1. Introducing network centrality for strategic transportation network design

Nothing is in the air.

What an idyll. People sunbathe right in front of major airports. Barbecues without the sound of aircraft flying above. Still, some do not seem to enjoy it. Crowded trains. A never seen price jump for rental cars. The British Navy picks up travelers on the European continent. Car manufacturers run short on parts (BBC News, 2010). Video-conferencing peaks. Perishable goods do not appear on store shelves (Economist, 2010). Politicians are stuck like everyone else (Erlanger et al., 2010). Those were some European days in April 2010. Only too well, everything came back to normal quickly.

It all started with a short note: the Icelandic volcano Eyjafjallajökull erupted on March 21, 2010; the largest fear of scientists being a likely breakout of the nearby-located volcano Katla, having a violent history of eruptions (Simons, 2010). About 500 people were temporarily evacuated. Journalists quote a farmer who had to leave all her animals behind (Spiegel Online, 2010a). Tourists are attracted to the site (Spiegel Online, 2010b). It was spectacular, but local. And it was petering out. Then came the second outbreak on April 14, 2010 (Devlin, 2010), causing the European airspace to be partially shut down for several days. The news were filled with the danger of flying through ash clouds. Companies started to reclaim their losses caused by the closed airspace. The airline industry stated that the disruption in flights resulted in costs of $400 million a day (Economist, 2010).

Eventually, people realized how much they depend on transportation networks.

The Eyjafjallajökull outbreak is a perfect example of how strongly modern societies rely on effective and efficient networks: to ensure the availability of products, to allow for mobility, to permit data exchange, to provide energy to households and production, to communicate worldwide, and so on. Transportation networks are interwoven with modern societies.

The design of transportation networks has been of interest to researchers for decades. Leonhard Euler's work on the seven bridges of Königsberg in 1736 is an early and prominent example of research on transportation networks (West, 2001, p. 26). Transportation network design is a relevant research field in Operational Research (OR), where seminal work on optimal network design from different viewpoints is available.

Consequently, it is legitimate to ask, what an optimal network is. What does the term *optimal* refer to? In cost-oriented OR models, an optimal network is one with minimal costs; for example resulting in minimal transportation cost. Having the above example of Eyjafjallajökull in mind, an optimal transportation network would have probably been a network without airplanes. When thinking of the Internet, the optimal network is available at all times. An optimal spider-web is a network that is structured to catch enough flies, yet not too difficult to construct, and strong enough to withstand threats. Defining optimality depends on the context; no general definition can be stated. Nature has developed networks that comply with many restrictions and are optimized to meet multiple goals. Modern artificially constructed networks must, equally, fulfill different aspects of desired performance, but we have not achieved this objective. Thus far, we can only marvel upon the efficiency that nature is able to construct suitable networks with, virtually without any central coordination (e.g. Tero et al. (2010)). There is a long way to go for modern science until this sophistication can be met. Overcoming the strong cost-orientation in traditional network design and widening the perspective to more encompassing objectives is a valuable first step.

Service and risk-management have become vital aspects of the performance of modern transportation networks from a market perspective. Manifold dimensions are used to describe network service. Unfortunately, there is no common understanding regarding which indicators best describe the service expectations for a transportation network. Even so, it is understood that transportation time, the reliability of schedules, and the frequency of departures are elementary aspects of it (Pfohl, 2004b, pp. 94-100).

These are among the relevant indicators for network performance in general and can be translated to network key performance indicators (KPIs). KPIs include cost and service elements but also keep track of further indicators such as risk. The wide spectrum of potential KPIs, and thereby their sheer number, creates a challenge for decision-making as it is infeasible to consider them all simultaneously.

Many of the KPIs are strongly influenced by the underlying network's appearance as expressed by spatial network centrality.[1] Network centrality describes to what degree certain locations in the transportation network assume an outstanding role for the network's operations. A star-shaped hub-&-spoke (H&S) network with an important

[1] Centrality may have an organizational connotation (in the sense of organizational centralization) apart from its spatial dimension. This thesis does not address challenges in finding suitable organizational structures to manage a transportation network. Whenever the term *centrality* is used in the following, it is understood in its spatial sense.

hub in its middle is the prototype of a central network, whereas a point-to-point (P2P) network is a decentral transportation network.[2]

Network centrality should be seen as a core KPI for transportation networks, but is currently not perceived as such, neither in academic transportation network design, nor in decision-making on transportation networks in the logistics sector. Transportation network design will benefit from exploring the relation between network KPIs and network centrality. Network centrality enriches cost-oriented decision-making by allowing for a sound inclusion of service-orientation and further aspects of network performance into network design.

1.1. Emphasizing the role of network centrality in transportation network design

The exceptional relation between centrality in transportation networks and network performance indicators is at the focus of this thesis. Network centrality influences network KPIs applied in network design and plays an exceptional, yet currently neglected role in transportation network design. Network centrality is the concept interlinking network appearance and network performance.

