GI_Forum 2018, Issue 2
Page: 302 - 321
Full Paper
Corresponding Author:
andreas.ch.braun@kit.edu
DOI: 10.1553/giscience2018_02_s302

Critical Infrastructure Analysis (CRITIS) in Developing Regions – Designing an Approach to Analyse Peripheral Remoteness, Risks of Accessibility Loss, and Isolation due to Road Network Insufficiencies in Chile

Andreas Braun, Johanna Stötzer, Susanne Kubisch and Sina Keller
Karlsruhe Institute of Technology, Germany

Abstract

Modernizing societies become increasingly dependent on critical infrastructures (CRITIS), one of the most important of which is the road network. Road networks are vulnerable to hazards from the natural environment (e.g. extreme weather conditions, seismic and volcanic events, and landslides) and social environment (e.g. intentional attacks, traffic jams, roadblocks). Conversely, road networks impose vulnerability on their social environment (e.g. on people trying to leave disaster zones). Investigating the particular vulnerability of a given road network in order to increase its resilience is crucial for disaster risk reduction by spatial planning. However, in many cases in developing countries, the vulnerability of people still seems more pressing than the vulnerability of CRITIS. This paper develops an approach for investigating road network vulnerability in developing regions, using a Chilean example. However, the approach is sufficiently generic to be applied to comparable situations in other countries.

Keywords:

critical infrastructure (CRITIS), road network vulnerability, Chile, spatial planning in disaster risk reduction, generic model

1 Introduction

Critical infrastructures (CRITIS), such as road networks, and electricity, telecommunication, health and IT infrastructures, are becoming ever-more important in the course of societal development: people's everyday lives increasingly depend upon these infrastructures. At the same time, CRITIS are vulnerable to adverse man-made and natural effects (Murray & Grubesic, 2007). Even the failure of a single CRITIS can have severe human, economic, social and political consequences (Chang, McDaniels, Mikawoz, & Peterson, 2007; Boin & McConnell, 2007; LaPorte, 2007). However, the interdependency of infrastructures typically causes cascade effects, where the failure of one infrastructure causes the failure of another

(Rinaldi, Peerenboom, & Kelly, 2001; Little, 2002). People quickly become affected by such cascading effects if healthcare systems are involved (Arboleda, Abraham, Richard, & Lubitz, 2006). For example, an earthquake causing an electric power outage which leaves a hospital without electricity for too long or the isolation of the hospital from road connections quickly threatens human lives. For such cases, the 2016 World Risk Report pinpoints exactly the linkages between transportation infrastructure and disaster risk, and discusses the importance of having redundant transportation infrastructure (Garschagen, Hagenlocher, Sabelfeld, & Lee, 2016). Hence, the vulnerability of CRITIS has to be analysed and understood in order to develop disaster risk reduction (DRR) strategies (Kröger, 2008; Murray & Grubesic, 2007).

While infrastructure is usually well developed within urban centres (in most countries), it is frequently less developed in peripheral spaces (Seitz & Licht, 1995). This phenomenon heightens spatial disparities, which can cause negative effects on spatial development (Wu & Gopinath, 2008; Venables, 2005; Rodriguez-Pose & Gill, 2004). Hence, especially in emergency situations, but also for regional development during post-disaster phases, analyses of CRITIS are important in developing countries.

This article exemplifies these issues using a Chilean example, tailoring and adapting existing methodologies to the requirements found there.

2 Central Chile: Related work in CRITIS

In a seminal article, Hollnagel (2011) defines safety as 'the ability to succeed under varying conditions' (p. 1). Complementing research on circumstances under which infrastructures fail, analysing the conditions under which they work well is the way to more resilient infrastructures. In this context, resilience is defined as 'the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions' (Hollnagel, 2011) (p. 16). Hence, resilience depends on the following key abilities.

The first is learning from past events to know, what has happened (i.e. disaster analyses). The second is responding correctly to actual events by knowing what to do (i.e. effective emergency response). The third step is monitoring what is critical in order to know what to look for (e.g. early warning systems). Finally, the fourth key ability is the anticipation of potential events, on which The second and third key abilities depend for knowing what to expect (e.g. through disaster simulation).

Hollnagels rationale is used to structure the literature survey on road network vulnerability in Chile (Section 3 below). The study concentrates on the fourth cornerstone: anticipation by analysing critical scenarios of road network failure. Most closely related to this approach are two studies. Miquel, Mery, & Novoa (2010) explicitly analyse the vulnerability of roads in Chile under conditions of snow and ice in mountainous areas, due, notably, to the different road materials used (outside urban spaces, only major roads are paved). They conclude that unpaved roads especially need attention through maintenance and stabilization. The authors' focus is on the vulnerability of roads as physical objects, however; they do not discuss road networks as topological objects. Dueñas-Osorio & Kwasinski (2012) analyse CRITIS interdependencies and cascading effects in the face of the 27F Maule earthquake. They conclude that vulnerability to disasters could be reduced by exploiting couplings between systems (e.g. between telecommunication and power systems).

Regarding the third cornerstone, monitoring, several studies have discussed the need to increase urban or coastal resilience to natural hazards (predominantly tsunamis) through spatial planning. General argumentations for this have been published by Camus, Arenas, Lagos, & Romero (2016), Khew et al. (2015), Tomita et al. (2016). Some particular case studies include suggestions regarding roads and road networks, but do not present complete CRITIS analyses (Villagra, Herrmann, Quintana, & Sepulveda, 2016; Lunecke-Herrmann, 2015; Leon & March, 2014; Contreras & Winckler, 2013; Herrmann, 2013; Monsalves-Gavilan, Pincheira-Ulbrich, & Mendoza, 2013).

Regarding the first cornerstone, learning from past disasters, a large body of literature exists. These studies analyse thoroughly the damage to CRITIS, roads among them, and present summaries of the consequences of the damage. They include analyses of the 27F Maule earthquake (León & March, 2016; Evans & McGhie, 2011; Abrahamczyk, Maiwald, Schwarz, & Lobos, 2010; Elnashai et al., 2010; Moehle, Riddell, & Boroschek, 2010; Tang et al., 2010;); Aravena, Cataan, & Guerra (2010) have a particular focus on institutional and social drivers and consequences (); other articles concern volcanic eruptions (Elissondo et al., 2016; Wilson, Cole, Stewart, Cronin, & Johnston, 2011).

Advanced insights exist into several major disasters and their consequences, as discussed in some of the studies referred to above. Furthermore, focused analyses of other potential cornerstones in spatial planning for urban and coastal settings exist. However, the analysis of CRITIS vulnerability and strategies for increasing resilience could be improved. This is particularly true for rural areas, which tend to be neglected by Chilean planning authorities. Coastal and urban areas receive much greater consideration. This study strives to provide a contribution to both areas: (1) it provides a methodology for explicit analyses of CRITIS vulnerability, presenting first results; (2) it focusses on the rural, peripheral space. Thus, this contribution aims to help create the second cornerstone of resilience for the Chilean road network – how to respond correctly to emergencies.

