Bridging the gap from graph theory to transportation planning in inter city networks.

Applying graph theory to the inter city transportation networks of Zwolle and 's-Hertogenbosch to explore the applicability of graph theory for planning.

Source: Author

Master thesis
Environmental and Infrastructure Planning
University of Groningen
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Location: Groningen
Date: 07-02-2017

Colophon

Project: Master thesis
Phase: Final version
Word count (ch 1-7): 32881 (including tables)

Theme : Transportation planning
Title: Bridging the gap from graph theory to transportation planning in inter city networks.
Subtitle: Applying graph theory to the inter city transportation networks of Zwolle and ‘s-Hertogenbosch to explore the applicability of graph theory for planning.

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Acknowledgements

First, I would like to thank my supervisor for his enthusiasm while guiding me into the unknown world of graph theory in inter city networks. Although neither of us initially knew where this research would be heading, it turned out to be an exciting project. Secondly, I would like to thank my friends and family who have supported me throughout the process and helped me with an ‘outside view’ to get a comprehensible content.

Abstract

Dealing with increasing complexity in transportation networks is causing problems for Dutch infrastructure planning. While planning overall is becoming more integrated internally and externally, infrastructure struggles in keeping up with this trend. Throughout this research, the applicability of graph theory in dealing with increasing complexity in networks as well as explaining spatial growth and decline has been studied. To combine the results of the graph theory study with complexity, the Dynamic Adaptive Planning approach is introduced as a method to account for complexity and translating the results into planning practice. Furthermore, new trends in infrastructure planning are studied and linked to graph theory. A case study on the network of the region of Zwolle is done with a subsequent comparative study of the more or less similar network of the region of ‘s-Hertogenbosch. The case study and comparison led to Zwolle in its respective railroad network as the most important of the two in its one hour travel network. The differences between the networks were measured using the contextualised indicator, the betweenness centrality as graph theory derivative. Throughout the case study, multiple methods of calculating the betweenness centrality are used but the method based on node pair weight as well as travel time turned out to be the most appropriate method for these cases to realistically represent outcomes for inter city networks. There are key factors for these two variables leading to this choice. First, divergent daily passengers for different cities in and network leading to a requirement to distinguish between nodes (node weight). Secondly, high transfer times and high differences in travel time between nodes requiring the value of travel time for inter city networks to present the distance between node realistically. The outcomes of the case study include a framework containing guidelines how to apply graph theory to inter city networks. Furthermore, by using the derivatives of graph theory, a tool is identified to compare different networks. To frame these results for transportation planning, the earlier introduced Dynamic Adaptive Planning approach is used as a framework to translate the results for the case of Zwolle into planning practice. The results can also be linked to new trends in infrastructure planning on a different scale. However, this topic requires a lot more research since it is still in its infancy.

Keywords: Transportation planning, Graph theory, (Rail)road networks, Dynamic Adaptive Planning

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List of Abbreviations

C_b:	Betweenness centrality
C'_b:	Relative betweenness centrality
C'_b-t_t:	Relative betweenness centrality based on travel time
C'_b-d_n:	Relative betweenness centrality based on node distance
CAS:	Complex Adaptive Systems
DAP:	Dynamic Adaptive Planning
MRT:	Mass Rapid Transit
P_i:	Node weight
TOD:	Transit-oriented Development
URTNs:	Urban Rail Transit Networks