Therefore, the **objective** of the thesis is twofold. Firstly, to conceptually **devise the relation between network centrality and network performance** in order to emphasize the outstanding importance of network centrality for network design. This aspect refers to the qualitative understanding of network centrality. Secondly, to **suggest quantitative measures for transportation network centrality**. These measures are necessary for analyzing and comparing in depth the centrality of transportation networks.

The research field of network design is well-developed. However, its strategic application to real life problems creates challenges for planners, including e.g. the requirement for detailed data on a long-term planning horizon. To bridge this gap between research and application, the identification of trade-offs that impact network design strategically is beneficial. The knowledge of strategic influence factors will not, most likely, help to find optimal transportation networks, but rather guide the design process. Transportation network centrality may serve as a very expressive influence factor for strategic network design. Thereby, it supports the identification of good design alternatives.

The general objective to emphasize the outstanding role of network centrality for transportation network design allows to formulate three subordinate goals set by this thesis.

2 Comparing the transportation distance of different networks (as one possible KPI) is a tangible example of the impact of centrality on network KPIs: a H&S network is typically characterized by longer transportation distances than a P2P network.

Enriching OR by generating strategic insights for ill-defined decision situations. The thesis strives to highlight that optimal network design in the way it has been conducted by researchers in OR is not sufficient to support good decision-making for strategic, long-term network design. Strategic decision situations are often characterized by high uncertainties, general assumptions, and expectations about future demand for the network being planned. At this stage, strategic insights into trade-offs involved in planning are more valuable to decision-makers than theoretically sound, optimal solutions on unreliable data. This aspect is not new in the literature, but appears to have been of lesser importance over the last few years. It is, therefore, necessary to reiterate and further enrich this line of thinking in the literature. A qualitative understanding of transportation network centrality and its relation to network performance is a significant step in this direction.

Implementing an algorithm to simulate network scenarios. The theoretically devised interdependencies between transportation network centrality and transportation network behavior will support the development of an algorithm for less-than-truckload (LTL) network design. The insights from a qualitative understanding of transportation network centrality allow to pre-structure the algorithm. Hence, the algorithm serves as an example for the practical implementation of the knowledge of the relation between network centrality and network performance.

Generating conclusions on non-measured network performance. It is challenging to assess all aspects of network performance simultaneously in a decision situation, even though simulations may be used to gather large amounts of data. It will be shown how the quantitatively measured network centrality of a network may be interpreted in order to draw conclusions on aspects of network performance that were not directly recorded. The interpretation is based on qualitative knowledge of network centrality and its relation to network performance.

1.2. Structure of the thesis

The line of argument of the thesis is illustrated in figure 1.1. This first chapter outlined the background and the objective of the thesis. The second chapter, *Transportation networks and their optimal design*, will broadly introduce the concept of transportation network design with the goal of presenting the width of the research field, but also of explaining the key deficiencies that exist for strategic decision-making. To do so, it will give fundamental information on transportation network design before presenting an overview of the manifold problems that were discussed in OR in order to solve various aspects of network design. This overview is structured around the time horizon for decision-making and the decisions to be made at each stage. Literature reviews in the field of OR would oftentimes be structured according to the solution techniques for existing problems.[3] Orienting the presentation around the planning time horizon appears more appropriate for this thesis, as it directly highlights one main deficiency, namely the sequential planning approach. Most importantly, the section will point out the strong cost-orientation of OR network design approaches. This thesis can by no means claim to be the first work to identify the additional importance of general, strategic insights in OR network design. Selected contributions from this literature stream are, therefore, presented after the weaknesses of standard transportation network design and its application in practice were highlighted. The chapter closes with a claim for more general insights into strategic network design. Network centrality will prove to be a helpful concept for this purpose.

The third chapter, *Transportation network centrality*, is devoted to presenting the outstanding role of transportation network centrality in transportation network design. The first section defines terms and will provide the reader with a fundamental understanding of network centrality. The second section, then, thoroughly discusses the impact of network centrality on six network performance indicators of transportation networks. This qualitative understanding of transportation network centrality will be exploited to structure network design later on. It is well known that several prototypes of transportation networks exist which differ in their advantages and disadvantages and are, therefore, applied in different environmental settings. Their performance is typically measured along different scales, including transport distance and time, service frequency, or schedule reliability. By relating these KPIs to network centrality, it is argued that it is the very concept of network centrality that determines the other KPIs and, therefore, is at the root of transportation network performance. In more concise terms, network centrality is *the* concept that discriminates networks from each other. In the forefront of these considerations, the remainder of the section is oriented to addressing the question of how the multifarious term of network centrality is understood and measured in different contexts in the literature. Research in social sciences is rich in network centrality indices and is consequently reviewed. The last remaining issue to be examined in the chapter is how indices from the social sciences were adapted to transportation networks. Airline networks provide the widest field of application and will serve as an example for transportation networks. They are even more interesting, as researchers have started to develop customized indices for the context of airline network analysis. Knowledge of existing measures of (transportation) network centrality sets the stage for developing a quantitative understanding of network centrality for LTL metrics in the subsequent chapter.