3 Overview of CRITIS research into road network vulnerability

Following the seminal article by Berdica (2002), numerous studies on road network vulnerability have been published. It is beyond the scope of this article to provide an exhaustive review, but for examples see Jenelius & Mattsson (2015), Mattsson & Jenelius (2015), Wang et al. (2014), Jenelius & Mattsson (2012), and Murray, Matisziw, & Grubesic (2008). Due to the large number of scientific disciplines and research questions involved, the field of research is diverse. Approaches are distinguished by: (1) the overarching research perspective on the particular problems (e.g. engineering sciences, mathematics, system theory, risk research, game theory, spatial economy, geography, spatial planning); (2) the operationalization of the road network; (3) the vulnerability concept (e.g. node-based vulnerability, vulnerability measures based on connectivity or accessibility, or conceptualized via reliability) and (4) the metric or indices applied to measure vulnerability.

Mattsson and Jenelius (2015) propose to distinguish between topological approaches on the one hand, and further approaches based on graph theory or system-based approaches. The latter types of approach additionally consider both the supply and the demand sides of road networks, which can be represented by numerical values for the flows along the network (e.g. travel time, traffic flow, logistic cost etc.), or can be based on less data-intensive indices, e.g. reduced accessibility (Taylor, Sekhar, & D'Este, 2006).

Which approach is applied in a particular study will basically depend on (1) the research or management problem at hand, and (2) the data available to solve it.

4 Developing an approach for Central Chile

Within Chile as a whole, the road network is vulnerable to numerous natural hazards (earthquakes, landslides, tsunamis), but also to events of human origin. Human action can reduce the usability of the road network, for instance by traffic jams or diverse road blocks, intentional attack, labour strikes etc. To give an example: many Chilean roads are toll roads. The toll-gates and tollbooths are operated by people. During disasters, the toll-gates may become additional obstacles, for instance by being damaged or by slowing down traffic, or by operators not appearing for work because they are themselves escaping the area. The toll-gates may thus hamper the disaster response by impeding transport into or evacuation out of affected places. Hence, road network vulnerability has to be assessed using an approach that accounts for road failures due to social as well as natural events.

Such an approach has been published by Atzl & Keller (2013) and Keller & Atzl (2014) and is based on systems theory (mainly in the version of Günter Ropohl (2012)). It considers the infrastructure as a system. In the environment of this system, other systems are found (the social system and the natural system). To reduce complexity, the reality of each system is not analysed in its entirety, but only the processes at the system/environment borders (see Figure 1). Each of the systems operates autonomously, and in each system,

certain events can promote or hamper the functioning of other systems. Although the drivers of these events may be hard to track within the systems, they become obvious at the system/environment border. For instance, the seismic mechanisms underlying an earthquake do not need to be fully grasped for infrastructure planning. What is important is how they relate to the road network. Seismic mechanisms cross the system/environment border as seismic events that disrupt roads. The infrastructure planner merely needs to ask where such disruptions are most probable, or where they would be most critical. The same is true for the social environment. The social and institutional mechanisms leading to a labour strike may be irrelevant to the infrastructure planner, as long as it becomes clear how they cross the system/environment border (for instance, as roads blocked during demonstrations, or tollbooths that are closed).

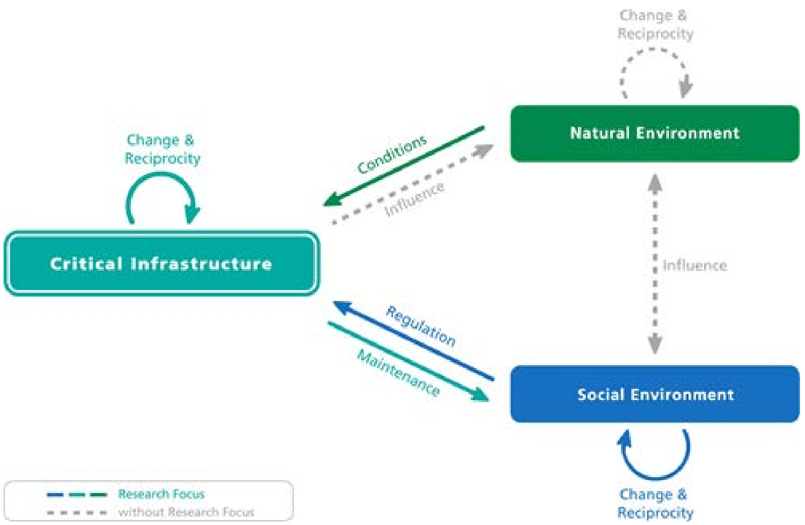

Figure 1: System theoretical model of roads and their natural and social environments. Each of the subsystems operates autonomously. At the system/environment borders, positive or negative influences become obvious. After Atzl and Keller (2013)

A second challenge of this study in Chile relates to data availability. Data-demanding approaches, requiring traffic flow data for instance, are simply unfeasible in Chile due to the limited amount of data available. Moreover, such approaches may impose other constraints. The more complex the data is, the greater the uncertainty about possible consequences in cases of disasters. While the traffic flow into an urban centre on a regular business day may be perfectly understood, the situation may change dramatically in an emergency. Hence, our approach builds upon less complex datasets. The demand-side of the road network is represented simply by how it is supposed to be used in an emergency – that is, by people trying to reach service centres or to be evacuated from them. The approach of this study builds upon graph theory, incorporating additional information. Finally, since the approach is incorporated into spatial planning, it needs to describe road network vulnerability in a spatially explicit way.

Vulnerability indicators: Remoteness Index

Taylor & Susilawati (2012) conceptualize road network vulnerability using a remoteness index (originally presented by GISCA (2009)), which is calculated for each of the nodes N of a graph G. They call the remoteness index '*ARIA*', standing for 'A Remoteness Index of Australia'. The rationale behind *ARIA* is not only to conceptualize the remoteness of a location on the basis of its position N within the graph G, but also to maintain a spatially explicit representation (Jenelius & Mattsson, 2015). Each geographical location, represented by coordinates (x, y), has a certain geographical distance $d_L(x, y)$ to its nearest service centres L. In the original article byTaylor & Susilawati (2012), service centres L are towns or cities, categorized according to the size of their population (see Table 1), and $d_L(x, y)$ is the distance a person has to travel along the road network, represented by E, to reach a service centre.