1. Introduction

1.1 Dilemmas in Dutch transportation planning

Over the last several decades, planning theory has gone through a paradigm shift leading away from the technical rational approach (Healey, 1996). Consequently, more deliberation has to be taken into account during the planning process in reaching consensus. Especially in a dense, crowded country like the Netherlands, where many people are living on little space, this will result in a lot of conflicts. A problem is occurring due to the approaching of the capacity of the Dutch roads and public transport (FD, 2016). Moreover, many people living in a small country demands a highly robust transportation network which is robust in terms of the contemporary required capacity as well as in terms of exploring the consequences of population and traffic increase in the future. Transportation planning can be seen as a part infrastructure planning, which focuses on physical networks, such as roads, specifically. This contains the parts of planning focussing on issues related to the transportation network. While Woltjer (2000) notes the need for a communicative approach, reaching for consensus in infrastructure planning, it can also be seen from a complexity perspective with time as non-linear (De Roo, 2010). This complexity perspective gets support from the high uncertainties and long-timescale in which transportation planning usually takes place (Wall et al., 2015). This results in several dilemmas regarding transportation planning deriving from the lack of experience in dealing with complexity. In this study, the complexity in transportation planning is seen as inevitably present requiring appropriate methods dealing with this for transportation planning. Moreover, due to the interrelatedness of different parts of planning, policy focussing on infrastructure only in the Dutch planning system can be seen as rather limited (Heeres et al., 2012).

In a world where integration between different policies is becoming more important, the physical infrastructure seems to be struggling in keeping up with this trend. It makes sense that a road, just a line from A to B, is hard to integrate in the surroundings due to the fact that it will always be seen as a barrier. Nevertheless, there are a lot of developments going on, aiming towards more “area-oriented” infrastructure planning (Struiksma et al., 2008) and integrating it in other policies as well. Infrastructure can be seen as part of an ever-increasing complex system dealing with a high degree of uncertainty regarding the future (Rauws et al., 2014). This increased complexity inevitably leads to changes which are nonlinear and unpredictable (Duit & Galaz, 2008; De Roo, 2010). Therefore, dealing with complex issues whilst aiming towards integrating infrastructure issues with other policies demands a new approach based on a robust system (Byrne, 2003). This system has to overcome the rigidity of the current infrastructure systems and be robust in terms of exploration and exploitation (Duit & Galaz, 2008).

Considering contemporary and future infrastructure trends such as integrated infrastructure planning (Arts et al., 2016), sustainable mobility (Banister, 2008) and transit oriented development (Yang et al., 2016), there are a lot of potential paths for infrastructure planning. Graph theory (see, e.g. Kansky, 1963; Derrible & Kennedy 2009;2010; Gattuso & Miriello, 2005) can provide a framework for dealing with uncertainty and complexity by explaining the expected growth or decline of cities on the basis of their location within the network. Therefore, in this research, the functionality of graph theory in providing a framework to increase the ‘adaptive capacity’ (Duit & Galaz, 2008) is being investigated. To provide a concrete example of the applicability of graph theory, the fast-growing region of Zwolle in the Netherlands has been studied and is part of a more comprehensive case study.

1.2 Research questions

In this research, the applicability of graph theory to face complexity in transportation planning is studied. The technical and easily comprehensible graph theory can provide a framework to understand transportation networks. Moreover, the derivatives of graph theory can be a valuable tool to figure out how to increase the robustness of transportation networks. Divergent from the majority of studies regarding graph theory in planning, this research will apply the elements of graph theory to inter city networks instead of metro networks. Inter city networks in this research are defined as networks containing multiple cities and should not be associated with the Dutch train type called Intercity. The results from graph theory based research have to be adapted to be suitable for cities and networks among cities. To deal with uncertainty in the future regarding transportation planning, in this research a complexity perspective has been advocated for. Considering transportation networks as complex adaptive systems (Rauws et al., 2014; Duit & Galaz, 2008) emphasises the need for approaches providing robustness to deal with high uncertainty. Thereafter, the new and upcoming trends in infrastructure are being discussed and then examined how these can be related to the previously mentioned topics of graph theory and complexity. This leads to the following research question:

"How can graph theory provide a framework for transportation planning in inter city networks while accounting for increasing complexity based on the case of the region of Zwolle?"

Following this research question, a quaternary of sub-questions has been developed to tackle the research question partially and expand its scope. These four sub-questions are divided into the previously mentioned topics and include:

1. How can transportation planning deal with increasing complexity and, therefore, be adaptive for the future?

To answer this sub-question, the complexity theory and its relation to transportation planning has to be studied briefly. Furthermore, the applicability of the complexity theory to face concrete issues in transportation planning, resulting in compatible and adaptive solutions have to be explored. Moreover, the feasibility in terms of implementation is a concern that has to be addressed as well.

