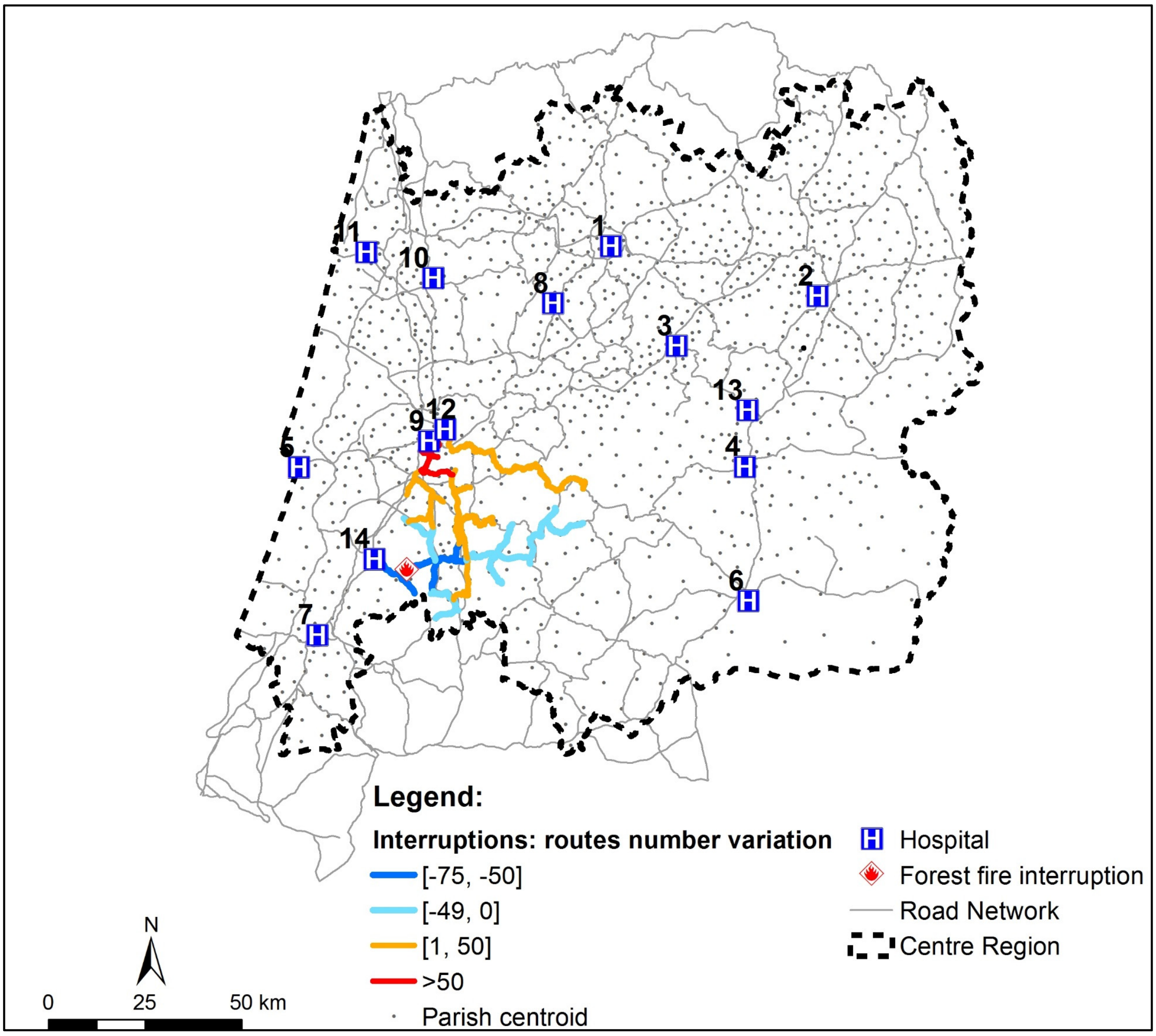

Figure 5-13: Forest fire interruption consequences—regional scale.

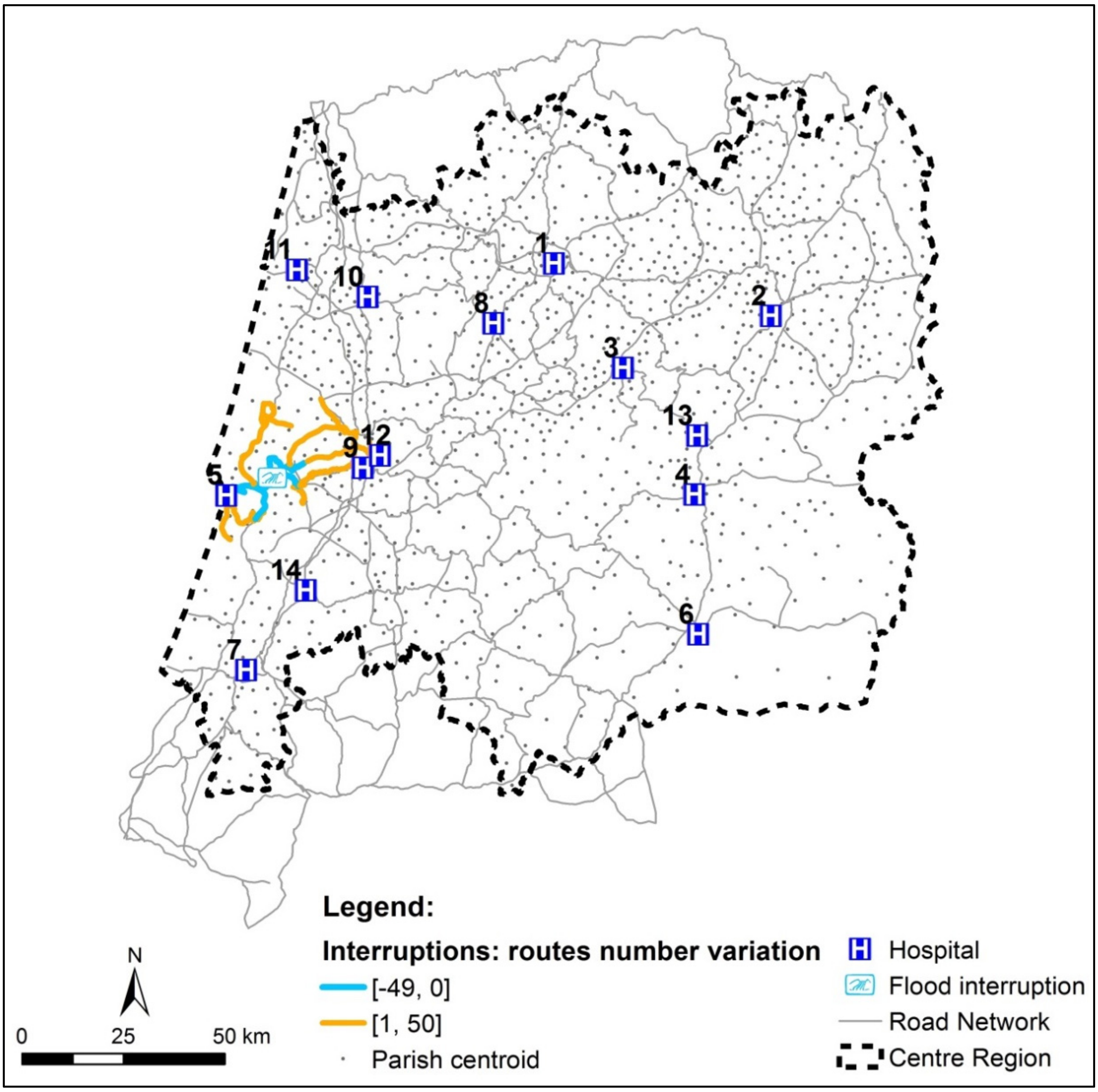

Figure 5-14: Flood interruption consequences—regional scale

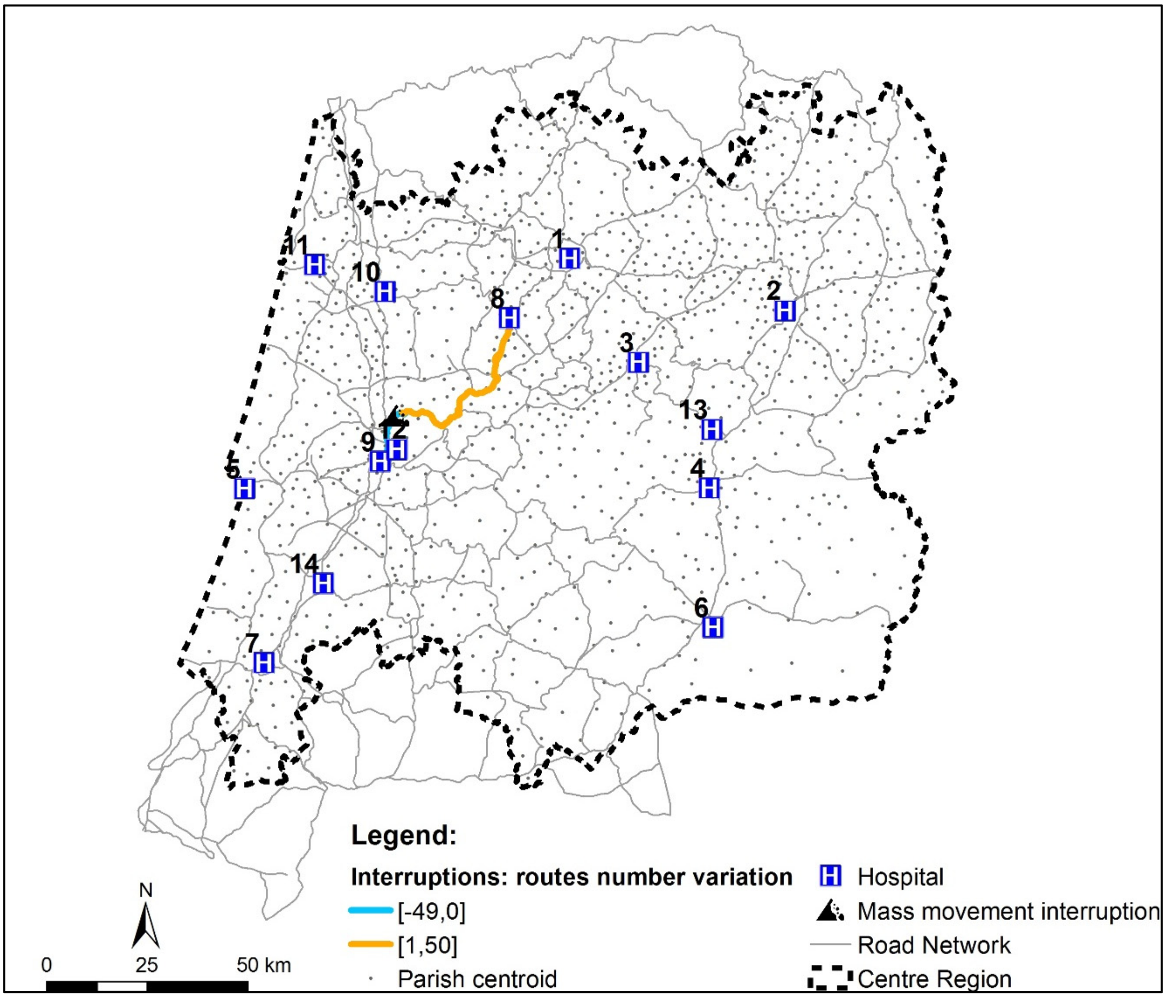

Figure 5-15: Mass movement consequences—regional scale

Figure 5-16 to Figure 5-18 show in greater detail the consequences of the interruptions caused by the forest fire and flood events for roads in the municipality of Coimbra. In the case of the forest fire interruption scenario, one particular road would have to connect an extra 50 parishes to the hospital (Figure 5-16). Comparing the results of applying the technique on a local and a regional scale, it is important to note that there are roads that may be insignificant on a regional scale but quite important on a local scale and vice-versa. However, the role that some roads which are only considered important on a local scale may play in the response to regional road network interruptions, such as the scenarios analysed in this study, is even more important.