Table 1: ARIA service centre categories A-E (GISCA, 2009), taken from Taylor and Susilawati (2012), modified

Service centre category	Population	Mean distance to service centre (km)
A	≥ 250,000	413
B	48,000-249,000	239
C	18,000-47,999	139
D	5000-17,999	88
E	1000-4999	43
(F)	(200-999)	(na)

As one would intuitively expect, the greater the distance $d_L(x, y)$, the 'more remote' a place is considered to be. Since not only the largest next service centre, but the nearest service centre of any size may be relevant to people, the index is summed over the distances $dL(x, y)$. *ARIA* is calculated as follows:

$$ARIA\ (x, y) = \sum_L min\left\{3, \frac{d_L(x,y)}{\overline{d_L}(x,y)}\right\} \tag{1}$$

Here, $\overline{d_L}(x, y)$ is the average road distance of all places to their nearest category-L centre. Due to this normalization, *ARIA* does not try to identify absolute remoteness (interpreted as the total distance of a place from its service centre), but relative remoteness: it tries to identify places that are more remote than other places within the same region. Furthermore, by applying a minimum function with an upper threshold of 3, *ARIA* introduces some outlier control. If the distance $d_L(x, y)$ of a place is more than three times greater than the average distance $d_L(x, y)$, its *actual* value is no longer relevant, but is limited to 3 instead. As pointed out by Taylor and Susilawati (2012), regional focusses of the remoteness R may be easily defined by introducing weighting functions $w(x, y) \geq 0$, modifying to:

$$R(x, y) = w(x, y) \cdot ARIA(x, y) \tag{2}$$

Places x, y may be given a weight of $w(x, y) = 1$ if they are inhabited places, but a larger weight of $w(x, y) = 2$ if particularly vulnerable people live there. For instance, places where many elderly people live (e.g. retirement homes) may be prioritized in disaster risk reduction by giving them a greater $w(x, y)$. As pointed out by Murray & Grubesic (2007) and Schintler, Gorman, Kulkarni, & Stough (2007), vulnerability analyses should therefore be based upon two focal aspects:

- Identifying vulnerable nodes N
- Identifying critical edges E

Taylor & Susilawati (2012) follow a similar approach, operationalizing a locality as vulnerable if the loss of a small number of edges E significantly raises the remoteness R. An edge E is considered critical if its loss leads to a significant increase of the remoteness of a sufficiently large number of nodes N. The initial remoteness of a place $R^0(x, y)$ may be analysed under failure simulations of road networks (Schintler, Gorman, Kulkarni, & Stough, 2007). For instance, a certain edge E may be deleted from the initial graph G^0, modifying it to G^1, and the remoteness is recalculated as $R^1(x, y)$.

$$\Delta R(x, y) = \frac{R^1(x,y)}{R^0(x,y)} - 1 \tag{3}$$

The identification of vulnerable nodes can be performed straightforwardly by defining an upper lower threshold K_E of the edges that would have to fail to cause $\Delta R(x, y) \geq 1$. $K_E = 3$ states that if not more than 3 edges E are disrupted to double a location's remoteness $R(x,y)$, the location at (x,y) is considered vulnerable. On the other hand, an edge E is considered critical if its disruption in G^1 causes at least K_N nodes to suffer a $\Delta R(x, y) \geq 1$. Finally, *ARIA* is designed to be interpolated over an entire study region. To do this, Taylor & Susilawati (2012) provide theoretical foundations that use integral functions, which, in practice, are unnecessarily complex. In this study, therefore, the interpolation is done by geostatistical techniques.

The system-oriented approach described above will be operationalized as follows. As shown in Section 4.1, the road network is interpreted as a graph G with nodes N and edges E. Any process in the environment of the infrastructure system affecting its functioning is operationalized as events Ω on N and E. For instance, damage to a particular road E_i will be modelled as Ω: $\exists E_i \rightarrow \nexists E_i$. Any failure of a service facility in a particular place N_i will be modelled as Ω: $L_i \in F \rightarrow L_i \notin F$. Any deterioration in quality of road E_i (caused e.g. by blocking evacuation routes) will be modelled as Ω: $\omega_{T1}(E_i) > \omega_{T0}(E_i)$. Of course, events Ω can be modelled in a probabilistic fashion depending on particular conditions c_n, i.e. as $p(\Omega|c_1, c_2, \ldots, c_n)$. Here, the systemic approach described above comes into play. Infrastructure is embedded into social and natural environments, which are epistemologically heterogeneous. For instance, the natural environment is epistemologically deterministic (although frequently it has to be understood in a stochastic or chaotic fashion), and the social environment is contingent (although probabilistic assumptions can frequently be made). Now, having separated the various systems in which infrastructure (represented by $G(N, E)$) is embedded, defining the events depends on the scientific contributions of social and natural scientists. They can apply their models in their usual fashion, as long as they are able to reformulate their outcomes as $p(\Omega|c_1, c_2, c_n)$. Such a system-oriented approach is helpful to consistently describe and analyse the complexity of the socio-technical embedding of the road network, without having to relate to the complexity of the systems involved in its entirety. This is because the subsystems involved are independent of each other, leaving the investigations into their particular properties to disciplinary scientists, who afterwards are 'obliged' only to translate outcomes into $p(\Omega|c_1, c_2, c_n)$. From the perspective of the infrastructure research, then, it is irrelevant how Ω was defined in the first place. Every such Ω and its consequences can be analysed in a consistent fashion.

5 Modifying ARIA for developing regions: ARI

Differences from developed regions that require adaption

Chile is characterized by various particularities, which require adaptation. Firstly, spatial disparities are immense in Chile – especially in regions distant from the capital, Santiago de Chile. Chile's unique geography, ranging over 4,300 km from north to south and only 180 km on average from east to west, implies large latitudinal disparities at the national level. More importantly, the political, administrative and economic system is relatively centralized, causing considerable disparities between urban and peripheral areas (Nolte, 2004). The same holds true at the regional level. For instance, Región XI de Aysen, covers an area of 108,494 km^2 and has 94,271 inhabitants, a population density of only 0.9 people/km^2. Most people, 65%, live in the two largest cities –Coyhaique and Puerto Aysen. Región XI is thus characterized by large spatial disparities. While 65% of the population live at no distance from a service centre, the remainder may have to travel hundreds of kilometres to get to one.

Secondly, especially in regions such as Región XI, the interpretation of a 'service centre' may be different. Since the remoteness index is supposed to be applied to the whole of Chile, one has to take into account that the capital of the Región Metropolitana (RM) (Santiago de Chile) has over 6.5 million inhabitants, and the capital of the Región V (Valparaíso) has 280,000 inhabitants. In contrast, the capital of Región XI, Coyhaique, has only 44,500 inhabitants. Nonetheless, at least in a political and administrative sense, the cities are functionally equal. Hence, service centres ought not to be categorized according to their population. Furthermore, whereas one service centre may possess a hospital but no fire station, the situation may be the opposite elsewhere. Hence, emergency agencies and other actors relevant in cases of natural disasters may not all be found in the same place.

Thirdly, road conditions differ within Chile. Only major roads and a limited proportion of minor roads are paved. These differences have to be taken into account by adapting *ARIA* to the Chilean context. (Such a modification is realized in the next section.) The fourth particularity is the lack of complex traffic data in Chile (such as travel time, traffic flow, probability of traffic jams). Such data either do not exist or are unavailable. It should also be noted that the traffic situation in Chile is different from developed regions. While in many European countries traffic jams on interurban roads are frequent, they occur almost exclusively within urban areas in Chile. The fifth argument is the lack of information about travel behaviour specifically during disasters in Chile. If one uses more complex datasets, performing disaster scenario analysis depends on knowledge about how, for example, travel flow changes in the face of disaster, but such knowledge is hardly available in developing regions.

These five particularities make it necessary to adapt the methodology. No complex datasets should be required in order to perform disaster analysis in developing regions; road quality must be taken into account; the definition of service centres should be adapted appropriately; and finally, the threshold for remoteness needs to be adapted.