2. How can graph theory be applied in inter city transportation networks?

This sub-question requires a deeper look into graph theory and its derivatives. Following a rather mathematical approach, graph theory has been introduced to planning from different perspectives, especially in metro networks. In inter city networks, it has been introduced to lesser extend and the literature on this remains rather limited. Therefore, graph theory has been studied extensively in order to understand its applicability to inter city networks.

3. How can graph theory be used to explain spatial growth and decline in Dutch cities?

This sub-question relates to explaining the differences in spatial growth that can be seen throughout Dutch cities. The endeavour of this sub-question is to try and link aspects from graph theory to growth or decline in Dutch cities. To answer this sub-question, a case study approach is being used to compare Dutch cities showing a lot of spatial growth with regards to certain characteristics derived from graph theory. On beforehand it was expected that cities located centrally in the network would show more potential growth than cities located on the edge of the network.

4. How do recent trends in Dutch infrastructure planning relate to the concepts of graph theory?

Finally, to answer this sub-question, a number of recent trends in Dutch infrastructure are studied. Moreover, a couple of these trends have been related to the complexity in transportation networks and the applicability of graph theory to networks. Subsequently, the feasibility of the implementation of ideas following from these trends has been tested in terms of robustness.

Related to other studies, this study has a unique point of view applying graph theory beyond borders of a city network. Moreover, linking this to the view of networks of complex systems which cannot be seen as closed systems (Kast & Rosenzweig, 1972), the point of departure for this study is on the edge of contemporary graph theory studies by linking this to complexity. Furthermore, through analysing other studies about trends in infrastructure planning, the abstraction of graph theory and complexity is bridged to planning practice.

1.3 Introduction to the studied areas

In this research, two cities in the Netherlands are studied. While the region of Zwolle is used as the subject for a case study, the region of ‘s-Hertogenbosch is used as a comparison to Zwolle as well as an example to apply the introduced framework to another network. The two cities are located in different parts of the country leading to divergent networks for both cities. In Figure 1.1 both cities and their location in the Netherlands are visualised. Throughout the next sections, the studies areas are introduced briefly.

Figure 1.1: Location of Zwolle & ‘s-Hertogenbosch in the Netherlands *Source:* Author, adapted from ArcGIS (2016)

1.3.1 The region of Zwolle

The region of Zwolle is located in the north-eastern part of the Netherlands with a travel time of around one hour to major cities like Amsterdam and Utrecht, which are assumed the most frequent destinations in this research. Furthermore, the municipality of Zwolle had a population of around 120 thousand in 2015 with a population increase of around 20% since 2000 (CBS, 2016a). Therefore, Zwolle can be seen as a fast-growing region with a growth rate among the highest in the Netherlands (CBS, 2016a). A growing region does also demand an extension of the transportation network. One way this has been accommodated is through realizing a new railway linking Zwolle and Lelystad and, therefore, decreasing the travel time to Amsterdam. This is an adequate way of providing more incentives to live in the region for people working in or near Amsterdam. Moreover, due to the relatively large size of the central railway station in Zwolle, the links to other cities are comprehensive and fast. Consequently, a part of the success of Zwolle as a region can be linked to the location in the transportation network including the good accessibility of big cities all around the Netherlands from Zwolle.

From the perspective of car owners, the location Zwolle is favourable as well. It is located near an important highway intersection and with direct access to one of the most important roads towards the northern provinces in the country. However, in contrast to the railroad, a direct highway link to Amsterdam is lacking and can be seen as a missing link.

The region has, however, also some issues with regards to uncertainty in the future. For example, the contemporary growth rate could be changing significantly in the future, leading to congestion and exceeding the capacity of the network. Preventing this would demand an adaptation of the transportation network. Moreover, the region is vulnerable to climate change due to its low location, close to the river IJssel, which has an increasing water deposit (Rijkswaterstaat, 2012). This could lead to floods and consequently the inaccessibility of certain parts of the network. On the other hand, climate change can lead to long dry periods, damaging the soil and also damaging roads. Consequently, the transportation system has to be robust to successfully deal with possible changes arising from uncertainty (Duit & Galaz, 2005), at all possible extremes. Also, a robust system requires the right institutions to assure this robustness (Olsen, 2009). For the relevant institutions to work fluently, they have to be integrated both nationally and locally (Buitelaar et al., 2010). Throughout this research, these uncertainties and institutional requirements are left somewhat neglected and to identify their implications this study suggests further research on this topic.