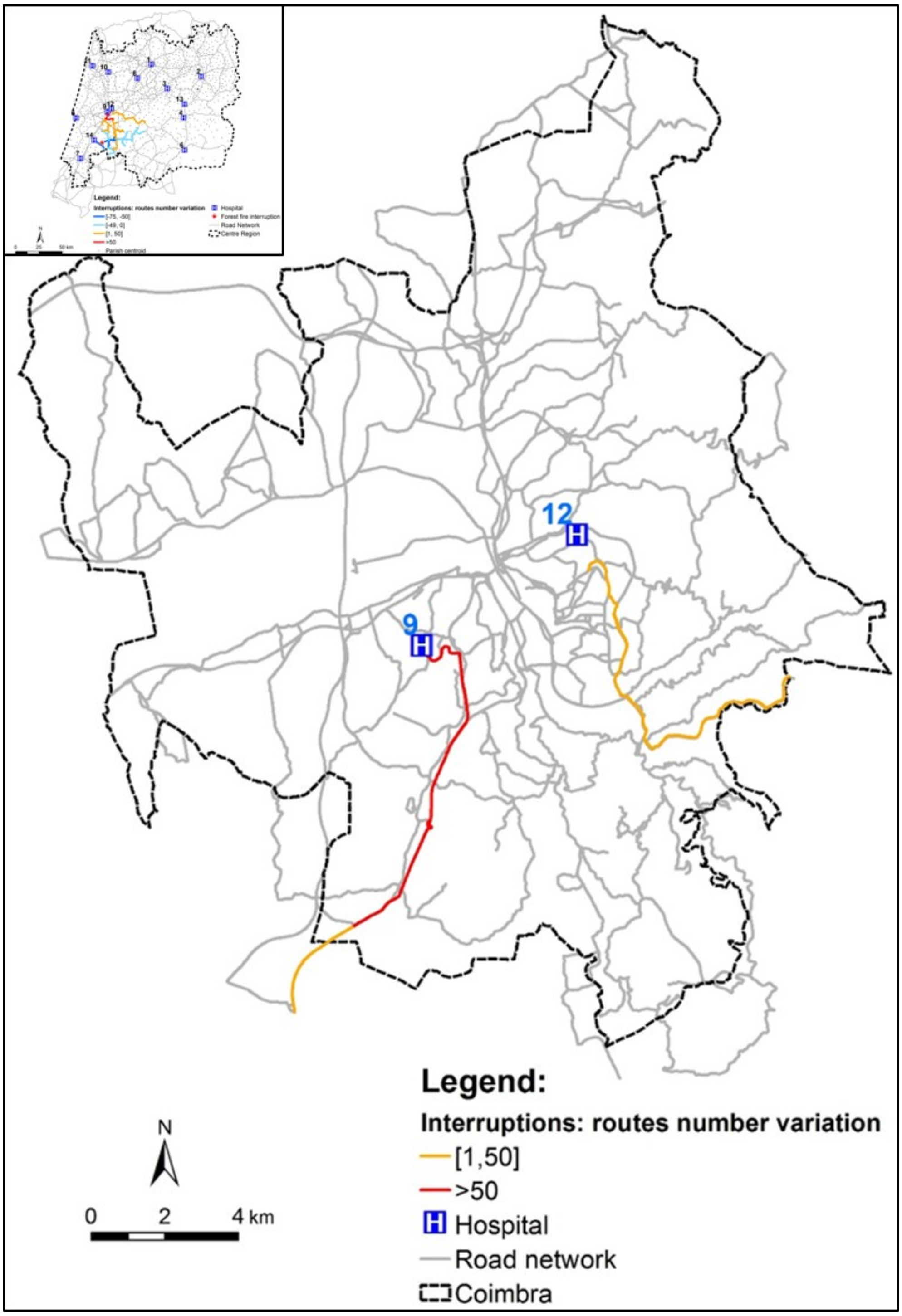

Figure 5-16: Forest fire consequences—local scale

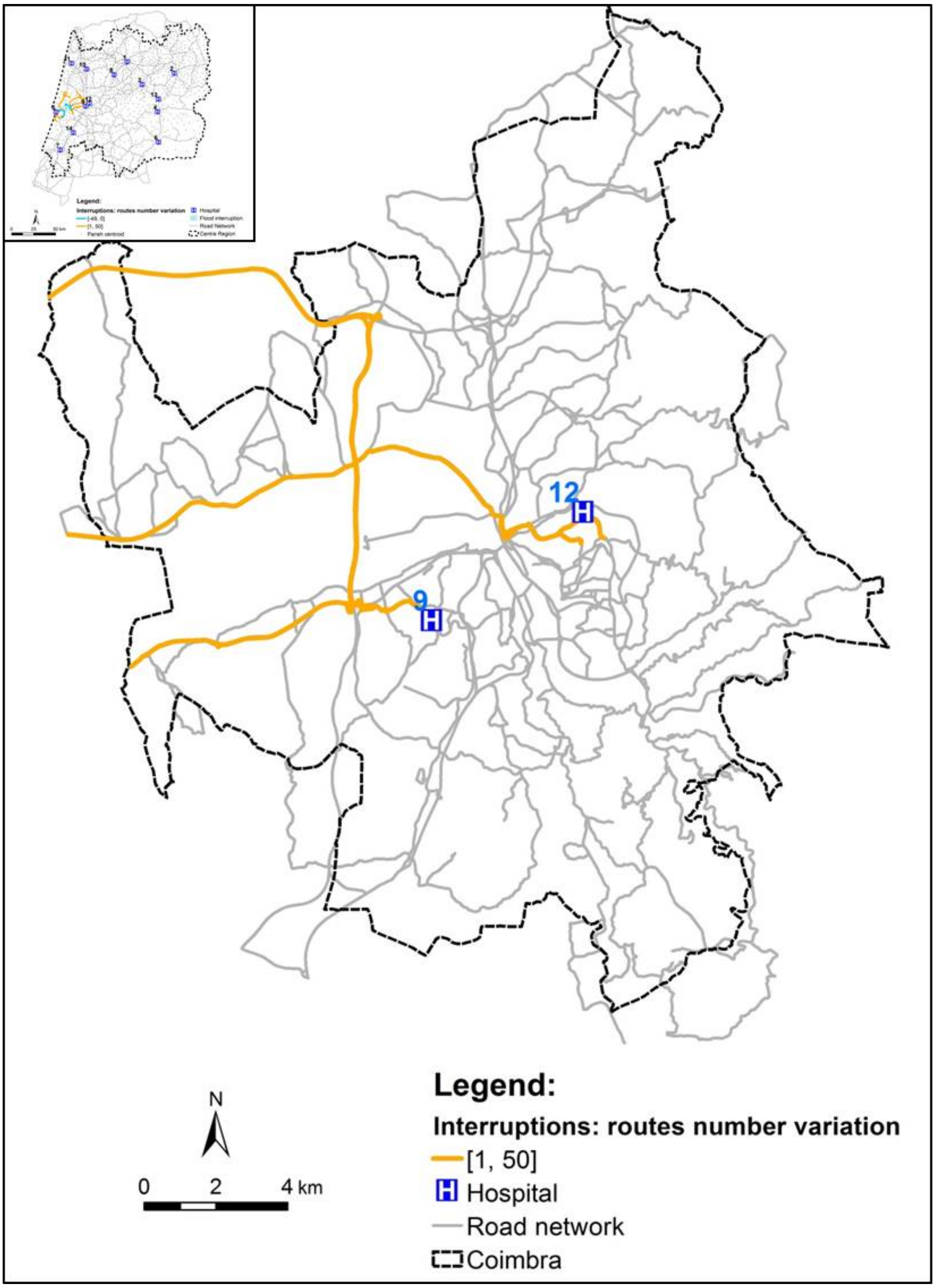

Figure 5-17: Flood consequences—local scale.

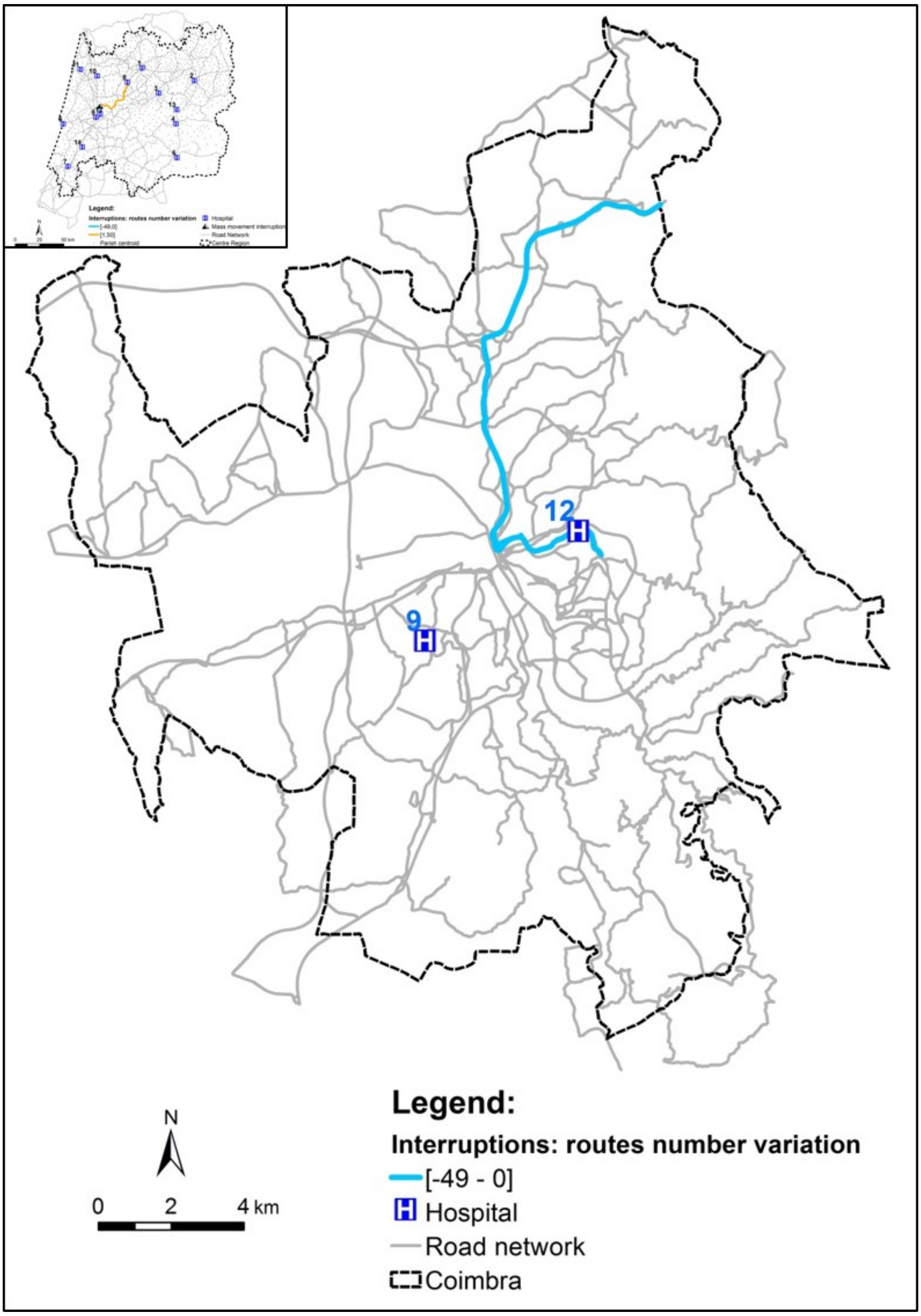

Figure 5-18: Mass movement consequences—local scale.

5.1.7. Structural evaluation – Results' Discussion

The structural characterization results of the network at local and regional scale showed the importance of taking into account the goals of the spatial model; furthermore there are variables that can be useful at regional scale and meaningless at local scale and vice versa. At this phase there was carried out tests with variables that aren't used very often in a link-based approach network analysis. It can be pointed the following example: degree is one of most common variables used in roads' structural evaluation; however results showed that Bonacich Power, a less used variable, can provide a useful insight of networks structure. Degree provides the number of roads that each road is connected to, but Bonacich Power accounts the number of roads that each road is connected to, taking into account role/power that each road has in the network flow. Alpha (α) is a variable that in the analysis assumed a relevant role in the regional as well as at local scale. The value of α is related with issues such the level of optimization of the network, for instance a triangular grid pattern network would probably have a α value higher than a tree pattern network, once in the first case the number of closed circuits will be higher than in the second case. The identification of the most significant variables in the network is due in large part to the biclustering technique application.

This new approach is compared with a more widely used approach - the mean geodesic distance variation. Although presenting similar results regarding the identification of the most important roads, these methods present different pros and cons. The application of the biclustering technique allows identifying connection patterns and identifying variables more relevant in the network configuration; on the other hand determining the shortest path between all node pairs, it does not address connectivity between nodes explicitly. However, unlike the biclustering technique, the mean geodesic distance variation allows assessing the costs of an interruption. One of the main problems it is that is not possible to take into account all the possible interruption scenarios, especially in large networks. In this work all the possible single link interruption scenarios were assessed, neglecting scenarios such as the area-covering interruptions. The combination of the biclustering technique with the mean geodesic distance variation proved to be useful in demonstrating the relation between connectivity and the overall network vulnerability; the higher is the level of connectivity of a link, the greater is the impact of its interruption in the network. It is relevant to verify that in the links' high level of connectivity, what can be strength in a normal situation, can be vulnerability in a road interruption scenario.

From a qualitative point of view the biclustering technique proved to be quite useful in areas such as allocation of resources, with the methodology providing criteria for prioritisation. It is assumed these results are an improvement on the constraints identified by authors such as Sohn (2006) and Eusgeld *et al* (2009). There is no longer any need to investigate several scenarios based on partial analysis in order to identify the most important roads. Using the methodology presented in this work, it is possible to obtain knowledge of the most important roads and outline the worst case scenarios using the quickest and easiest method, in order to assess the expected costs, define alternative paths and thus be better prepared, as argued by Johansson and Hassel (2010). These tools are useful for risk management actors, for civil protection agents who need to decide on the effective allocation of human and physical resources and define priority areas, and for the government institutions which design the network of facilities.

The application of the LRSRM model to 3 real-world road interruptions, based on the, showed that biclustering technique can play an important role in risk management, since it enables the more important roads in a network structure to be identified and the consequences of a road interruption to be evaluated on both a local and a regional level. Also in spite of the importance of certain roads to the regional system, some prevention measures, such as land-use planning, or disaster response measures, including prioritising evacuation decisions, are mainly carried out by local authorities. Recently Chang *et al* (2014) claimed that new approaches to characterising the resilience of sets of infrastructure systems are urgently needed, on community and regional scales. In this study, based on a regional scale, the network finds new equilibriums in all three scenarios to mitigate the impact of the interruptions. The regional system is able to reorganise itself, although this would have consequences for local dynamics. It is therefore important to determine the most important roads on a local scale, since there are cases in which an interruption to the regional road network will increase the problems already present in the local road network. Moreover, authors, such as Tavares and Santos (2013) claim that integrated risk management on a local level is the best way to achieve a governance practice that is recognised by citizens and fosters resilient communities.

5.2. Functional evaluation of the network

In both the structural and functional evaluations the vulnerability and uncertainty component will be addressed. The Gravity Index is based on a threefold approach thus the results were analysed by taking the three components of the formula into account, the Mobility Index, service capacity and distance friction function (Figure 5-19). The uncertainty component will be addressed through road interruption scenarios, the consequences will be evaluated in terms gravity index variation taking into account the variation in the three components of the equation.