Mathematical adaptions for the requirements of developing regions

The particularities in Chile are mathematically accounted for as follows. Firstly, the greater spatial disparities do not allow for limiting the $d_L(x, y)/d_L(x, y)$ to an upper value of three by applying the minimum function. The minimum function performs outlier control. It limits to the value of 3 the distances to service facilities *L* for particular places with $d_L(x, y)/d_L(x, y) > 3$. While the mathematics are straightforward, the logic behind this needs some explanation. *ARIA* assumes that places which are more remote than three times the average are extraordinary phenomena, because the 'typical' place in the Australian study region is not extremely isolated (i.e. it is not more than three times the average of other places): places in the Australian study region are more or less homogeneously dispersed (see Taylor & Susilawati (2012), Figure 1, p. 766). Note that this is not true for Chile (or other developing regions). Here, places are considerably more dispersed. Some places, e.g. in Región XI, are much more isolated than three times the average (see Section 2). By defining the minimum function on an upper threshold of 3, a place 30 kilometres from the nearest hospital, for example, would be treated in the same way as one that was 300 kilometres from the nearest hospital (assuming an average distance of 10 kilometres). This, of course, would not adequately describe regional conditions. Keeping in mind, particularly, that the methodology developed here is intended to be sufficiently generic to be applied to different regions worldwide (it will be uploaded via QGIS repositories once finished), a slight adaptation has to be made: the upper limit of 3 is replaced by an upper limit of θ in the remoteness function, where θ is region-specific and can be defined by the researcher according to regional conditions. This adaptation is mathematically simple; it represents a modification which is relevant to regional science (see Sections 1, 2 and 5.1.).

Secondly, as stated above, service centres (termed *L* by Taylor and Susilawati (2012)) are defined differently. Instead of cities of different sizes, here, *L*s are agencies or services required in disasters (see Table 2). The rationale behind this is that, in an emergency, injured people will have to travel not to the nearest city, but to the nearest hospital.

Table 2: *ARIA* service centre categories A-E used for the *ARI* index

Service centre category	Type
A	Hospital
B	Fire department
C	Police
D	Food & Water supply

In case of fire, help will not necessarily come from the nearest city, but from the closest fire station. And finally, people will depend on the nearest supplies of food and water. Hence, service centres are differentiated functionally and not according to their populations. We therefore refer to them as *F*s.

Thirdly, the differences in road network quality have to be addressed. Travelling along a dirt road takes considerably longer than travelling along a paved or even a gravel road. *ARIA* does not integrate travel time parametrically, and this is not altered in our method. Including travel time explicitly, as other approaches do, increases the amount of data required to a level that cannot be maintained in Chile (where, for most situations, travel time data are not available). In addition, even if data were available, including travel time explicitly would not be relevant. The aim of this approach is to identify peripheral spaces and not to make assumptions about individual mobility. Consequently, we introduce a weighting parameter $\omega_T = f(r_T)$, where r_T is the type of road. The parameter is set as $\omega_T = 1$ for paved roads, is $\omega_T = 3$ for gravel roads and $\omega_T = 6$ for dirt roads. Road quality is set as $\omega_T = 1$ for paved roads, $\omega_T = 3$ for gravel roads, and $\omega_T = 6$ for dirt roads. Note that these values are not taken explicitly from the literature; they come from the experience of the authors who, during the last six years, have spent several months investigating in Chile. However, comparative studies from Chile (for several types of vehicles and different road materials) come to similar values (Echaveguren & Arellano, 2015; Arcos, Sanchez, & Villada., 2008; Pradena & Echaveguren, 2008). The threshold for remoteness θ = 6. The rationale for this is the large spatial disparity. As Figure 2 (left) shows, the distances from places to their nearest hospitals are relatively heterogeneous. Assuming that all places with a distance that is more than three times greater than the average are treated identically does not seem justified with regard to this heterogeneity. Hence, the value was doubled to θ = 6.

Given these adaptions, the *ARIA* index can be modified to the following formula, to give a more generic *ARI*:

$$ARI\ (x,y) = \sum_F min\left\{\theta \cdot \frac{w_T \cdot d_F(x,y)}{w_T \cdot \overline{d_F}(x,y)}\right\} \qquad (4)$$

These modifications aside, *ARI* is applied in the same fashion as ARIA to describe the remoteness *R* of a location, to calculate its change Δ*R* under simulated failure scenarios, and to identify vulnerable links on the basis of $\varkappa_E$ and critical links on the basis of $\varkappa_N$. Furthermore, *ARI* can also be interpolated on the basis of geospatial techniques.

6 Basic approach of the large-scale implementation

The implementation of the generic accessibility index/model described here relies on Open Street Map (OSM), which is a freely and widely available source of road network and city point data, including point data on the service facilities. OSM data have been evaluated for accessibility tasks in Chile by Steiniger, Poorazizi, Scott, Fuentes, & Crespo (2016). Steiniger et al. admit some quality constraints but recommend the data in the absence of other alternatives, given that in Chile road data are administered by several ministries, and are often inconsistent and always hard to acquire.

The software used for this approach is PostgreSQL version 9.3.14, and pgRouting (v. 2.4.1) to provide geospatial routing and other network analysis functionality. The OSM data of the study region are imported into a spatial database. The graph needed for routing is then created, by defining a file which names the road classes required, resulting in the routable $G(N, E)$. The data preparation of the OSM dataset is performed in an automated fashion. The transformation of the simple road network into a topologically correct graph ensures fast computation for large datasets. In the next step, the attributes of the point data are considered with respect to the existing service facilities – hospitals, police stations and fire stations. These previously separate datasets are merged into a graph enabling routing capabilities. Next, the places of interest (POI), mainly settlements and disaster facility locations, are merged with the road network. The algorithm automatically finds the node N on the graph which is closest to the POI. Information regarding the vertex (node on the graph) to which it is nearest, and at what distance, is then associated with the POI. When no such vertex is available, new vertices are integrated automatically. The edges E are split in two by these new vertices. Afterwards, the Dijkstra Algorithm is used to find the shortest paths from all the vertices of the POI to all the vertices of facilities of type F, using road distances and weigtings for the paths. Finally, the *ARI* index is calculated using Equation 4. The actual index calculation, therefore, is based on the shortest paths between all towns and cities. Optionally, the weights of single road segments are adapted according to road attributes, e.g. surface material and speed limit. In the case of Chile, there are three categories for the attribute 'road surface': asphalt, gravel and dirt.

7 Preliminary results

In a preliminary study, Región XI de Aysen was analysed regarding road network vulnerability. As functional centres (Fs), hospitals were used, of which five are found within the Región (Coyhaique, Puerto Cisnes, Puerto Aisen, Chile Chico, Cochrane). At the outset, the status quo – (i.e. the actual status of the road network, without any disruption) of *ARI* was calculated on the basis of the values presented in Figure 2. Table 3 visualizes the findings.

As Figure 2 (centre) shows, the *ARI* describes remoteness R in Región XI in a plausible fashion. Places close to hospitals yield low values; places distant from them yield larger values. Due to the ω_T values, it is not only distance that influences *ARI,* but also road quality. For instance, places 07, 40 and 41, despite being fairly close to Puerto Cisnes hospital, yield high values, since people have to travel over dirt roads to get there. The opposite is the case for paved roads, like place 12. The area in the triangle Coyhaique – Puerto Cisnes – Chile Chico, where paved roads are found, yields the lowest values.