1.3.2 The region of ‘s-Hertogenbosch

The second studied area is the region of ‘s-Hertogenbosch. Located just below the river Meuse, ‘s-Hertogenbosch is the capital of the province Noord-Brabant. Even though the city now has less inhabitants than the cities of Eindhoven, Breda and Tilburg (CBS, 2016b), it is the oldest city in the province (Cox, 2005). The location of ‘s-Hertogenbosch is favourable due to being within half an hour travelling of the big cities Utrecht and Eindhoven and being within one hour travelling of almost the entire Randstad area by train (NS-Reisinformatie, 2016). The region is chosen as comparable to Zwolle mostly because of the similarities in their relative location within the network as well as a comparable population size. Moreover, due to the different location within the Dutch transportation network, an almost entirely different part of the network is studied leading to a more holistic view on the Dutch network. Regarding the future, ‘s-Hertogenbosch may face similar problems as Zwolle. This is, however, not elaborated upon in this research and can be the subject of further research.

1.4 Research outline and structure

The research has been divided into seven different chapters written in a customary order. In the first chapter, an introduction on the issue, the research questions and the studied areas have been outlined. The second chapter contains a literature overview on the issue from multiple angles, identifying and elaborating on complexity theory and graph theory and trends in infrastructure planning. The third chapter contains an overview of the different methods used throughout the research as well as the sources of data and the process of analysing the data. In the fourth chapter, the data is presented and analysed, being the core part of this research. In the fifth chapter, the results of the data analysis are presented. In the sixth chapter, a conclusion of the research is presented as well as a discussion. In the seventh and final chapter, a reflection of the entire research process has been outlined. A summary of the research outline is visualised in figure 1.2.