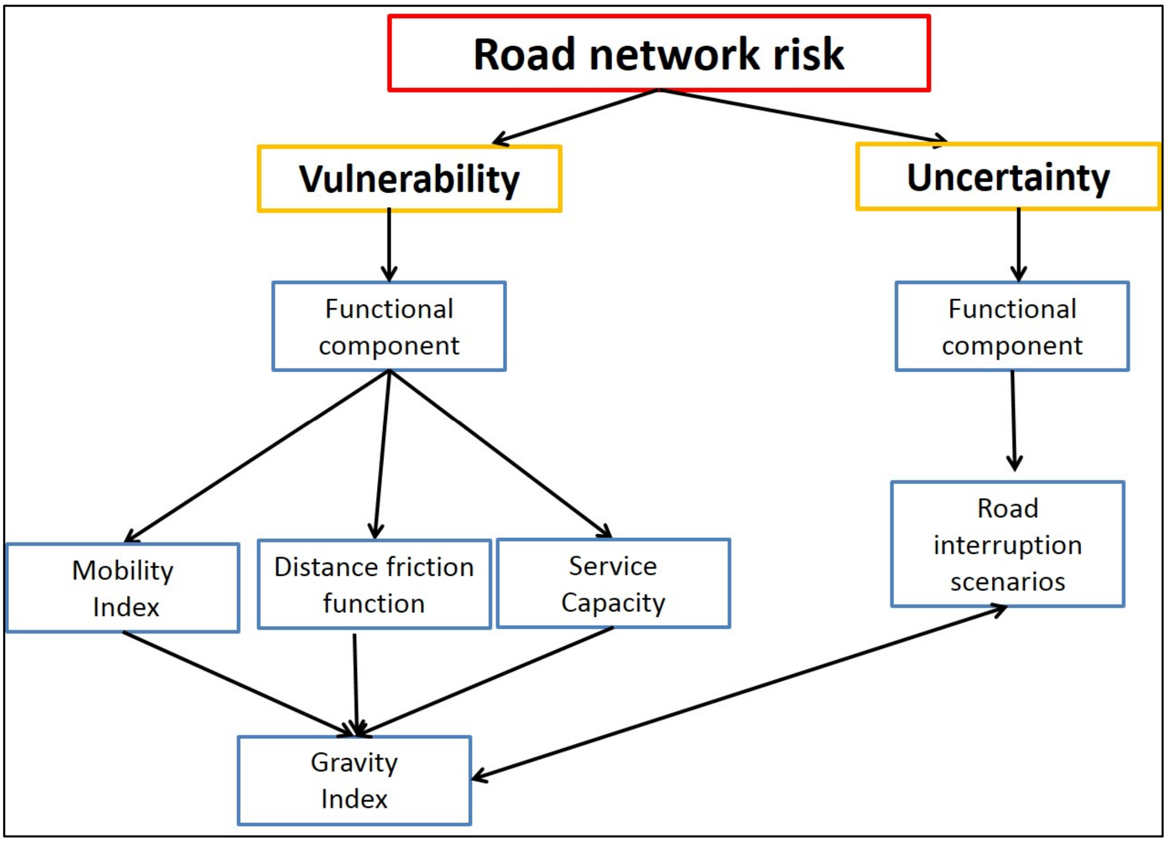

Figure 5-19: Functional component – results' framework

5.2.1. Mobility Index

The Mobility Index represents the population's ease of travel taking into account its social vulnerability characteristics (age, literacy…). This is assessed on the basis of stepwise multiple regression analysis having as a dependent variable, the proportion of car usage for daily travel; it is assumed that higher car usage for daily trips equates with higher mobility. The question is to what extent the population's social vulnerability influences the ease of travel. The variables selected in a first phase present significance (sig) values varying from 0 to 0.812 (Table 5-19). Based on the collinearity statistics analysis (Table 5-20) it was concluded there is no collinearity among the variables used in the Mobility Index.

Table 5-19: Variables' significance levels

Variables	**sig**
Residents aged 65 or over (%)	0
Ratio of dependent young people	0
Activity rate (%)	0.006
Family size (average number)	0.007
Children aged under 6 (%)	0.019
Single-person households comprising one individual aged 65 or over	0.171
Total adult illiteracy (%)	0.362
Single parents (%)	0.392
Resident population (n)	0.612
Couples with children (%)	0.691
Disabled people (%)	0.812

Table 5-20: Mobility Index variables - Collinearity Statistics

Variables	**Collinearity Statistics**	
	Tolerance	**VIF**
Ratio of dependent young people	.578	1.73
Activity rate (%)	.447	2.24
Family size (average number)	.368	2.72

The application of the stepwise multiple regression analysis resulted in a $R^2 = 0.78$. Three variables were selected from the eleven included in the model (Table 5-19) as the ones that best explain the dependent variable – the proportion of car use for daily journeys. The tolerance is higher than 0.2 and the VIF values are lower than 5, which means that there isn't multicollinearity among the variables.

From an analysis of Table 5-21, it can be concluded that the larger the family and the number of dependent of young people, the greater the proportion of car use will be for daily journeys. There is also a positive correlation between the dependent variable and the activity rate, which can be seen as an indicator that access to jobs is closely related to the use of a car.

Table 5-21: Explanatory variables

Variable	Coefficient
Family size	4.257
Ratio of dependent young people (%)	0.189
Activity rate (%)	0.198

Figure 5-20 shows a wide range of values in terms of Mobility Index; it varies from –1.5 S.D. (below the regional average) to 1.5 S.D. (above the regional average). The analysis of the results indicate a strong relation (R^2 = 0.9) between the density of the road network and the Mobility Index values, the lowest values in terms of density of the road network correspond to the lowest values of Mobility Index. The results indicate that the areas with higher mobility correspond to parishes with an activity rate, a family size and a ratio of dependent young people higher than the regional average.

The analysis of Figure 5-20 and Table 5-22 shows the service area of Hospital 6 as well as the service area of Hospital 2, both located in Eastern zones of the Region, as having the lowest values in terms of Mobility Index; on other hand the service area of Hospital 11, Hospital 10 and Hospital 7, all located in the Western zone of the Region, present the highest values. According to the results, 76% of the population that live less than 10 minutes from a hospital has a mobility level above the regional average; however only 44% of the population that lives more than 60 minutes from a hospital have a mobility level above the regional average. The results indicate that as the distance to the Hospitals increases, there also increases the percentage of residents with a low level of mobility (Figure 5-21).

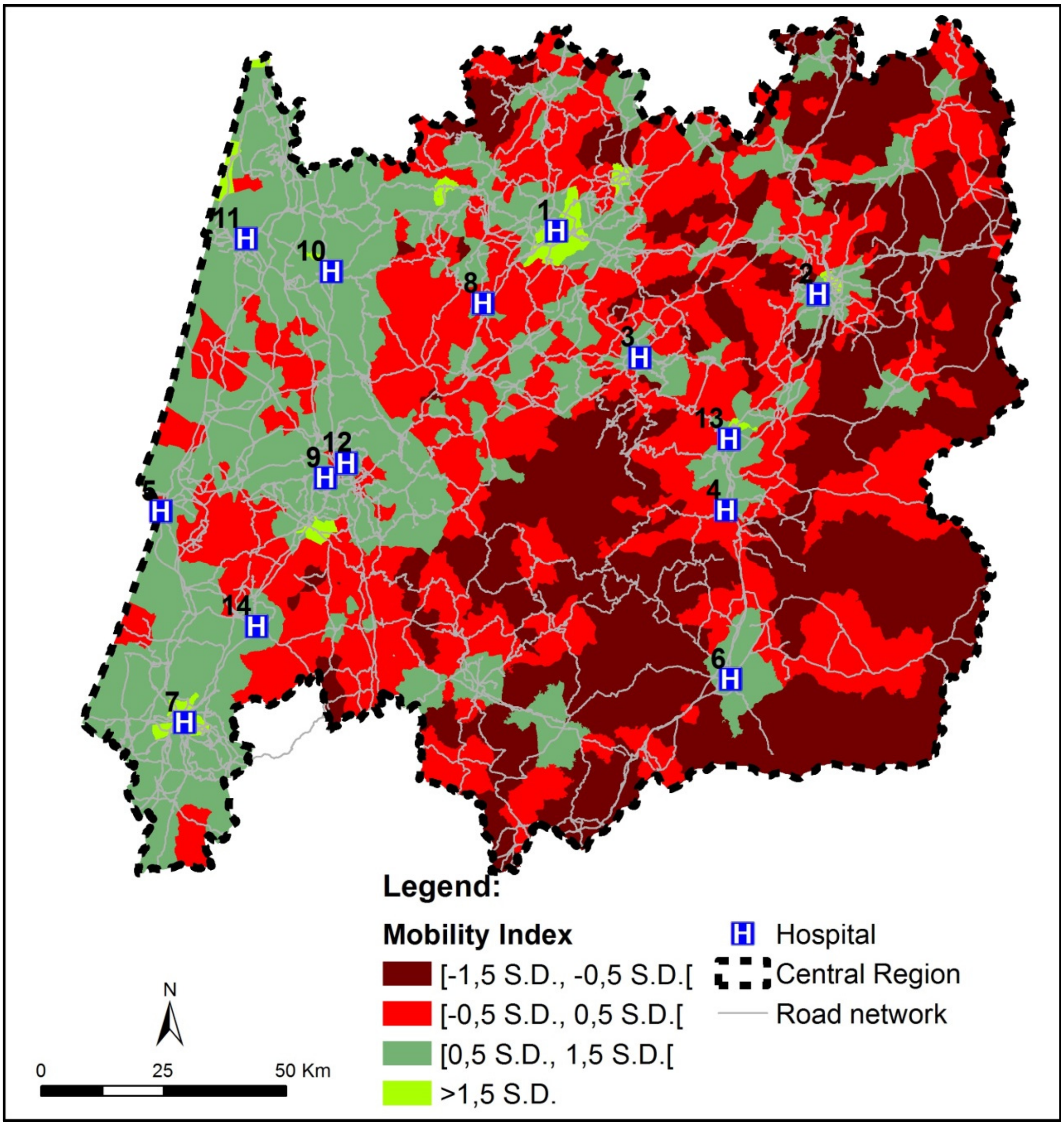

Figure 5-20: Mobility Index per parish

The Mobility Index is focused on the use of the private car; however public transport can be relevant for mobility especially in urban areas. Therefore the role of public transport in the population’s mobility was an explored research hypothesis.

Due to the lack of data, it was not possible to take into account public transportation with a service area of less than 50kms, except for urban public transport. The analysis included the urban public transport and the bus stops of the express and high quality connections (Figure 5-22).

Table 5-22: Parishes average values per hospital service area

Hospital ID	Parishes average values per hospital service area			
	Activity rate (%)	Family size (n)	Ratio of dependent young people	Mobility Index
6	31	2,1	14	8,8
2	33	2,2	15	9,9
4	34	2,3	16	10
3	36	2,4	17	11,2
14	35	2,3	17	11,2
1	37	2,6	21	12,9
13	42	2,4	19	13,1
12	42	2,5	19	13,4
8	40	2,5	20	13,5
5	43	2,6	20	14,3
9	44	2,6	20	14,6
10	47	2,7	20	15,2
7	47	2,6	23	15,8
11	46	2,7	22	15,9

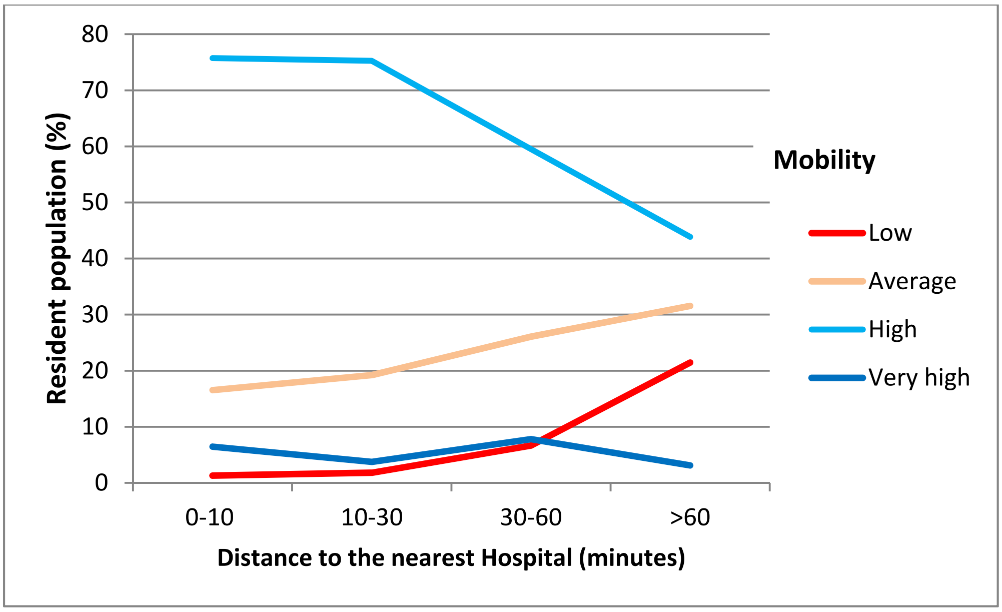

Figure 5-21: Mobility Index and resident population

In this context the public transport issue is only relevant as an alternative for residents with low mobility. In this case study 53% of the resident population with a below average mobility index live more than 50kms from the nearest hospital and of that 53% only 4% of the population lives in a parish served by public transport that can transport this population to the nearest hospital. The results point to the fact that a significant percentage of the population has a low mobility index, live at a distance greater than 50kms from the nearest hospital and that in most of these cases, public transportation cannot be considered an alternative.