Particularly isolated places are 29 to 31 in the south, and the places far north of Puerto Cisnes. Here, construction of an additional road may reduce people's vulnerability in case of disasters.

Table 3: Summary of the CRITIS analysis of the road network. Numbers and names of places as in Figure 2. ARIsq is the value assuming status quo conditions (i.e. intact road network). Vuln. refers to the vulnerability of a place. It represents the number of roads whose failure would lead to a significant increase in the remoteness of the place

No.	Name	ARI_{sq}	Vuln.	No.	Name	ARI_{sq}	Vuln.
1	La Tolva	1.76	7	23	Fachinal	0.68	3
2	El Venado	1.68	5	24	Mallin Grande	1.03	1
3	La Junta	1.52	3	25	Puerto Guadal	0.94	0
4	Rio Claro	1.78	6	26	Puerto Bertrand	0.58	3
5	Puente Rosselot	1.59	5	27	Cochrane	0.00	0
6	Puyuhuapi	0.94	2	28	Tortel	1.81	3
7	Las Termas	1.48	2	29	Rio Bravo	0.01	0
8	Puerto Cisnes	0.00	0	30	Villa O'Higgins	0.01	0
9	Puerto Gaviota	1.59	5	31	Teniente Merino	0.01	0
10	El Lobo	0.35	4	32	Puerto Chacabuco	0.10	5
11	Villa Amengual	0.56	1	33	Puerto Aysen	0.00	0
12	Villa Maniguales	0.31	2	34	Parque Eden	0.06	2
13	Villa Ortega	0.37	0	35	Melinka	1.06	3
14	El Balseo	0.13	0	36	Estero Pitipal.	2.85	6
15	Coyhaique	0.00	0	37	Bahia St. Dom.	2.93	5
16	Valle Simpson	0.11	9	38	Melimoyu	3.61	0
17	El Blanco	0.25	12	39	Lago Verde	2.50	7
18	Balmaceda	0.27	11	40	Villa La Tapera	1.20	2
19	Villa Cerro Cast.	0.45	7	41	Rio Cisnes	1.64	4
20	Puerto Ibanez	0.54	3	42	Puerto Murta	1.74	0
21	Peninsula Levican	0.90	6	43	Rio Tranquilo	1.51	0
22	Chile Chico	0.00	0				

In the next step, critical links were identified (see Figure 2). First, road segments were removed from the dataset one by one (i.e. there was no simultaneous removal of several segments). Then, places $\varkappa_N$ that suffered at least $\Delta R(x,y) \geq 1$ were identified. If $\kappa_N \geq 2$, the road was considered critical, highlighted in red in Figure 2 (right). A large road segment in the north of Puerto Cisnes was identified as being critical, because as many as 11 locations will become isolated if the road is disrupted there. To the south and to the north of Coyhaique, other critical segments are found. This is where 16, 17 and 18 connect to their service centre (Coyhaique hospital). This situation could be improved by connecting these locations to Chile Chico as well. Another segment leading to Chile Chico is critical. If it is disrupted, places 18 and 19 cannot reach their service centre. Here, spatial planning could reduce road network vulnerability, by connecting the small road segment running south-west of 19 with the road segment running south-east from Chile Chico.

8 Discussion

This paper has presented a modification (*ARI*) of the *ARIA* index by Taylor & Susilawati (2012) and GISCA (2009), for spatial planning purposes in Chile. Note that mathematically *ARI* is similar to *ARIA*, but takes into account some particularities of the country. Hence, it maintains the advantages of an existing, tested and validated method, correcting only for some locally determined shortcomings. ARI does not provide substantial contributions to the methodological advancement of CRITIS research according to the state of the art in developed countries. However, research in developing countries follows a different logic of innovation. Here, the question is not so much finding methodological innovations in the sense of new and better algorithms, exploiting new and better datasets, combining individual disciplines perspectives and elaborating more potent explanatory models. Rather, innovation is more strongly focused on the question of how insightful and valid analysis can be performed in a context of data scarcity, uncertainties in datasets and gaps in basic knowledge. At the same time, particularities have to be taken into account that differ from those of developed countries. For instance, road materials vary, conditions regarding traffic jams differ, contrasts between centres and periphery are much more pronounced. These are the typical challenges that technology-intensive research methods (e.g. remote sensing, GIS, CRITIS) face in developing countries (Braun, Sturm-Hentschel, & Hinz, 2018; Sturm-Hentschel, Braun, Hinz, & Vogt, 2013). This is where the contribution of this paper lies.

CRITIS research based on *ARIA* and *ARI* has several advantages from the perspective of spatial planning and regional science (see Sections 1, 2, 4 and 5). Firstly, the indices maintain a geographical perspective by using geographical distances $d(x, y)$. They do not reduce the spatial distribution of objects to their topological dimension, i.e. to $G(N, E)$. Such a perspective is insightful for other disciplines active in CRITIS research (e.g. some engineering and economics disciplines). However, spatial planning always needs to relate its considerations and decisions to geographical space.

A particular advantage of the indices is the normalization: the indices use relative remoteness, which stresses the relationship between remoteness and spatial disparities (Wu & Gopinath, 2008). Spatial disparities are important to spatial planning, because they often concern negative phenomena (such as differences in public welfare, local unemployment and rural depopulation), which spatial planning tries to manage proactively (Wu and Gopinath, 2008; Venables, 2005; Rodriguez-Pose and Gill, 2004).

Región XI de Aysen: Road Network and Initial Situation | **Región XI de Aysen: ARI values: status quo** | **Región XI de Aysen: Critical roads (several isolated places)**