The remainder of the thesis will demonstrate how transportation network centrality can be exploited for network design. To this point, the thesis will have been oriented upon transportation networks in general. From here forward, the discussion will be focused on one field of application, namely that of road-based LTL networks. Notwithstanding, the general concepts can be easily applied to other transportation

3 Examples of this type are Laporte (2009), Wieberneit (2008), or Grünert and Irnich (2005).

networks that possess similar characteristics. The similarities between LTL networks and passenger airline networks will explicitly be dealt with, but applications to e.g. air cargo networks, structured intermodal transportation networks, and express mail networks may also be considered with ease.

Chapter 4, *Less-than-truckload network centrality*, encompasses two important aspects. At first, logistics service providers (LSPs) in general are presented as these are the main providers of LTL networks on the European market. The chapter then continues to illustrate the LTL business: the market, the offered services, the customer demand, and the operations. It thirdly outlines suggestions on how network centrality - more precisely network concentration - can be measured expressively for LTL networks. This is a necessary step to operationalize the conceptual claim from chapter 3 for further application and discussion in chapter 6.

Chapter 5, *An algorithm for less-than-truckload network design*, presents an algorithm in detail that was developed to generate LTL networks in order to compare network scenarios. Qualitative transportation network centrality was a fundamental element for the development of the algorithm. It allows to identify the network appearance that best suits the given context and leads to the desired network performance. The algorithm creates and tests transportation networks of this appearance and accounts for various KPIs that may serve to compare the networks in detail. It is a practical application of the concept of network centrality and it is, therefore, valuable to present the logic behind the algorithm. The reasoning behind the algorithm, including the role of centrality, is discussed. This frames the more technical algorithm details on input and output, as well as on the detailed procedure. The main goal here is to present the way of thinking that structures the algorithm. The algorithm presentation itself merely supports this aim and will clarify the results obtained using the algorithm.

The sixth chapter, *Generated networks and their performance*, once again focuses on two important aspects. It will firstly present, in the form of a case study, the results generated for a project that the algorithm was applied in. The project was conducted with a large LSP and aimed at identifying options for LTL network redesign on a European scale. Insights are obtained, allowing the generation of managerial implications that are relevant for the field and, in their core, related to network centrality. These are presented subsequently. Quantitatively measuring network centrality by the indices suggested in chapter 4 supports conclusions regarding typical network performance that was not in the set of measured KPIs. Lastly, the information acquired this far serves to review the benefits generated by the underlying knowledge of transportation network centrality. The conclusions stated here regarding network centrality bring us full circle to the conceptual contribution of the thesis. Chapter 7 summarizes and therein closes the thesis.

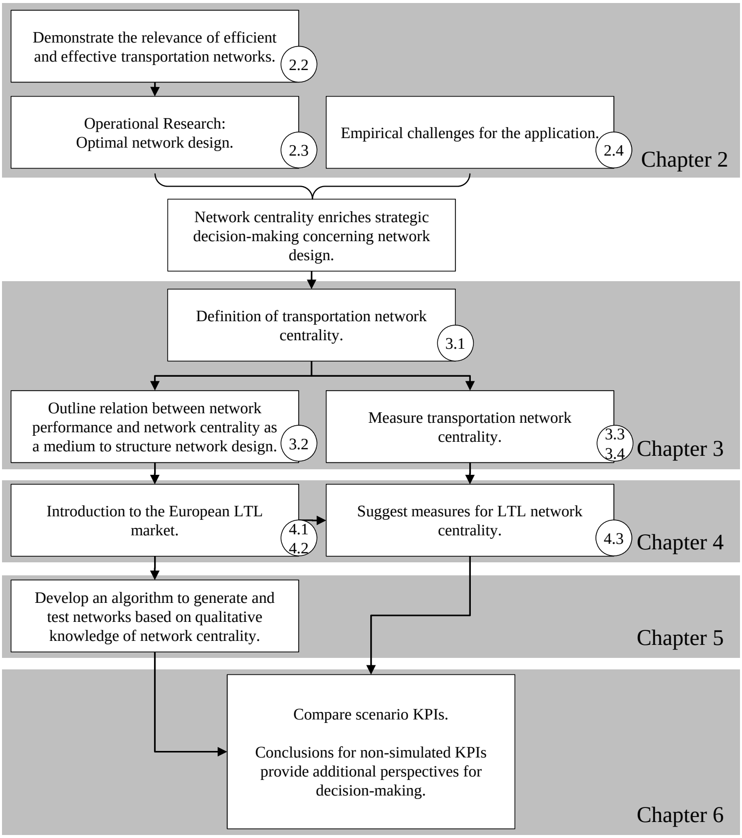

Figure 1.1.: Line of argument.