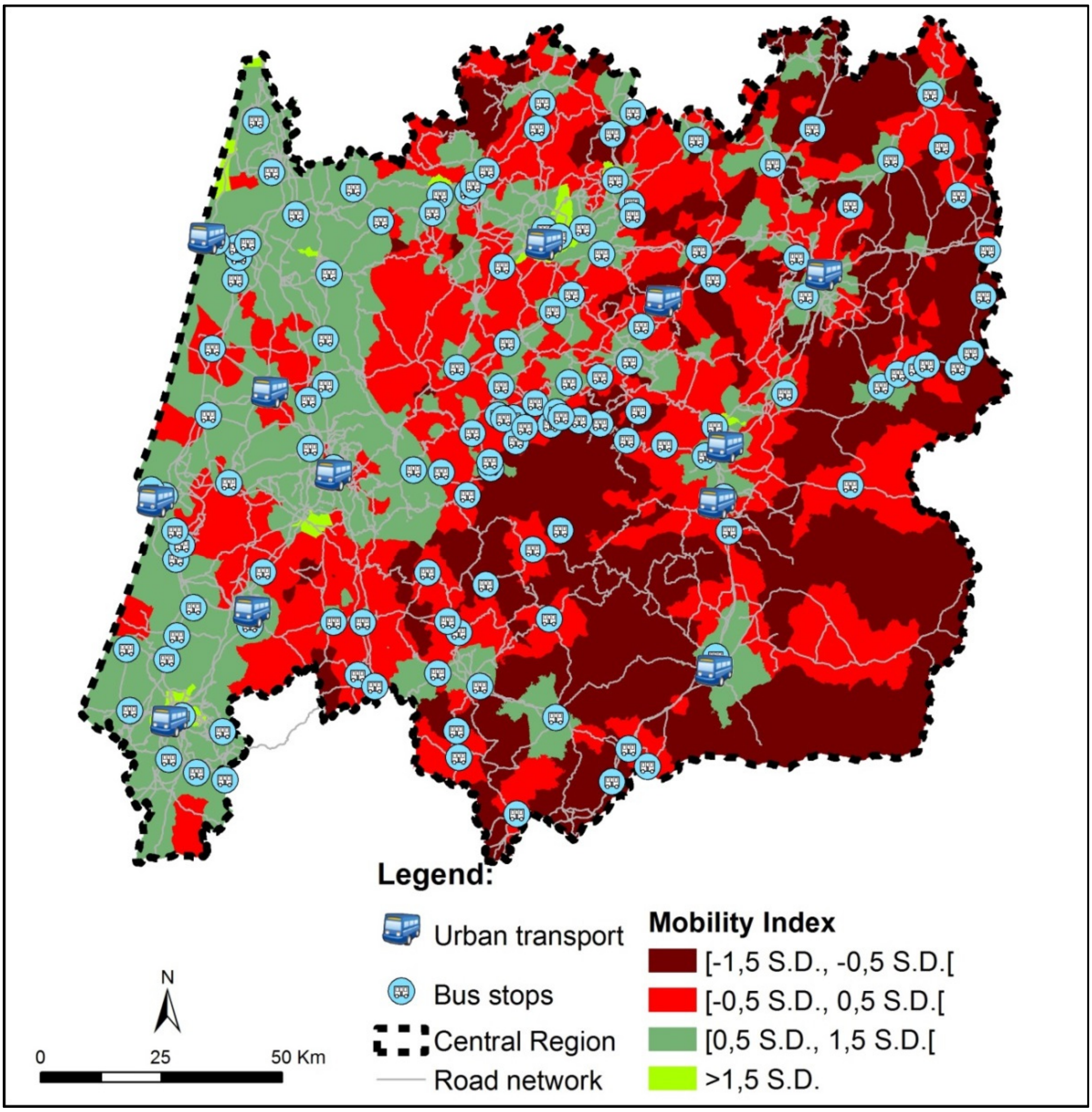

Figure 5-22: Public transport and Mobility Index
Source: IMTT (2014)

5.2.2. Service capacity (*Sj*)

The service capacity is measured based on the number of beds per hospital (Figure 5-23). In Figure 5-23 the spatial disparity of resources is evident, as the number of beds varies in a significant way. The municipality of Coimbra contains 41% of the total number of beds for the Central Region.

Still, the most important issue is if these spatial disparities impact or can impact the accessibility of the population to health services. But this is not an entirely simple calculation. For example, there is a Hospital with only 24 beds, the lowest number of the entire Region, but it is less than 30km from a Hospital with 599 beds. Thus, the number of beds per hospital is a good indicator of the hospitals' service capacity, but it is a variable that must be analyzed by taking into account other variables.

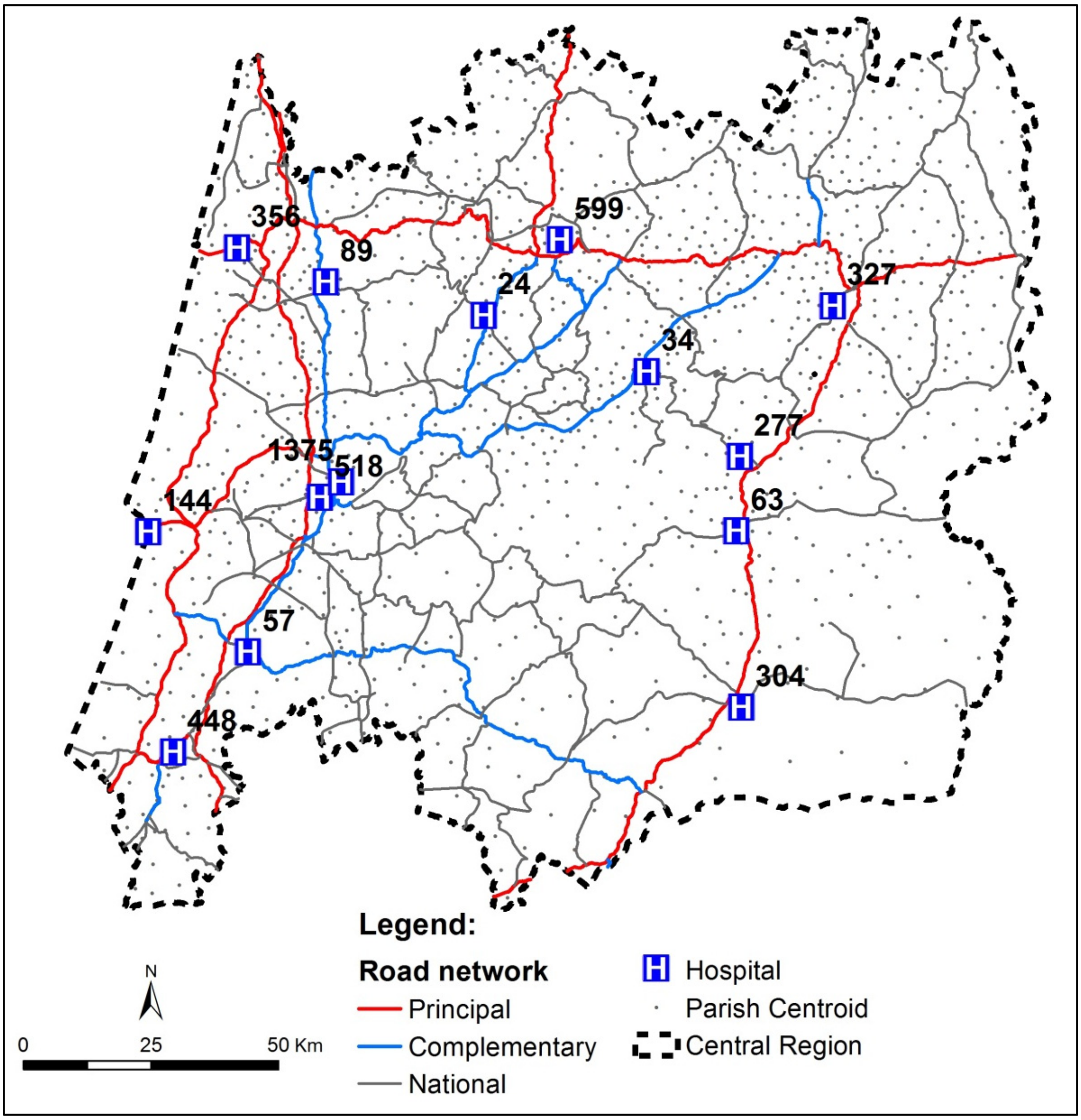

Figure 5-23: Hospital capacity per hospital
Source: Portal da Saúde (2012)

5.2.3. Distance friction factor

The basic premise of this section is to confirm correspondence between the following measures. Will the lower values of the sinuosity index, lead to correspondingly lower speed and thus higher time spend in travel?

In a first phase there seems to be no relation between the sinuosity index and the time spend in travel; however, in routes that present a sinuosity index lower than 0.5, it was verified a $R^2 = 0.43$ between the sinuosity index and time spend in travel. This value is the result of a regional average; some tests in Hospitals' service area, such Hospital 7 service area, indicate a correlation value of $R^2 = 0.6$. Regardless of the regional scale contingencies, 0.43 is used in this work as a friction factor of the distance.

5.2.4. Gravity Index results

Figure 5-24 presents the average Gravity Index values for each link (GI_L), the cartographic representation of the results allows identifying some service complementarities between hospitals, such the case of Hospital 11 and Hospital 10, as well as identifying spatial hotspots as are the cases of Hospital 9 and Hospital 12.

Although the Gravity Index per link is determined by variables other than just distance to the Hospitals, it is possible to identify in Figure 5-24 cases where the lower the distance to the Hospital, the higher it is on the Gravity Index.

Analysing Table 5-23 the results indicate that 58% of the roads' length has a gravity index below the regional average and only 11% of the roads' length has a gravity index clearly above the regional average. The reasons that explain a value like 58% can be high distance between the parish(s) and the nearest hospital; and can also be an indicator of a low mobility of the parish(s) population or a low level of resources of the Hospital. The results show that more than half of the road network present low levels. This can be an issue in terms of the quality of the service that is provided to the population, in this case the quality of the health services that are provided to the population. Still, returning to the objectives of this work, the main point is that only the interruption of some point of

11% of roads' length can have significant consequences in the normal road network flow.

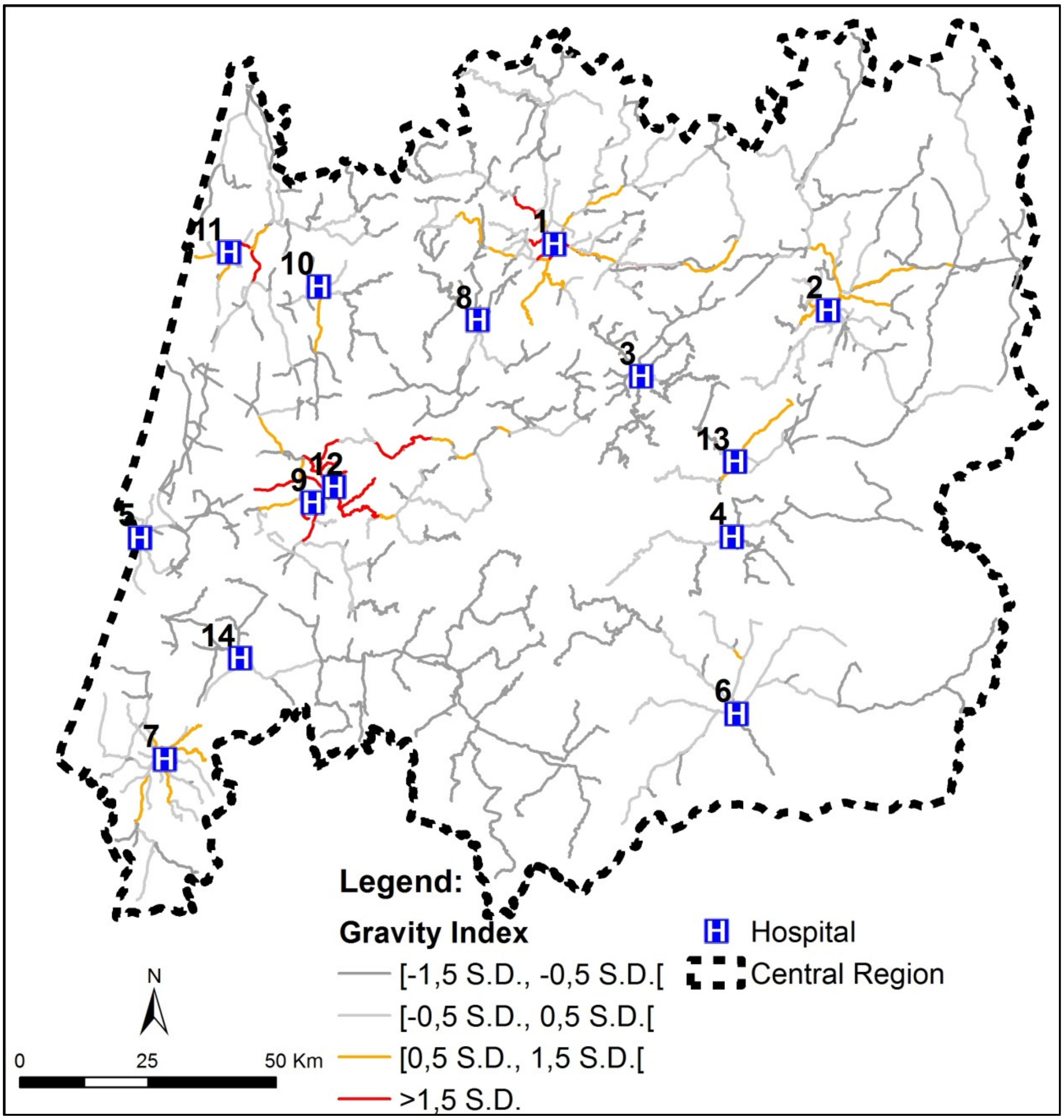

Figure 5-24: Gravity Index per link

Table 5-23: Gravity model per roads' length

Gravity model - Classification	Roads' length	
	Km	%
[-1,5 S.D., -0,5 S.D. [	2968	58
[-0,5 S.D., 0,5 S.D. [	1587	31
[0,5 S.D., 1,5 S.D. [	368	7
>1,5 S.D.	218	4
Total	5141	100

Inequalities between the East and West zones are also evident (Figure 5-25): on one hand the service areas of Hospital 3, Hospital 14, Hospital 8 and Hospital 4 present the lowest values, whereas the service areas of Hospital 11, Hospital 7 and Hospital 12 have the highest values (Figure 5-25 and Table 5-24). However, it is important to note that there may be different reasons for similar values: Hospital 7 and Hospital 11 present high values because the populations they serve register high values on the Mobility Index. On the other hand, Hospital 12 presents a high value on the Gravity Index because it has one of the largest number of beds in the case study.