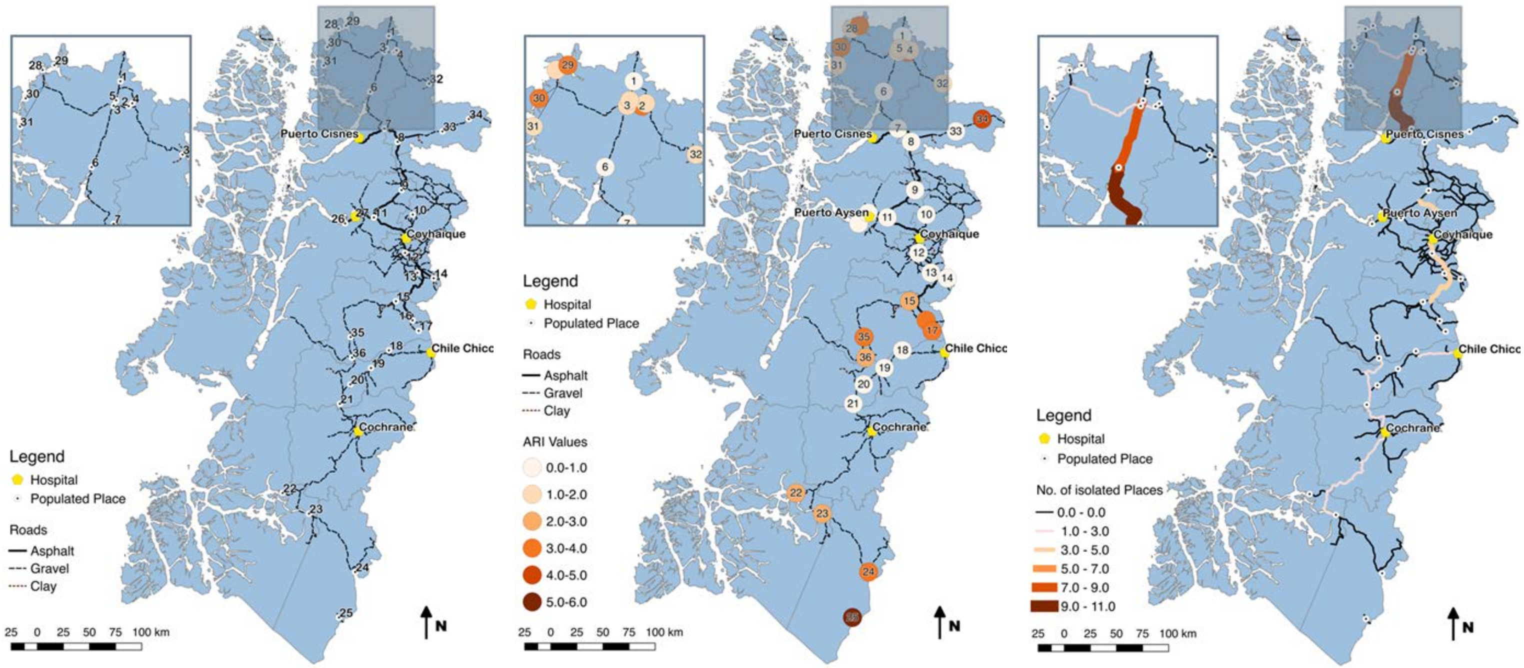

Figure 2: First results of the vulnerability analysis. Left: map showing the region and its road network, infrastructures and centres of population. Centre: ARI values for the centres of population (status quo). Right: Identification of critical roads, i.e. roads causing at least two places to double their ARI values if disrupted

The indices require relatively little data – just some basic representation of the road network and its quality, for instance in a GIS, and information about the location of the service centres *F*. More sophisticated data sources (such as traffic flow, travel time etc.), which furthermore differ according to the scenario under investigation, are not required. Hence, the indices are applicable to large countries such as Chile. Although the indices require little data, they do provide some information on the demand-side of the road network as well, because *ARIA* (and hence *ARI*) does not consider *G*(*N, E*) merely topologically. Rather, *ARIA* and *ARI* implicitly account also for demand and road users' behaviour. They assume that people in disaster scenarios will try to reach a service centre – or get reached by emergency agencies from a service centre. Remoteness *R* is straightforwardly defined by people's possibilities to get aid from the service centres. Hence, the indices are applicable to spatial planning efforts in disaster risk reduction. The fact that *ARIA*/*ARI* are relatively data-sparse make them relatively straightforward to interpret, analyse, compare and modify. For instance, the indices can be meaningfully interpolated to produce spatially-explicit maps, thus highlighting spatial disparities in terms of remoteness and disaster resilience. Such interpolation may not be possible for more sophisticated algorithms. Another advantage is the interpretability by a large range of actors. Taylor & Susilawati (2012) produced visual maps and failure scenarios which can be interpreted correctly by various actors, such as political stakeholders and emergency agencies. A final advantage of the mathematical simplicity is that the indices can be adapted to the particular requirements of the study site at hand.

However, these advantages have to be set against several considerable disadvantages. First of all, since *ARIA* and *ARI* primarily focus on distances *d*(*x, y*) to service centres (*L* or *F* respectively), they cannot be used effectively to assess the vulnerabilities within the service centres. Although regional capitals will have $d(x, y) = 0 \forall L, F$, i.e. implying a remoteness $R = 0$, the results may be misinterpreted. It does not mean the road network is not vulnerable there; it simply shows that *ARIA* and *ARI* are not meaningful within urban areas, and that other methods have to be applied to assess road network vulnerability there (Lomax, Schrank, Turner, & Margiotta (2003).

Secondly, since the indices do not use traffic flow, they are, of course, not meaningful in contexts which depend on the analysis of such data, for instance in network economy. These disciplines will acknowledge that *ARIA* and *ARI* stress resilience strategies in disaster risk reduction by spatial planning and that their particular research question will have to rely on other descriptors of road network vulnerability. Thirdly, the upper thresholds for remoteness θ are defined individually for different regions. This makes sense given the disparities between the different regions in Chile (regarding policy, socio-economics, demographics, geography). Nonetheless, having a considerable difference between θ_{IX} and θ_X (Región IX and Región X), for example, may create interpretation problems at the borders (where the interpolation of ARI_{IX} and ARI_X may contrast sharply). Nonetheless, the disparities change gradually from the central to the remote regions, such that these interpretation problems seem to be manageable. Finally, an important drawback of the indices is that they do not take into account the physical geography of the study sites, most of all the topography. Other approaches have been published in which topography is explicitly considered, which is crucial for calculating travel costs for instance. In order to analyse remoteness of places in the face of disaster, topography also plays a role, but may be less relevant. Furthermore, it is easy to include topography in future work, by extending ω_T to $\omega_T = f(r_T, T_o, \ldots)$, where topography T_o is represented by various appropriate factors.

As for any other method, *ARI* should not be overrated. It is an index, purpose designed for a particular problem (peripheral remoteness), from the perspective of particular disciplines (regional science), for a particular objective (vulnerability reduction, or increase in the resilience of CRITIS in developing countries). The authors assume that *ARI* is readily applicable and sufficiently generic to be transferred to similar settings in other countries. For other settings, different indices would have to be elaborated.

Road network vulnerability analysis based on *ARI* is relevant for spatial planning, because the index easily allows the analysis of disaster and planning scenarios. The model and concept of implementation presented here allow real-time application in case of any disaster affecting parts of the road network. The exclusion of these affected roads from the graph and a recalculation of the accessibility index enables the identification of critical areas, characterized by insufficient access to service facilities. Disaster scenarios can be simulated by intentionally degrading the graph (e.g. by deleting edges) and analysing the consequences. Planning scenarios can be evaluated and compared straightforwardly. *ARI*, thanks to its mathematical structure, allows for three different strategies to be compared. Consider a scenario analysis which demonstrates that a subregion is prone to becoming isolated during disasters, since it is connected by only a single dirt road ω_T which, due to its winding course, implies a lengthy journey d_F to the hospital *F*. We refer to the the first strategy as the ω_T *-strategy*. It consists in improving road quality. The second, d_F *-strategy,* consists in building a shorter, more direct road. The third is the *F -strategy*, which consists in leaving the road network as it is and constructing a hospital *within* the isolated subregion instead. Note that these strategies can be straightforwardly analysed and compared with a consistent methodology, e.g. modifying the road network and service centres in a GIS and recalculating *ARI*, followed by Kriging. The results would be ΔR layers for each of the strategies under comparison. These layers could be integrated easily into cost-benefit analyses, in the planning process.

9 Conclusion and future work

The approach for the analysis of road network vulnerability in Chile presented here is derived from published and tested literature. It combines the requirements of spatial planning for disaster risk reduction with the requirements of developing countries, where data availability is an issue. The approach has been proven to be generally feasible. In future work, the road networks of the entire country will be analysed (after some further evaluation of the methodology). Despite the fact that the approach was developed for Chile, thanks to its generic structure there are no a priori limitations for a transferability to comparable cases.

Future analysis will build upon the general research lines in the 2016 World Risk Report (Garschagen, Hagenlocher, Sabelfeld, & Lee, 2016) and the approach proposed by Schintler, Gorman, Kulkarni, & Stough (2007) for the analysis for CRITIS vulnerability. The latter propose to analyse CRITIS according to the following workflow. The first step is infrastructure assessment, for example of the road network, according to several parameters, namely density, capacity, bottlenecks, structure, baseline maintenance costs and interdependencies. For transport infrastructures, this translates into areas that are densely developed with major and minor roads leading to numerous locations (hospitals, power plants, administrative centres etc.) and connecting roads. This provides a general evaluation of the state of vulnerability of the critical infrastructure.

Schintler, Gorman, Kulkarni, & Stough's next step is verification. The general image of CRITIS vulnerability is verified by failure simulation, which consists in identifying the most vulnerable nodes and most critical edges. This step confirms whether the general assessment of CRITIS vulnerability is correct and leads to the third step, consequence estimation. For each failure scenario, three types of consequences are evaluated. Firstly, the population affected (e.g. the number of people isolated); secondly, the businesses affected (e.g. an economic indicator of the number of enterprises isolated, or their percentage contribution to the last gross regional product); thirdly, the interdependent infrastructures affected (e.g. the number of hospitals becoming unreachable in case of infrastructure failure).

The consequences of the most severe failure scenarios will then be integrated into spatial planning. Here, three types of strategies for vulnerability reduction can be compared using the indices proposed, as described above.

References

Abrahamczyk, L., Maiwald, H., Schwarz, J., & Lobos, D. (2010). Das Magnitude 8.8 Maule (Chile)-Erdbeben vom 27. Februar 2010 - Ingenieuranalyse der Erdbebenschäden. *Bautechnik*, 87(8):462–473.

Aravena, H., Cataan, C. F., & Guerra, P. (2010). Dimensiones geográficas territoriales, institucionales y sociales del terremoto de Chile del 27 de febrero del 2010. *Cuadernos de Geografía*, 1(1):34–54.

Arboleda, C., Abraham, D., Richard, J., & Lubitz, R. (2009). Vulnerability assessment of health care facilities during disaster events. *Journal of Infrastructure Systems*, 15(3):149–161.

Arboleda, C., Abraham, D. M., Richard, J., & Lubitz, R. (2006). Impact of interdependencies between infrastructure systems in the operation of health care facilities during disaster events. In *Joint International Conference on Computing and Decision Making in Civil and Building Engineering: June*, 14–16.

Arcos, C., Sánchez, S., & Villada, C. (2008). Evaluación de rutas para el transporte de productos perecederos en el sector rural. *Biotecnología en el Sector Agropecuario y Agroindustrial*, 6(2): 40-46.

Atzl, A., & Keller, S. (2013). A systemic approach for the analysis of infrastructure-specific social vulnerability. In Cutter, S. L., & Corendea, C. (Eds.), From Social Vulnerability to Resilience: Measuring Progress toward Disaster Risk Reduction. Bonn, Germany: United Nations University, Institute for Environment and Human Security, 17: 27-43.

Berdica, K. (2002). An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy*, 9(2):117 – 127.

Boin, A., & McConnell, A. (2007). Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience. *Journal of Contingencies and Crisis Management*, 15(1):50–59.

Braun, A.C., Sturm-Hentschel, U., & Hinz, S. (forthcoming): A Settlement Process Analysis in Coastal Benin – Confronting Scarce Data Availability in Developing Countries. In: Hinz, S., Braun, A.C., & Weinmann, M. (Eds.), *Object and pattern recognition in remote sensing – Modelling and monitoring environmental and anthropogenic objects and change processes*. Whittles-Publishing: Dunbeath/Scotland, 361-387.

Camus, P., Arenas, F., Lagos, M., & Romero, A. (2016). Visión histórica de la respuesta a las amenazas naturales en Chile y oportunidades de gestión del riesgo de desastre. *Revista de Geografía Norte Grande*, 1(64):9–20.

Chang, S., McDaniels, T., Mikawoz, J., & Peterson, K. (2007). Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 ice storm. *Natural Hazards*, 41(2):337–358.

Contreras, M., & Winckler, P. (2013). Pérdidas de vidas, viviendas, infraestructura y embarcaciones por el tsunami del 27 de febrero de 2010 en la costa central de chile. *Obras y proyectos*, 3(14):6–19.

Dueñoas-Osorio, L., & Kwasinski, A. (2012). Quantification of lifeline system interdependencies after the 27 February 2010 mw 8.8 offshore Maule, Chile, earthquake. *Earthquake Spectra*, 28(S1): S581–S603.

Echaveguren, T., & Arellano, D. (2015). Análisis estadístico de la velocidad de operación de vehículos pesados en pendientes ascendentes. *Obras y Proyectos*, 18(2015):6–18.

Elissondo, M., Baumann, V., Bonadonna, C., Pistolesi, M., Cioni, R., Bertagnini, A., Biasse, S., Herrero, J., & Gonzalez, R. (2016). Chronology and impact of the 2011 Cordón Caulle eruption, Chile. *Natural Hazards and Earth System Sciences*, 16(3):675–704.

Elnashai, A., Gencturk, B., Kwon, O., Al-Qadi, I., Hashash, Y., Roesler, J., Kim, S., Jeong, S., Dukes, J., & Valdivia, A. (2010). *The Maule (Chile) Earthquake of February 27, 2010: Consequence assessment and case studies.* Technical report, Mid-America Earthquake Center. Retrieved from: https://www.ideals.illinois.edu/handle/2142/18212.

Evans, N., & McGhie, C. (2011). The performance of lifeline utilities following the 27th February 2010 Maule Earthquake Chile. In *Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society*, 14–16.

Garschagen, M., Hagenlocher, M., Sabelfeld, R., & Lee, Y. (2016). Infrastructure as a risk factor. In *World Risk Report - 2016*. UNU-EHS and BEH.

GISCA (2009). Centre for the social applications of geographic information systems, University of Adelaide, Adelaide, Australia. Retrieved from: http://www.gisca.edu.au/products_services/ariav2_about.html.

Herrmann, G. (2013). Regulation of coastal zones and natural disasters: mitigating the impact of tsunamis in Chile through urban and regional planning. *Issues in Legal Scholarship*, 11(1):29–44.

Hollnagel, E. (2011). Prologue: The scope of resilience engineering. In Hollnagel, E., Woods, D., & Leveson, N. (Eds.), *Resilience Engineering. Concepts and Precepts*, (2) CRC Press, Boca Raton.

Jenelius, E., & Mattsson, L.-G. (2012). Road network vulnerability analysis of area-covering disruptions: A grid-based approach with case study. *Transportation research part A: policy and practice*, 46(5):746–760.