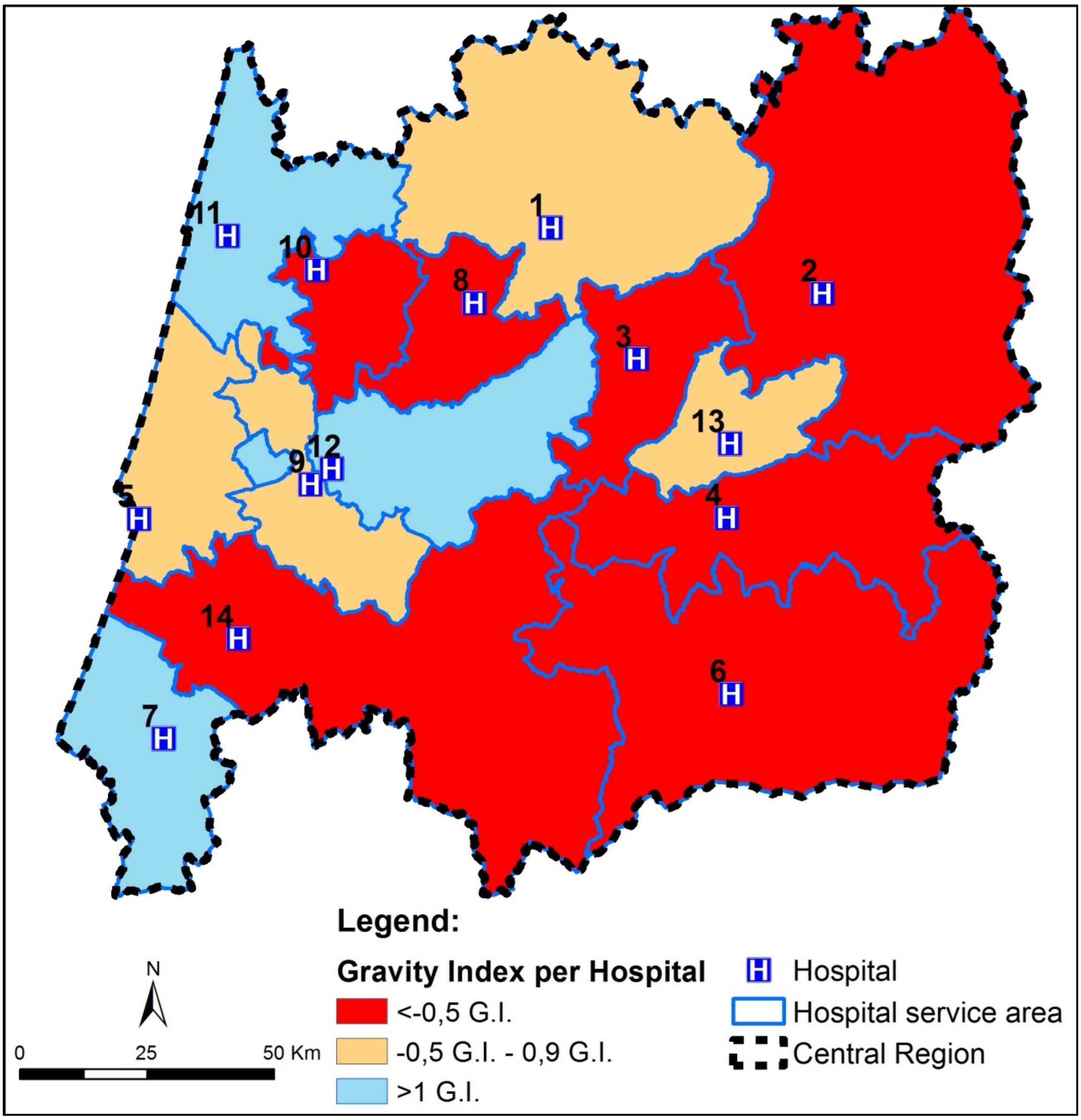

Figure 5-25: Gravity Index and Hospital service area

From an analysis of Table 5-24 it can be seen that Mobility Index of the populations served by Hospital 2 and Hospital 6 – located inland – are the lowest in the case study. On the other hand, the mobility indexes for the populations served by Hospital 11 and Hospital 7 – located in Coastal zones – are the highest in the case study.

An analysis of Table 5-24 shows that in the case of Hospital 12 it takes, on average, 47 minutes from the nearest parishes to this health facility; in the case of Hospital 14 the average drive time is 44 minutes.

Table 5-24 Gravity Index results (*) standardised values

Hospital ID	Mobility Index (average/hospital service area)	Hospital service capacity (n beds)	Average drive time distance (minutes)	Gravity Index (*)
3	12	34	21	**-1,1**
8	13	24	16	**-1.1**
14	11	57	45	**-1.1**
4	11	63	29	**-1**
2	10	327	33	-0.7
10	15	89	17	-0.7
6	9	304	37	-0.6
5	14	144	20	-0.3
1	13	599	31	0.6
9	14	518	20	0.9
13	14	277	16	0.9
11	16	356	21	1
7	16	448	16	1.2
12	14	1375	47	1.9

Summing up, the results show significant inequalities in terms of access to hospitals. There were clear differences between Western and East zones, as well as between areas with rough physical conditions, such as steep slopes, and flat areas. It is possible to identify a geographical pattern; generally speaking, as the Gravity Index moves further away from the coast, the values for the hospitals are lower. It is also worth noting that Hospital 14 and Hospital 12 present an average drive time of 45 and 47 minutes respectively, which means that in some parishes the population has to drive for more than 60 minutes to reach the nearest hospital.

In terms of the lowest values, Hospital 2 is a problematic case even though it is not the health facility with the lowest gravity index value. This is because the Mobility Index for the parish populations served by this hospital is the second lowest of all the hospitals in this study and the average drive time from the nearest parishes to this health facility is 33 minutes.

Among the highest values, the polarisation of resources is matter of concern. 58% of beds available in the Central Region are concentrated in Hospital 9 and Hospital 12, which are located in the same municipality. Due to this polarisation of resources, it is possible to identify roads in Figure 5-24 with Gravity Index above the regional average which, if interrupted, would probably mean that a significant number of parishes would be further away from a health facility with a service capacity above the regional average.

5.2.5. Road interruption scenarios

The values of the Gravity Index depend on three components: number of parishes and mobility of its population served by each hospital, distance between each parish and the closest hospital and the resources available in each hospital. The higher the mobility of the population and the higher the amount of resources the higher the Gravity Index will be; in an inverse association: the lower the distance between the parishes and the nearest hospital the higher the Gravity Index will be. In this third phase three scenarios were tested in order to evaluate the importance of variables such as the capacity of each hospital in terms of road interruptions consequences (Figure 5-26).

Based on the results obtained (Table 5-25) it is possible to conclude that the interruptions would have different consequences. Scenario 2 would be the scenario with the lowest variation in terms of gravity index variation; the consequences would be endured by Hospital 2, the Gravity Index would decrease because it would be necessary to travel more to serve the same number of parishes that would be served in a normal scenario. Scenario 1 and Scenario 3 would cause greater disturbance in the system; thus they will be subject of closer attention.

In Scenario 1, the Gravity Index of Hospital 1 would increase because it would serve fewer parishes with the same amount of resources, the consequences of the interruption would be divided between Hospital 3 and Hospital 2 (Figure 5-27). The decrease of the Gravity Index would not be significant because the parishes affected present a Mobility Index above the regional average, also the average distance variation, in comparison with a normal scenario, would not be significant. In this scenario the main issue is that a population would be served by Hospitals with fewer resources than Hospital 1.

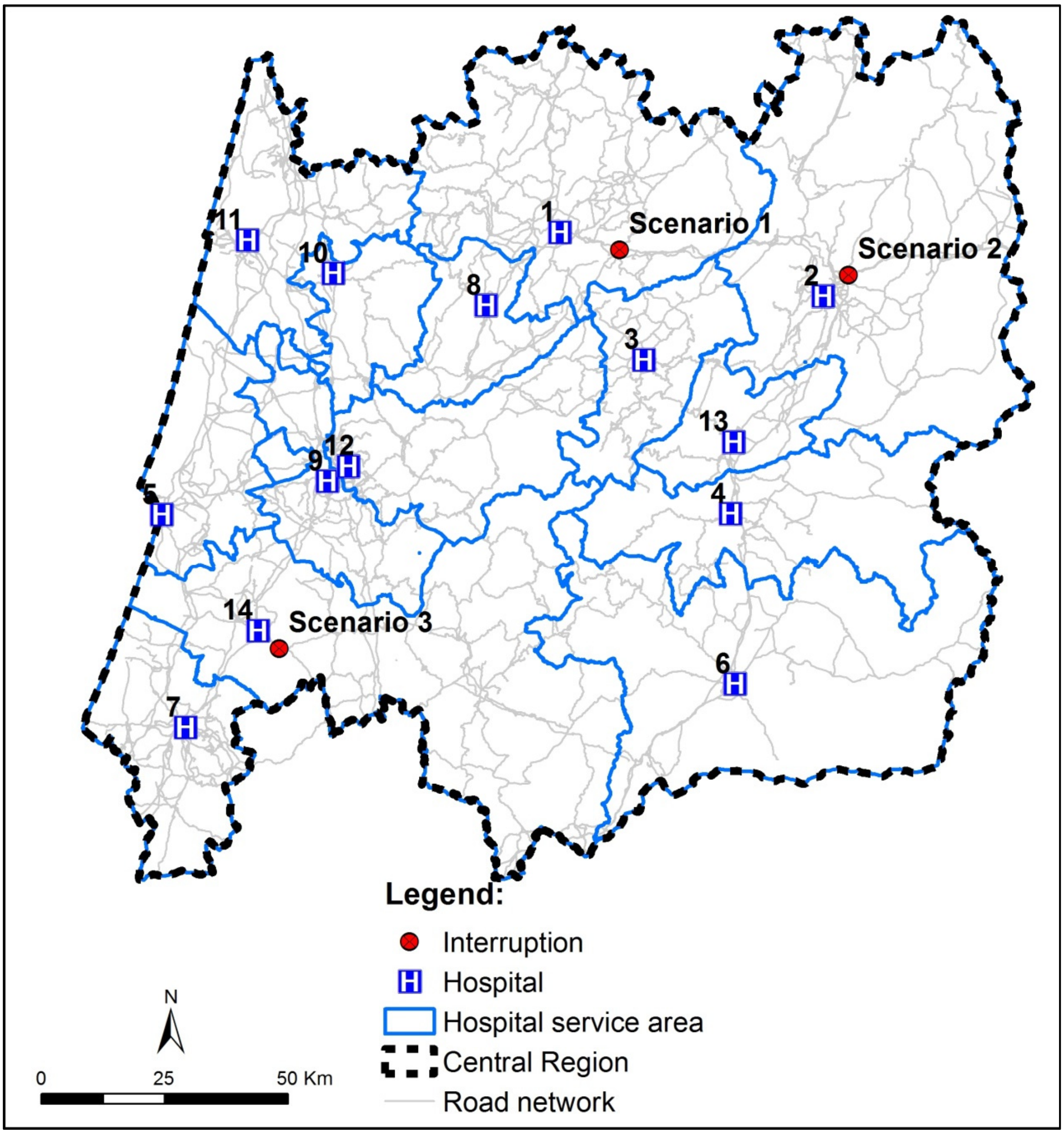

Figure 5-26: Interruption scenarios

In Scenario 3 the interruption of one of the main accesses to Hospital 14 is simulated. As a consequence its Gravity Index would increase dramatically, because most of its parishes would have to be served by Hospital 9 and Hospital 12 (Figure 5-28). In this Scenario, the population would be served by hospitals with more resources, thus the decrease of the Gravity Index of Hospital 9 and Hospital 12 is not in the same proportion as the increase of the Gravity Index of Hospital 14. In this scenario the main issue is that the residents would have to travel a longer distance to reach the closest hospital. However, it would be a hospital with more resources than the hospital which serves the parishes in a normal scenario.

Summing up, in all the scenarios the regional system presents the ability to reorganize itself and the consequences are mainly observed at a local scale.

Table 5-25 Gravity Index interruption consequences

ID	**Gravity Index Hospital ($\overline{GI_J}$)**	**$\overline{GI_J}$ variation (%)**		
		Scenario 1	**Scenario 2**	**Scenario 3**
3	**-1.1**	-1.1	0	0
8	**-1.1**	0	0	0
14	**-1.1**	0	0	188
4	**-1**	0	0	0
2	-0.7	-2.9	-7.2	0
10	-0.7	0	0	0
6	-0.6	0	0	0
5	-0.3	0	0	0
1	0.6	5.6	0	0
9	0.9	0	0	-48.4
13	0.9	0	0	0
11	1.0	0	0	0
7	1.2	0	0	0
12	1.9	0	0	-4.7

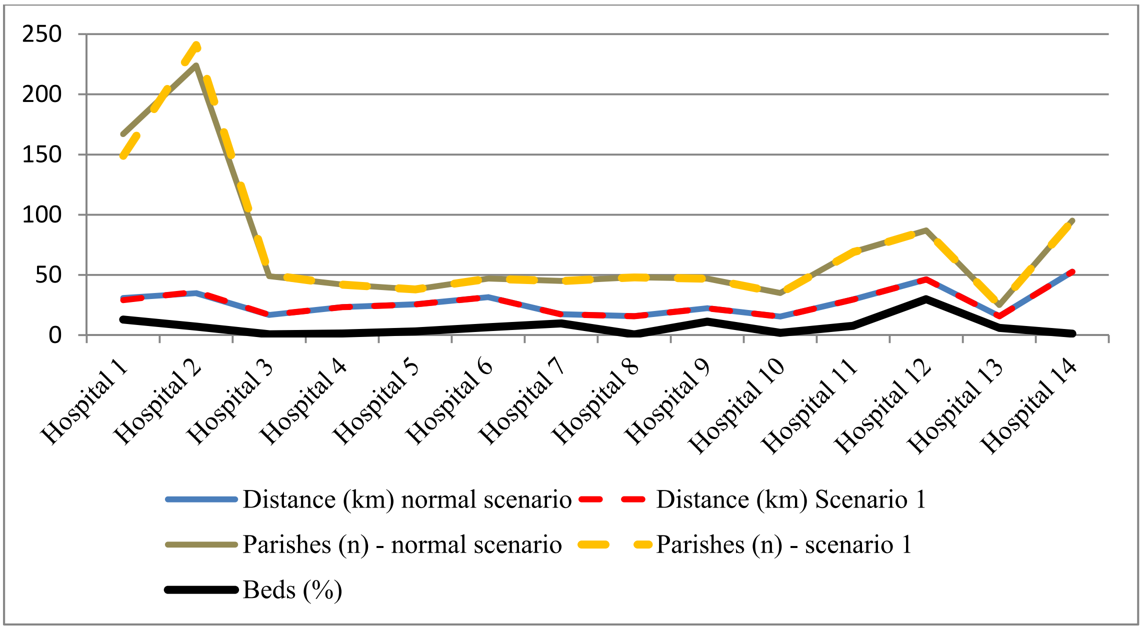

Figure 5-27: Scenario 1 interruption consequences

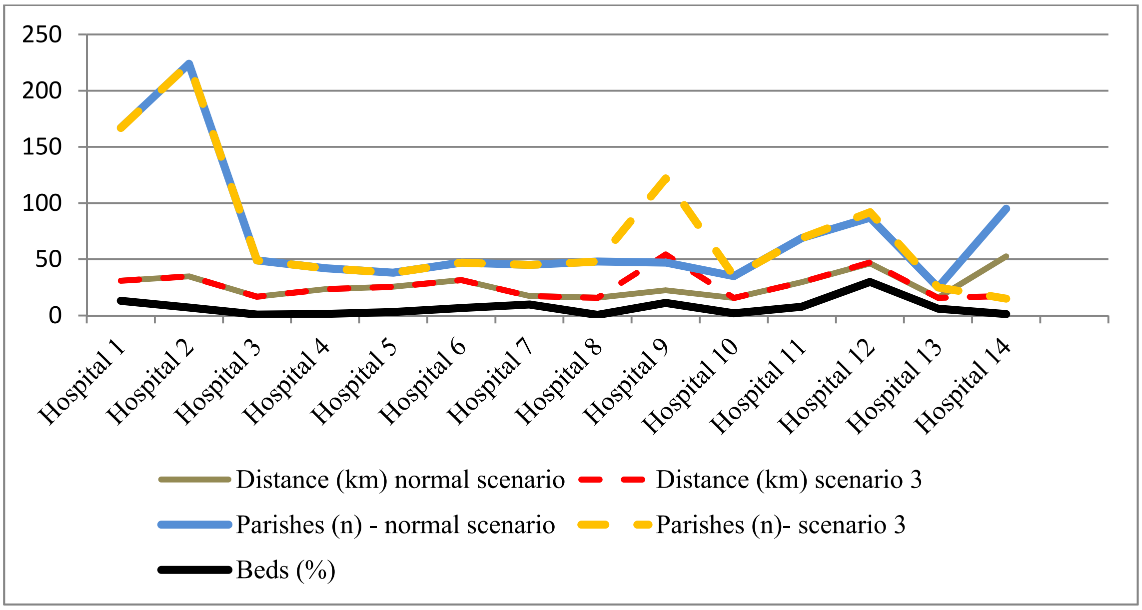

Figure 5-28: Scenario 3 interruption consequences

5.2.6. Functional evaluation – Results' Discussion

The goal of the gravity model approach is to identify the roads which interruption can have bigger consequences in the roads' network flow. At this phase the road is evaluated from a functional perspective.