Jenelius, E., & Mattsson, L.-G. (2015). Road network vulnerability analysis: Conceptualization, implementation and application. *Computers, Environment and Urban Systems*, 49:136 – 147.

Keller, S., & Atzl, A. (2014). Mapping natural hazard impacts on road infrastructure - the extreme precipitation in Baden-Württemberg, Germany, June 2013. *International Journal of Disaster Risk Science*, 5(3):227-241.

Khew, Y., Jarzebski, M., Dyah, F., Gu, J., Esteban, M., Aranguiz, R., & Akiyama, T. (2015). Assessment of social perception on the contribution of hard-infrastructure for tsunami mitigation to coastal community resilience after the 2010 tsunami: Greater Concepción area, Chile. *International Journal of Disaster Risk Reduction*, 13(2015):324–333.

Kröger, W. (2008). Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools. *Reliability Engineering & System Safety*, 93(12):1781–1787.

LaPorte, T. (2007). Critical infrastructure in the face of a predatory future: Preparing for untoward surprise. *Journal of Contingencies and Crisis Management*, 15(1):60–64.

León, J., & March, A. (2014). Urban morphology as a tool for supporting tsunami rapid resilience: A case study of Talcahuano, Chile. *Habitat International*, 43(2014):250–262.

León, J., & March, A. (2016). An urban form response to disaster vulnerability: Improving tsunami evacuation in Iquique, Chile. *Environment and Planning B: Planning and Design*, 43(5):826–847.

Little, R. (2002). Controlling cascading failure: Understanding the vulnerabilities of interconnected Infrastructures. *Journal of Urban Technology*, 9(1):109–123.

Lomax, T., Schrank, D., Turner, T., & Margiotta, R. (2003). *Selecting travel reliability measures*. Texas Transportation Institute. Retrieved from: https://static.tti.tamu.edu/tti.tamu.edu/documents/TTI-2003-3.pdf.

Lunecke-Herrmann, M. (2015). Urban planning and tsunami impact mitigation in Chile after February 27, 2010. *Natural Hazards*, 79(3):1591–1620.

Mattsson, L., & Jenelius, E. (2015). Vulnerability and resilience of transport systems–a discussion of recent research. *Transportation Research Part A: Policy and Practice*, 81:16–34.

Miquel, M., Mery, J., & Novoa, E. (2010). Estabilización y mantenimiento de caminos no pavimentados sometidos a condiciones de hielo-nieve en zona de montaña. *Journal of Construction*, 9(2):97–107.

Moehle, J., Riddell, R., & Boroschek, R. (2010). *Learning from earthquakes: The mw 8.8 Chile earthquake of February 27, 2010*. Technical report, Earthquake Engineering Research Institute.

Monsalves-Gavilan, P., Pincheira-Ulbrich, J., & Mendoza, F. (2013). Climate change and its effects on urban spaces in chile: A summary of research carried out in the period 2000-2012. *Atmósfera*, 26(4):547–566.

Murray, A., & Grubesic, T. (2007). Overview of reliability and vulnerability in critical infrastructure. In Murray, A., & Grubesic, T. (Eds.), *Critical Infrastructure – Reliability and Vulnerability*. Springer, Berlin/Heidelberg/New York.

Murray, A., Matisziw, T., & Grubesic, T. (2008). A methodological overview of network vulnerability analysis. *Growth and Change*, 39(4):573–592.

Nolte, D. (2004). Das politische System: Verfassung und Verfassungspraxis. In Messner, D., & Nolte, D., (Eds.), *Chile heute – Politik, Wirtschaß, Kultur*. Vervuert – Frankfurt am Main.

Pradena, M., & Echaveguren, T. (2008). Quality management in road maintenance based on the approach to the client principle. *Revista de la Construcción*, 7(2):102–108.

Rinaldi, S., Peerenboom, J., & Kelly, T. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, 21(6):11–25.

Rodriguez-Pose, A., & Gill, N. (2004). Is there a global link between regional disparities and devolution? *Environment and Planning A*, 36(12):2097–2117.

Ropohl, G. (2012). *Einführung in transdisziplinäres Denken*. Berlin: Edition Sigma.

Schintler, L., Gorman, S., Kulkarni, R., & Stough, R. (2007). Moving from protection to resiliency: A path to securing critical infrastructure. In Murray, A., & Grubesic, T. (Eds.), *Critical Infrastructure – Reliability and Vulnerability*. Springer, Berlin/Heidelberg/New York.

Seitz, H., & Licht, G. (1995). The impact of public infrastructure capital on regional manufacturing production cost. *Regional Studies*, 29(3):231–240.

Steiniger, S., Poorazizi, M., Scott, D., Fuentes, C., & Crespo, R. (2016). Can we use Openstreetmap POIs for the evaluation of urban accessibility? In *International Conference on GIScience, Short Paper Proceedings*, (1).

Sturm-Hentschel, U., Braun, A., Hinz, S., & Vogt, J. (2013). Detecting and characterizing settlement changes in developing countries using VHSR data: Case of the coastal area of Benin. In Krisp, J., Meng, L., Pail, R., & Stilla, U. (Eds.), *Earth Observations of Global Changes (EOGC)*. Springer-Verlag, Berlin-Heidelberg.

Tang, A., Cooper, T., Dueñas-Osorio, L., Eidinger, J., Fullerton, B., Imbsen, R., Kempner, L., Kwasinski, A., Pyrch, A., Schiff, A., & Wang, Y. (2010). *Preliminary report 27 February 2010 m w 8.8 offshore Maule, Chile earthquake*. Technical report, Technical Council on Lifeline Earthquake Engineering (TCLEE).

Taylor, M., Sekhar, S., & D'Este, G. (2006). Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics*, 6(3-4):267–291.

Taylor, M. A., & Susilawati (2012). Remoteness and accessibility in the vulnerability analysis of regional road networks. *Transp. Res. Part A*, 46(5):761–771.

Tomita, T., Arikawa, T., Takagawa, T., Honda, K., Chida, Y., Sase, K., & Olivares, R. (2016). Results of post-field survey on the mw 8.3 Illapel earthquake tsunami in 2015. *Coastal Engineering Journal*, 58(02):1650003.

Venables, A. (2005). Spatial disparities in developing countries: cities, regions, and international trade. *Journal of Economic Geography*, 5(1):3–21.

Villagra, P., Herrmann, G., Quintana, C., & Sepulveda, R. (2016). Resilience thinking and urban planning in a coastal environment at risks of tsunamis: the case study of Mehuín, Chile. *Revista de Geografía Norte Grande*, 1(64):63–82.

Wang, Z., Chan, A., Yuan, J., Xia, B., Skitmore, M., & Li, Q. (2014). Recent advances in modeling the vulnerability of transportation networks. *Journal of infrastructure systems*, 21(2):06014002.

Wilson, T., Cole, J., Stewart, C., Cronin, S., & Johnston, D. (2011). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, Southern Patagonia, Chile. *Bulletin of Volcanology*, 73(3):223–239.

Wu, J., & Gopinath, M. (2008). What causes spatial variations in economic development in the united states? *American Journal of Agricultural Economics*, 90(2):392–408.