This study demonstrates that accessibility is multifaceted and remarkably territorial. The results of the gravity model can be seen as a step forward from a methodological point of view, but can also be seen as a contribution to risk management policies.

Analysing the results, the main problem is the level of vulnerability identified in some roads' network sections. One major issue is the polarisation of resources in one particular municipality in the Central Region, which means that the interruption of the roads identified with the highest values according to the Gravity Model can have serious impacts on a regional system of health care provision. As a counterpart of the polarisation of resources there are parishes where it is necessary to drive for over an hour to reach the nearest hospital. Since the gravity model proposed in this work is a compound index, it is possible to claim that these vulnerable sections exist for more than one reason. Hospital 2 is a problematic case even though it is not the health facility with the lowest gravity index value. This is because the Mobility Index for the parish populations served by this hospital is the second lowest of all the hospitals in this study and the average drive time from the nearest parishes to this health facility is 33 minutes. The results allowed the identification of accessibility gaps across geographical areas and population groups. Even in a normal scenario there are significant disparities in terms of accessibility to health care, which can get worse in a road network interruption scenario. Still, the results of the road interruption scenarios showed that longer distances don't always mean worst situations, the residents can go to more distant hospitals than they would in a normal scenario, but that can mean access to more resources. However, in this context the level of mobility of the population is important, travelling longer distances can be irrelevant to a population with a high level of mobility but can also be almost impossible for a population with a low level of mobility. The results indicate that a significant percentage, almost 50%, of the population with low mobility lives in parishes where public transport to the closest parishes is not an option.

The results represent a step forward in terms of the methodological issues that are important to an integrated assessment of accessibility. However, they are also important for politicians and technicians, since the case study identifies situations worthy of concern, the results identified issues that should lead to a reconsideration of how resources are allocated. From a resources management perspective, there is a need for careful prioritisation and sequencing of road transport projects (Novak et al. 2012). Moreover, the pre-positioning of emergency supplies may be an effective mechanism for improving responses to natural disasters (Rawls and Turnquist 2010).

In most studies (Paez et al. 2010; Ortega et al. 2012; Stepniak and Rosik 2013) the accessibility results are cartographically represented on the basis of administrative areas or cell units. However, a link-focused representation enables characteristics that cannot be detected by areal analysis to be identified. An area-based analysis is useful for the technicians and politicians responsible for managing an administrative area. Existing research has shown that the performance metrics, terminology, methodologies and even the underlying modelling assumptions used in network disruption studies can vary dramatically depending on the application, problem domain, and the specific goals of the research (Sullivan et al. 2010). The cartographic representation of results allows the roads that connect each parish centroid to the most accessible hospital to be identified, as well as the roads that are further away from the national road network. It also enables the service area of each hospital to be outlined and ranked according to its importance. Nevertheless, a link-focused analysis alone is not enough; the importance of a link depends on the significance of the points it connects, meaning that a parish- or hospital-focused analysis is also important.

As in the work of Bono and Gutiérrez (2011), in this study both network and spatial analysis enables the effects on geographically dispersed but interconnected assets, which would otherwise be underestimated or not easily recognised, to be captured more effectively. This study was carried out on a regional scale; future research will focus on a local scale, paying particular attention to the more problematic areas such as the service area of Hospital 2. An analysis of the most problematic areas on a local scale can prove useful, since it enables local administrators to move beyond mitigation to include a focus on adaptation, in practical terms (Tavares and Santos 2013).

Speed and time have dominated the debate on transport (Banister 2011). However, the work presented here demonstrates the need to re-think the dominant paradigm.

5.3. Structural-Functional Road Model (SFRM)

This phase is focused on bringing together the modelling approach, described in the previous two phases – structural and functional characterization of the network - in order to discuss how to manage the critical infrastructure vulnerability. In spite of the importance of uncertainty component in risk analysis, SFRM is focused on the vulnerability component (Figure 5-29).

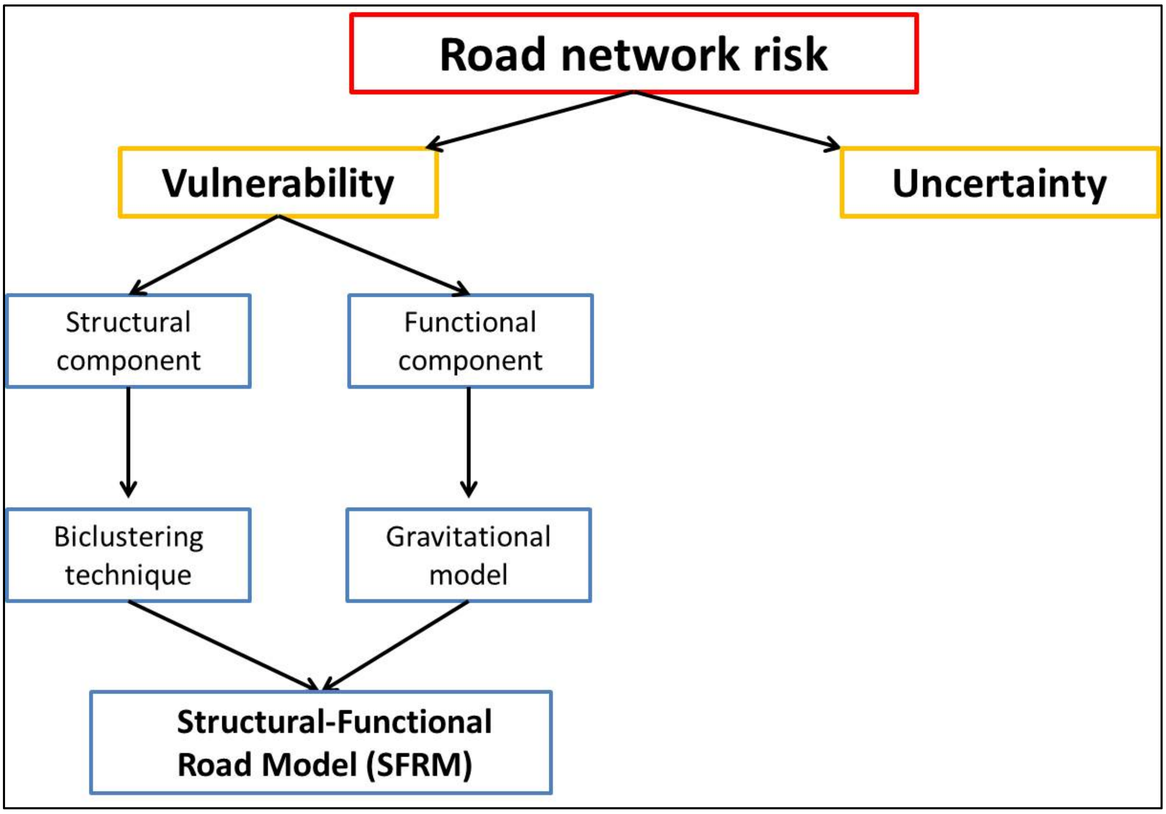

Figure 5-29: Structural – Functional Road Model results' framework

SFRM results should be analysed taking into account that it is critical infrastructure-based, specifically in this case, it is a hospital-based model, thus it cannot be read as the conventional trip-based models. Critical infrastructure-based model systems are different from the conventional trip-based model systems in the following aspects: first, critical infrastructure-based systems recognize that travel is derived from the need to pursue activities at different points in space and time, and thus focus on modelling activity participation; second, critical infrastructure-based model systems use a tour-based structure to represent and model travel patterns; third, activity-based systems accommodate interactions and joint activity participation among individuals in a household (Transportation Officials, Cambridge Systematics, 2012).

This phase is focused on presenting the results of the application of the formula proposed in the Methodology chapter to a real-world problem:

$$SFRM_l = S_{W1} + F_{W2} \tag{32}$$

$$w1 = \frac{1}{\sum R} * (R_1 * ACV_1) \tag{33}$$

To each bicluster is multiplied the ranking algorithm normalized value per the correspondent ACV value. Bicluster 1 can be pointed as example:

$$B1S_{W1} = \frac{1}{10} * (3 * 0.997) = 0.2991 \tag{34}$$

The same calculus is repeated to each of remain 3 biclusters (Table 5-26).

Table 5-26 Biclusters' score

Designation	Ranking algorithm	Bicluster score	Bicluster score stand
Bicluster 1	3	0.2991	0.45
Bicluster 2	4	0.3992	1.34
Bicluster 3	1	0.0987	-1.34
Bicluster 4	2	0.1980	-0.45

The results of the structural and the functional component were standardized and then summed. The functional component presents a wider range of value, in relation to the mean values, than the structural component. Table 5-27 shows that the road with the highest value is mainly determined by the functional component. Still, the influence of the functional component is smaller as the SFRM values become lower and lower. It is even possible to identify in the 20 highest value cases where the structural component value is higher than the value of the functional value; also there is one road among those with the 20 highest values that in the structural assessment, it was not possible to include in any bicluster- therefore it has a value of zero – and presents a value regarding the functional component above the average.

Table 5-27 SFRM results - the 20th highest values

SFRM Ranking	Structural component	Functional component	SFRM
1	-0.45	9.46	9.01
2	0.45	5.04	5.49
3	-0.45	5.14	4.69
4	-0.45	4.47	4.02
5	-0.45	4.00	3.55
6	-0.45	3.65	3.20
7	0.45	2.37	2.82
8	0.00	2.68	2.68
9	-0.45	2.94	2.49
10	0.45	1.68	2.13
11	-0.45	2.49	2.04
12	-0.45	2.45	2.00
13	-0.45	2.37	1.92
14	1.34	0.43	1.77
15	0.00	1.62	1.62
16	0.45	1.08	1.53
17	1.34	-0.02	1.32
18	1.34	-0.02	1.32
19	0.45	0.84	1.29
20	1.34	-0.06	1.27

The results (Table 5-28) indicate that only 19% of the roads' length is 0.5 S.D. above the regional average, indeed only 5% of the roads' length is 1.5 S.D. above the average. The values are in accordance with the 80/20 principle, i.e. 80% of the streets are less connected (below the average), while 20% of the streets are well connected (above the average); out of the 20% there is 1% of the streets that are extremely well connected. The 80/20 principle was formulated by Jian (2007) based on 40 US urban street patterns and he concluded that about 80% of streets with a street network have length or degrees less than the average value of the network, while 20% of streets have length or degrees greater than the average.

Concerning the relation between the highest values and the roads' hierarchy it is possible to observe the following trend: on the one hand, there are the national roads where the highest percentages correspond to the lowest values in terms of the SFRM model; on the other hand, there are complementary roads where the highest percentages correspond to the highest values in terms of the SFRM model (Table 5-29).

Although there is a trend, it cannot be claimed that the highest SFRM values correspond to the highest roads' hierarchy.

Table 5-28: SFRM classification per roads' length

SFRM Classification	Length	
	km	%
<-0,50 Std. Dev.	1225	35
-0,50 - 0,50 Std. Dev.	1578	46
0,50 - 1,5 Std. Dev.	471	14
1,5 - 2,5 Std. Dev.	110	3
> 2,5 Std. Dev.	75	2
Total	3459	100

Table 5-29: SFRM Classification and roads' hierarchy

SFRM Classification	Percentage of roads' length			
	Highway	Complementary	National	Total
<-0,50 Std. Dev.	10.7	11.7	77.7	100
-0,50 - 0,50 Std. Dev.	25.6	10.3	64.1	100
0,50 - 1,5 Std. Dev.	27.6	22.5	49.9	100
1,5 - 2,5 Std. Dev.	36.3	26.0	37.7	100
> 2,5 Std. Dev.	18.3	48.9	32.8	100

The next question is if the territorial dynamics is related to the road network vulnerability. Analysing Table 5-30 and Figure 5-30, the relation between the territorial dynamics and SFRM results becomes evident.

Table 5-30: SFRM Classification - Percentage of roads' length per territorial unit

Roads' length distribution per territorial unit and SFRM classes (%)					
Classification	<-0,50 Std. Dev.	-0,50 - 0,50 Std. Dev.	0,50 - 1,5 Std. Dev.	1,5 - 2,5 Std. Dev.	> 2,5 Std. Dev.
Beira Transmontana	13.5	14.7	19.8	18.6	0.0
Beira Alta	15.2	20.0	19.1	28.4	8.7
Beira Baixa	12.0	14.4	0.0	0.0	0.0
Central rise	42.2	17.6	14.2	11.8	18.4
Coastal zone	17.0	33.4	47.0	41.2	72.8
Total	100	100	100	100	100

The results demonstrate that SFRM is related to territorial dynamics. The roads with SFRM values above the average are mainly concentrated in the Coastal zone; 73% of the roads' length with a value 2.5 Std. Dev. above the average is located in the Coastal zone, neither Beira Baixa nor Beira Transmontana have roads with a value 2. 5 Std. Dev. above the average. Concerning the lowest values the results indicate that 42% of the values 0. 5 below the average are located in the Central Rise.

Figure 5-30 shows that the most significant concentration of values above the average is located in the Municipality of Coimbra, where there are located 2 of the 14 hospitals of the Central Region. Furthermore the importance of Aveiro, Coimbra and Leiria is evident in the map; in a crisis scenario the maintenance of an arterial route between these 3 areas should be a priority. Viseu plays a very important role in the network configuration of Beira Alta; Guarda also plays an important role in Beira Transmontana, but still it is not as important as the role Viseu plays in Beira Alta. Castelo Branco is the only district capital where the SFRM values are average or, in some cases, below the average. From the structural perspective, among the roads that are connected to Castelo Branco only A23- a highway that connects Castelo Branco to Guarda- presents a connectivity level above the regional average. From the functional perspective the Gravity Index of the service area of Castelo Branco Hospital is below the regional average; also the average Mobility Index of the population served by Castelo Branco Hospital is the lowest of the Central Region.

Based on the results, it is almost possible to design a corridor, which starts in Leiria, passes by Coimbra, Aveiro, Viseu and ends in Guarda. Still, there are two problems, the first is related to the low consolidation level of this corridor.The second problem is related to the necessity of how to relate this corridor to the rest of the Central Region territory in order to achieve a more cohesive territory.

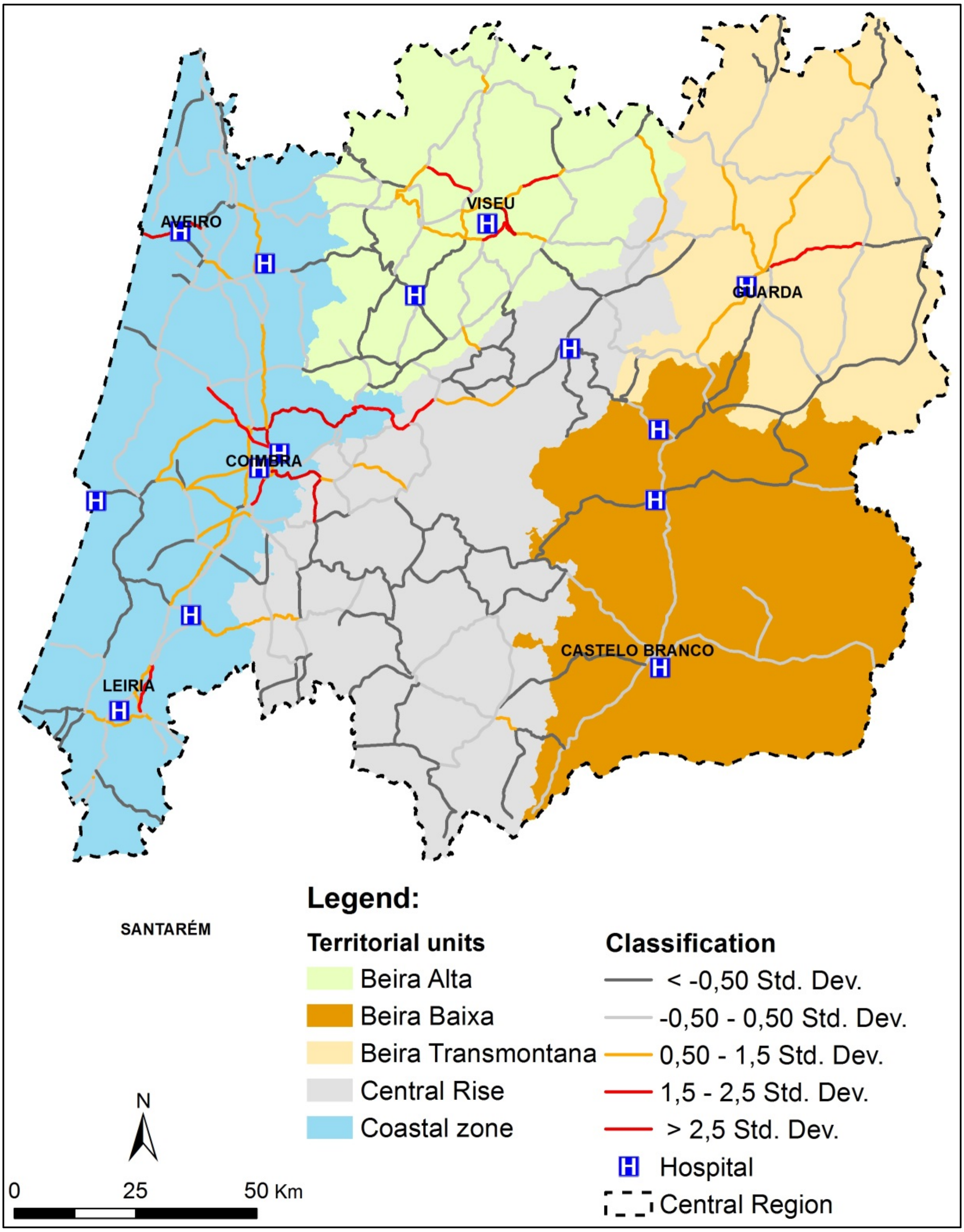

Figure 5-30: SFRM cartographic representation per link and territorial units

Just as in this work, CCDRC (2011a) an analysis of accessibilities in the system of the Central Region identified what this institution classified as structural corridors between Aveiro and Leiria, as well as between Aveiro and Guarda (Figure 5-31). CCDRC (2011a) also identified a corridor between Guarda and Castelo Branco, which wasn't identified in the present analysis. In the CCDRC (2011a) report as in the SFRM analysis the need to promote a higher cohesion between Eastern and Western areas was identified.

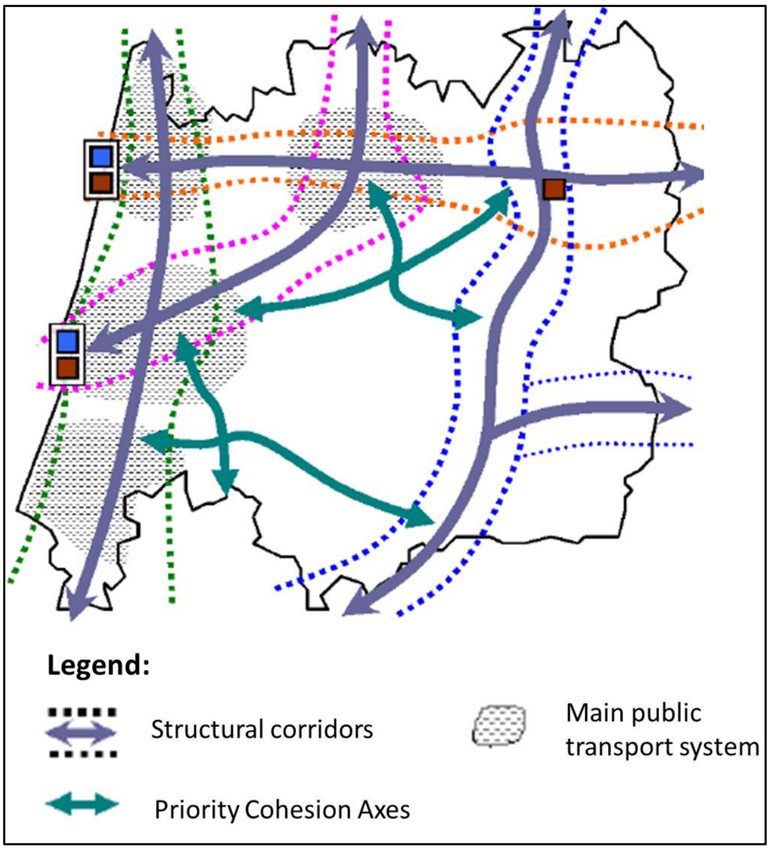

Figure 5-31: Accessibilities System
Source: CCDRC (2011a)

5.3.1. SFRM – Results discussion

One of the basic premises of this work is that a good knowledge of the territorial dynamics will allow a better definition of strategies to prevent and mitigate vulnerability to disruptions in the road transport system. The results of the application of the SFRM to the Central Region demonstrate the importance of the integration of the structural and functional component in the road network vulnerabilities analysis. SFRM is a step forward because it promotes an integrated assessment of structural and functional components, quantifying the share of accountability of each of the components in a road's level of vulnerability. The hypothesis that a dangle road, a meaningless element from a structural perspective, can play an important role in the accessibility to a critical infrastructure was confirmed. There are also cases where a road can play an important role in the accessibility to a hospital but its interruption doesn't have significant consequences in the normal functioning of the system because other road(s) can play the same role/access without substantial costs, such as an increase of travel time. The analysis of the SFRM outputs point out that the most important roads do not always correspond to the highest hierarchy roads, such as highways. Cases were identified where national roads are more important than the highways to the normal functioning of the system. This is a finding that can raise questions concerning road network management, once there can be cases where the local authorities are responsible for the maintenance of roads relevant to the regional system. This SFRM output also contributes to confirmation that a good knowledge of systems' dynamics is fundamental for a better definition of strategies. Although SFRM has been applied to the hospitals, it is interesting to verify that the results of the model are in line with the diagnosis and strategies that have been defined by the regional authorities (CCDRC, 2011). The territorial units with highest average SFRM values are also the areas identified by the regional authorities as most active from an economic and social point of view. The application of SFRM to a real case study allowed us to confirm that local territorial dynamics is a fundamental subject in critical infrastructure management.

The results of this thesis should help planning agents to identify areas where improvements should be introduced and emphasize a better understanding of the importance of territorial dynamics. There is a wide range of solutions that can prevent interruptions due to natural hazards: this work presents an innovative approach to defining priorities, not only in the prevention phase but also in the response to disruptive events, including awareness of the consequences of road disruption for the rescue services sent out to communities. SFRM is a useful tool because it identifies the key transportation routes to critical infrastructure. In the case study presented in this work hospitals were chosen, but the model can be applied to other area with other critical infrastructure. Therefore, it is important in the mitigation phase to define the paths of access to critical infrastructure. On the other hand, in the recovery phase it is important to include paths in the model that are the most important for the critical infrastructure versus the shortest path to the perimeter of damage, at this phase the question is which roads should be considered a priority for reconstruction during the recovery phase.

6. Conclusions

Critical infrastructure play a fundamental role in society's normal functioning. In spite of its importance, critical infrastructure concept is in flux (Pursiainen, 2009) none of the definitions that have been advanced have full consensus (Moteff, 2003; Popescu and Simion, 2012); this lack of consensus brings many problems related to the ways in which infrastructure is valued, leading to challenges in resource allocation or investment decisions. There are authors (Apostolakis and Lemon, 2005; Utne, 2011) and institutions (EC, 2008) that define critical infrastructure as physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens. Nevertheless, in this work several examples are found that show that critical infrastructure are critical because of the value they have in the normal functioning of the territorial system. As Roelich et al (2015) also suggest, this work shows that there is a need to rethink current infrastructure valuation, because focusing only on the physical infrastructure rather than the service it provides is unhelpful. Thus, in the definition of critical infrastructure risk management strategies, it is essential to incorporate population characteristics, such the level of mobility. There is the need to take into account the critical infrastructure's physical characteristics, but, unlike the current status quo, the strategies should take into account a heterogeneous and constrained demand. There are authors such Morency et al (2011) and Martínez and Viegas (2013) that analyzed how the different social groups, such as low-income people, face mobility challenges; still these works are not integrated with the characteristics of the territorial system.

The main research contribution of this thesis, within the critical infrastructure management context, is the SFRM – Structural Functional Road Model- a model that identifies the most vulnerable roads, using an integrated approach of the structural and functional components (Figure 6-1). Network measures can be applied widely in transportation practice to identify critical nodes and links in a system, which can provide necessary warning for potential attacks or faults. However, human behaviours are too complicated to be fully captured through a topological structure. So exploring the relationship between the underlying topological structure of transportation systems and the human movements on them is a challenging, but necessary task (Lin and Ban, 2013).

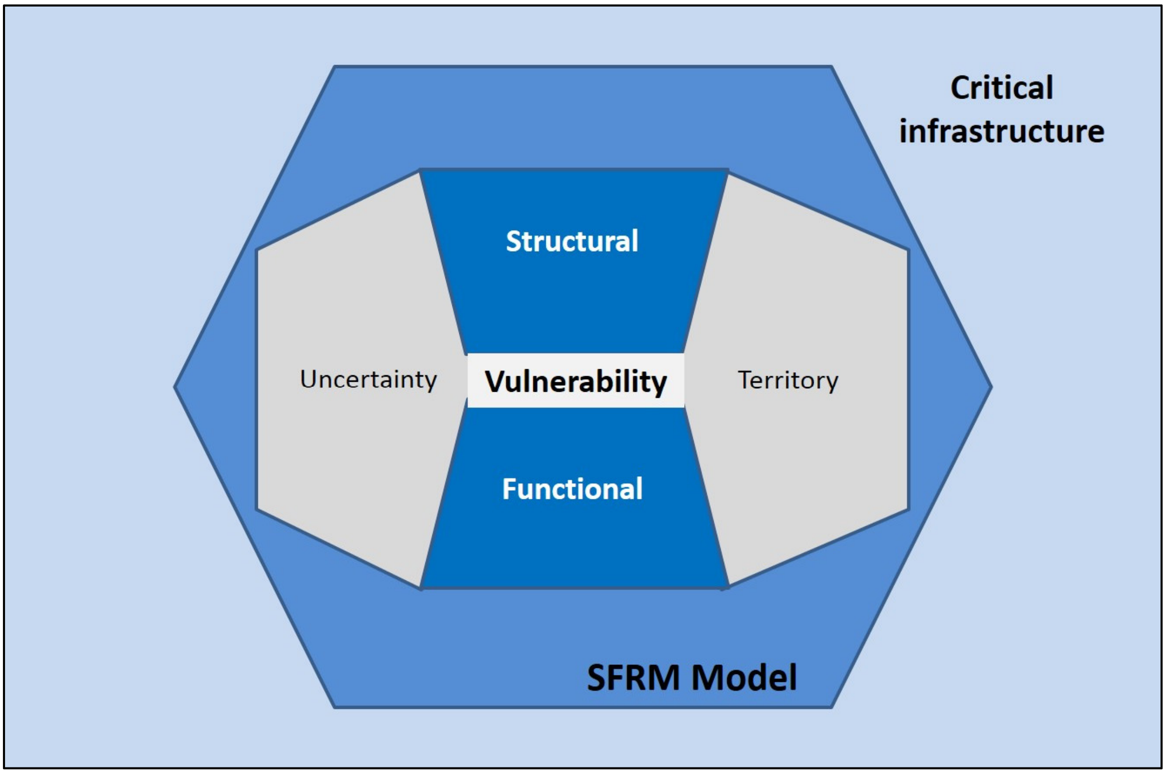

Figure 6-1: SFRM Model Framework

This work is dedicated to vulnerability assessment rather than to the evaluation of the multiple threats that can affect the normal functioning of the system. There is a need for establishing priorities; the resources are limited and the mitigation of hazards impact is not the sole objective of public policy on resource allocation. There is a need to determine which mitigation strategies to pursue from among the viable options (Murphy and Gardoni, 2007). There may be large costs associated with remedies and restoration of the transport system to a fully operational state. It is thus of interest to study the magnitude and distribution of impacts due to disruptions in different parts of the network, so that resources for prevention, mitigations and restoration can be suitably allocated (Jenelius, 2015).

Although the focus is on vulnerability, the uncertainty concept is also present throughout the work. As Johansson (2011) has already claimed, without uncertainty there is no risk; if it is for certain that there will be an explosion in a factory, there is no reason to talk about explosion as a risk. In this context the notion of risk involves some kind of loss or damage that might happen and the uncertainty of the transformation it would cause in an actual loss or damage. In spite of how much dedicated effort is put into improving the understanding of systems, components and processes through the collection of representative data, the appropriate characterization, representation, propagation and interpretation of uncertainty remains a fundamental element of the risk analysis of any system (Aven and Zio, 2011). The uncertainty component is fundamental in the decision making process, no robust decision exists that makes the choice of decision immune to uncertainty (Cox, 2012). Furthermore, the nature and scope of uncertainty may have implications on the range of groups to be involved and appropriate procedures to address uncertainties and to debate how decisions should be made in the light of unresolved uncertainty (Klinke and Renn, 2012). There are cases where the uncertainty is related to the limitations or even absence of knowledge concerning the possible outcomes of undesired effects; SFRM can be seen as a contribution to decrease the level of uncertainty. The scope of uncertainty analysis put forth in this work encompasses the structural and functional component of road network that may influence its vulnerability. This approach can be seen as a practical application of what has been conceptualized by Nielsen and Aven (2003) and Aven (2010). Representations of uncertainty are added to the analysis from the limited knowledge of causal relations in the system, still expressions of uncertainty should not be seen as part of the model, since it must be ascribed to itself and not to the system represented.

Territory plays a fundamental role in critical infrastructure management. Road network is strictly related to space and territory, thus it is relevant to analyse the impact of critical infrastructure management on spatial disparities and territorial cohesion. Ideally, a road network should be well-balanced, and capable of providing a population with similar conditions of access to critical infrastructure. Throughout this thesis it is possible to find several examples that demonstrate a territory's fundamental role in critical infrastructure management. The relevance of scale of analysis can also be pointed out as a result that shows that the role of the variables changes as the spatial area also changes. Road interruption scenarios demonstrate that the network at regional scale may have the capacity to reorganize itself and the consequences are mainly observed at local scale. Through the analysis, the results have demonstrated that the territorial dynamic plays a fundamental role in critical infrastructure management and the SFRM outputs were no exception. The highest SFRM values are mainly concentrated in the territorial units that CCDRC (2011a) points to as being more dynamic in an economic perspective. Furthermore, corridors between Aveiro and Leiria as well as between Aveiro and Guarda were identified; the need to promote higher cohesion between Eastern and Western areas also became obvious. The results prove the importance of an integrated approach between structural and functional components. For example, a dead end road is a meaningless element in a structural perspective, still it can be a very important road in a functional perspective since it can be the only access to a critical infrastructure such a Hospital.

This work brings a new perspective on critical infrastructure management largely thanks to spatial data techniques, which enable the data, from different sources, to be assessed in a more effective way. Cartographic representation was useful in the identification of spatial patterns and discussion of inequalities in the population's accessibility to critical infrastructure. Spatial modelling allowed us to identify spatial complementarities that otherwise wouldn't have been identified, such as the complementarities between Hospital 11, in Aveiro, and Hospital 10, in Águeda. The identification of these relationships can help to guide the management of transportation infrastructure towards efficient and equitable outcomes. Furthermore, the cartographic representation allowed the creation of scenarios, by simulating road interruptions whose consequences are evaluated by submodels that contribute to an efficient analysis.

Figure 6-2 shows the methodological dynamics that leads to SFRM, still the main point is that the assessment of road network vulnerability provides a set of outputs concerning issues such as territorial appraisal, road network classification or the different levels of population mobility. In spite of the variety and quality of the work that have been developed concerning the risk assessment and management of infrastructure networks, there is still a need for an integrated and applicable framework that accounts for the complexity of decentralized, networked systems that rely on human operation within a socio-technical context (Gómez et al, 2014). The model here proposed can be seen as a contribution for establishing a link between risk assessment and risk management. It can serve as an example that the SFRM results can lead to reformulation of the traditional road network functional hierarchy (highway, principal, national, municipal); results show that, especially at local scale analysis, the interruption of a national road can have more significant consequences than the interruption of a highway. The identification of the most vulnerable roads in the road network allows a more targeted decision, taking into account the specificities of each case. The results of SFRM assessment allow the selection and implementation of prevention and recovery activities and the establishment of risk management priorities for critical infrastructure stakeholders.

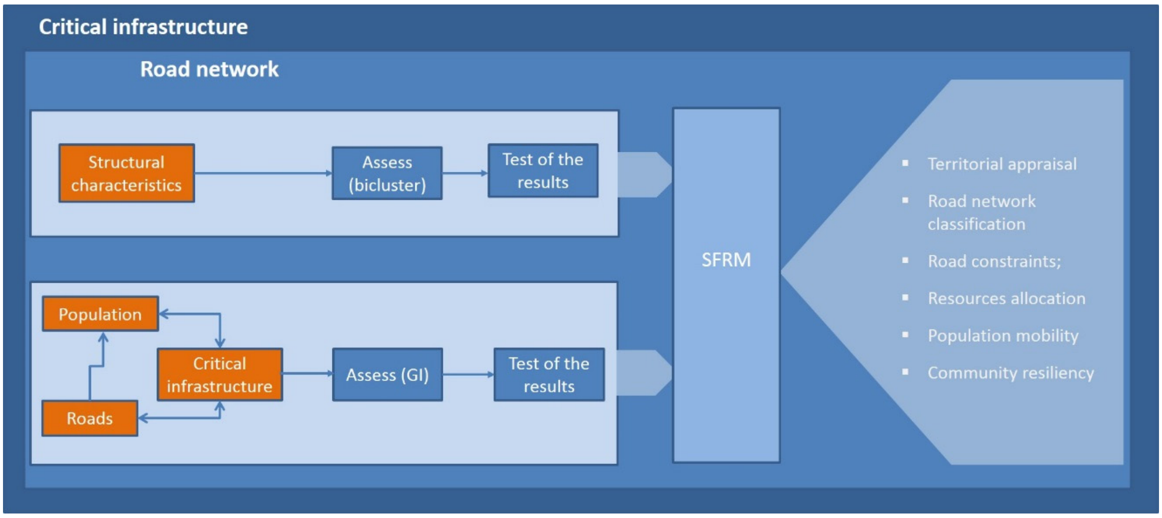

Figure 6-2: SFRM dynamics and outputs

Once the road network vulnerabilities are assessed, the following stage is focused on the risk management activities that can be implemented involving the stakeholders and the community (Figure 6-3). The model provides an assessment that leads to a more accurate judgement- acceptance, avoidance or transfer of the vulnerability level- and to a more informed decision making process. SFRM assesses the road network vulnerabilities from different approaches, which means it has a wide range of available options, considering territorial governance, social resilience and resources optimization. Promoting resilience strategies in preparation for critical infrastructure breakdowns is a tough call (Boin and McConnel, 2007), because the critical infrastructure breakdown is a possibility, and systems resilience is built on that system's ability to alter non-essential attributes, in order to be able to adapt to the circumstances (Manyena, 2006). A deep knowledge of the system attributes will allow stakeholders to define better resilience strategies. A road network classification helps identify where intervention is most needed and to determine issues such as if the road network structure is the most appropriate taking into account the resources allocation. Thus, the model here proposed supports resources allocation decisions concerning roads maintenance, priority roads to be restored. Moreover, the identification and adequate explanation of resources allocation options helps to promote public-private partnerships. The share of relevant information across the community and stakeholders contributes to build awareness of problems such as the access to public transport and helps to promote community partnerships.

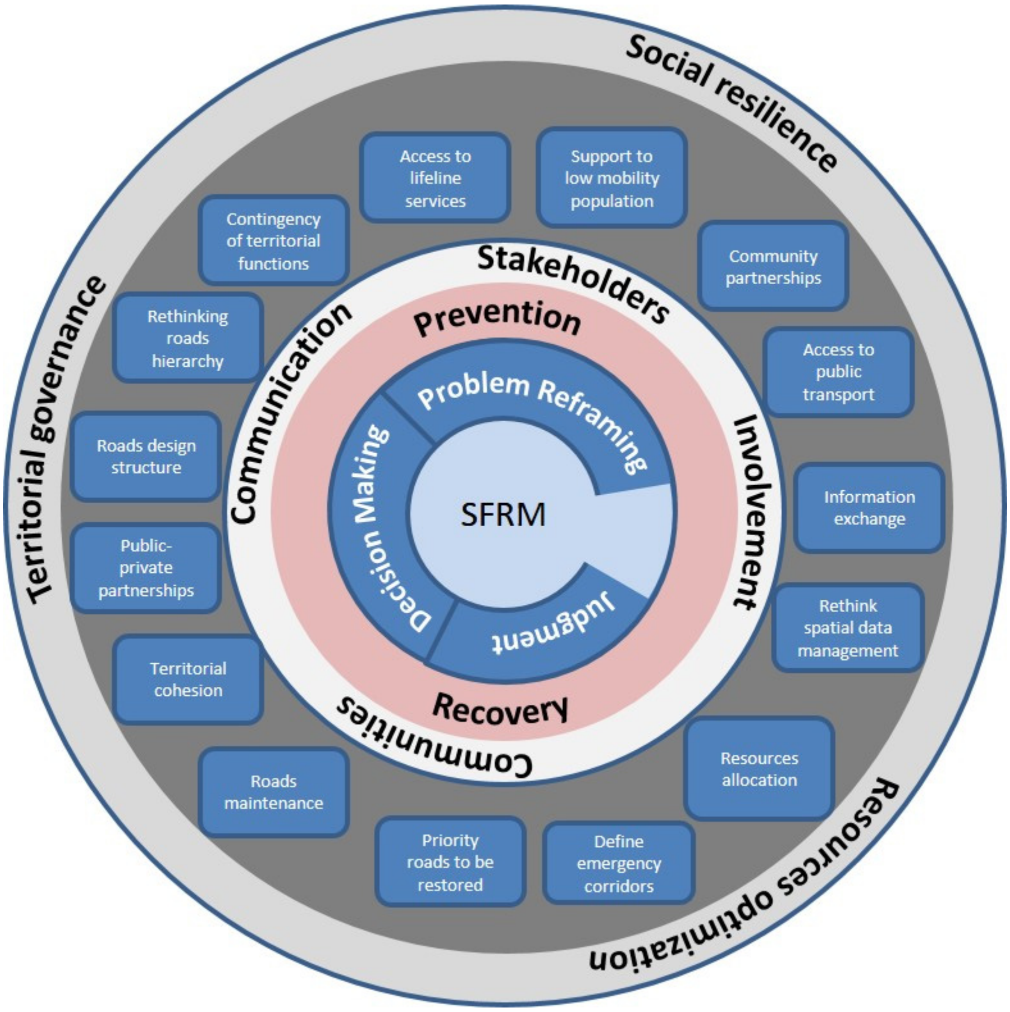

Figure 6-3: SFRM outputs and research challenges

Figure 6-3 demonstrates that critical infrastructure, such as road networks, are socio-technical systems, there are stakeholders and communities involved in the operation of a geographically dispersed network. Human involvement is fundamental to manage the complexity of this network system that plays different roles at different scales.

Summing up, the model here proposed allows optimizing resources, human and physical, because the resources are allocated according to the specificities of each case. The results of SFRM could also lead to reconsidering the way that critical infrastructure are located in a territory, as for instance in the case study where disadvantaged communities were identified regarding accessibility to Hospitals.

In spite of the best efforts, there are research limitations that should be referred. The model proposed here can be a useful tool in the assignment of roles and responsibilities to the different actors, although one of the main limitations of this work is in not having included the stakeholders' input. Some directions are indicated for resources allocation as well as the enhancement of the level of mobility of the population; still the feasibility of those proposals, some of them involving public – private partnerships, has not been assessed. SFRM is also limited by the fact that the model is static; it does not take into account the time dimension measuring variables such as the progressive degradation of a system's normal functioning in a road interruption scenario, which is important in determining organizational issues such as the number of institutions and amount of resources allocated in the different phases of the emergency response. However, the model proposed here allows simulating several scenarios without the need of changing the underlying data, which means that it is possible to obtain a set of results in a short period of time.

As for research challenges one of the next steps is to evaluate the level of acceptability of the road interruption consequences as well as to develop a flexible decision-making framework, providing support for taking into account the input of the several stakeholders involved in critical infrastructure management. SFRM may be used not only to display the facilities in a given area on a local and regional scale, but also to serve as a tool for better spatial reasoning, leading to better risk management decisions. Thus, one of the next steps is to take SFRM to judgment and decision making levels or even to reframe the problem. The proposed model can also be applied to a region located in a different cultural or economic context than the case study. Still spatial modelling is always dependent upon the context; the application of SFRM to other case studies would allow assessing the degree of dependence upon the context.

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