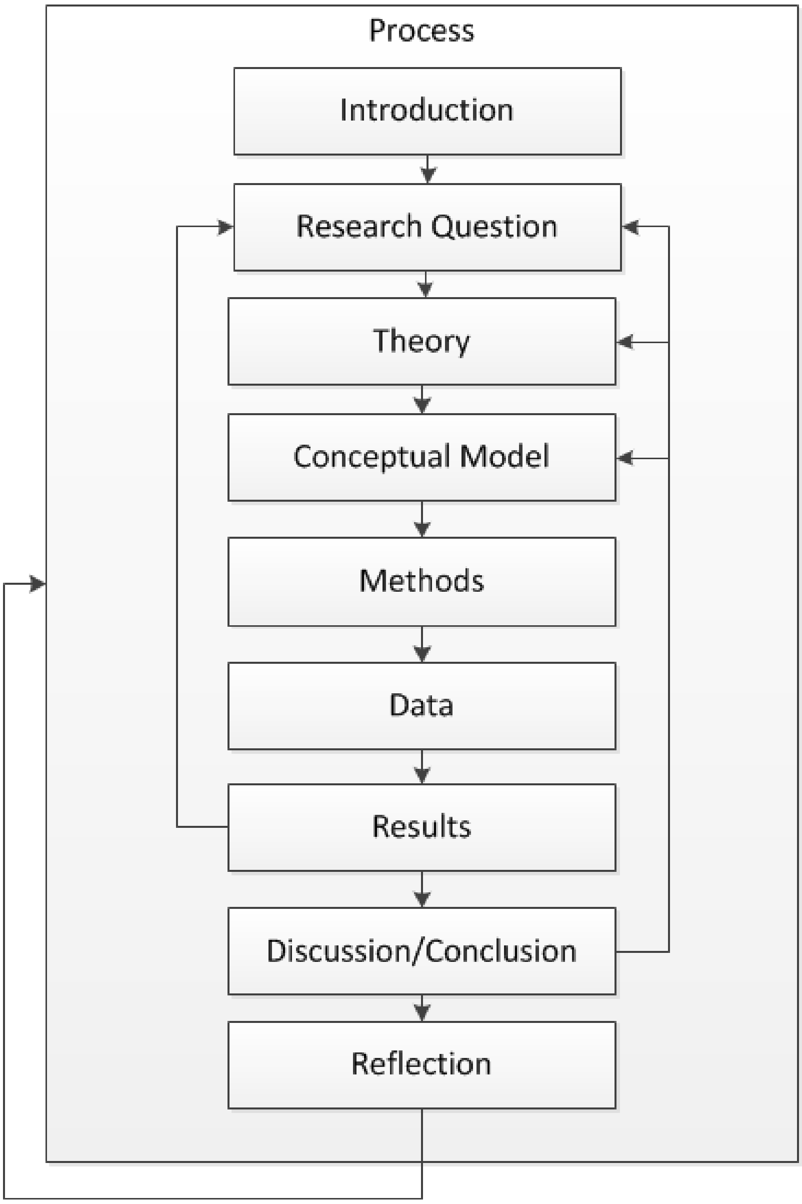


Figure 1.2: Research outline *Source:* Author

1.5 Reader's guide

To enable a pleasant reading experience for the reader, a few guidelines guiding through the research are given to clarify the different parts of the study. Throughout the theory review, an effort is put in emphasising the applicability of complexity theory and graph theory for this research. For readers having much prior knowledge about the use of complexity theory in planning, chapters 2.1.1 and 2.1.2 can be seen as superfluous with only chapter 2.1.3 and further containing information specifically related to this research. For readers having much prior knowledge about graph theory, chapters 2.2.1 up till and including 2.2.5 can be seen as superfluous providing a summary of the existing literature about the applicability of graph theory with only chapter 2.2.6 and onwards providing new information related to the context of this research. For readers having no prior knowledge at all about graph theory, chapters 2.2.1, 2.2.2 and 2.2.3 provide a general introduction to graph theory to understand its basics while the next chapters elaborate on the ways graph theory can be applied to planning.

In chapter 4, the framework which is applied throughout the case study and comparative study is introduced in chapter 4.2. For the case study, in chapters 4.3.1, 4.3.2 and 4.3.3 multiple angles for the network of Zwolle are introduced including the contemporary railroad network of Zwolle (4.3.1), the railroad network of Zwolle in a situation before the establishment of the Hanzelijn (4.3.2) and the road network of Zwolle (4.3.3). Chapter 4.3.4 compares all of the methods and outcomes the different methods lead to. In chapter 4.4 a comparative study is done in which chapter 4.4.1 contains the case selection, chapter 4.4.2 the elaboration of the case and 4.4.5 the comparison to the network of Zwolle.

2. Theory

In this chapter, the relevant theories on the topic are outlined. The chapter consists of four parts containing three different perspectives on the topic followed by a conceptual model summarizing these different perspectives and bringing them together. The first perspective is the perspective of infrastructure networks as complex systems. The second is the perspective of graph theory in (rail)road networks and the last perspective is the perspective of new trends in infrastructure planning. These three perspectives are chosen out of other possible perspectives to provide a holistic view to understand networks as well as understanding potential implications for the future of transportation networks. Therefore, the three perspectives have a complementary role and are all required for this research.

2.1 Infrastructure networks as complex systems

Complex systems are chosen as point as departure for this study since transportation networks can be linked to complex systems. Hence, Von Ferber et al. (2012) identify transit networks as complex networks. Von Ferber et al. (2012:201) describe complex networks as 'the nucleus of a new and rapidly developing field of knowledge that has its roots in random graph theory and statistical physics'. This links complexity to graph theory for a first time. Dueñas-Osorio and Vemuru (2009) show an example of a complex infrastructure system using only 'dots and lines', which is shown in figure 2.1. This figure illustrates how complex infrastructure systems can be or can become in the future. Moreover, since the world is getting more connected, the world can be seen as one big complex multi-modal infrastructure system. Throughout this section, a more detailed study on complexity with regards to infrastructure planning is done. However, a brief explanation of complex systems is given initially.

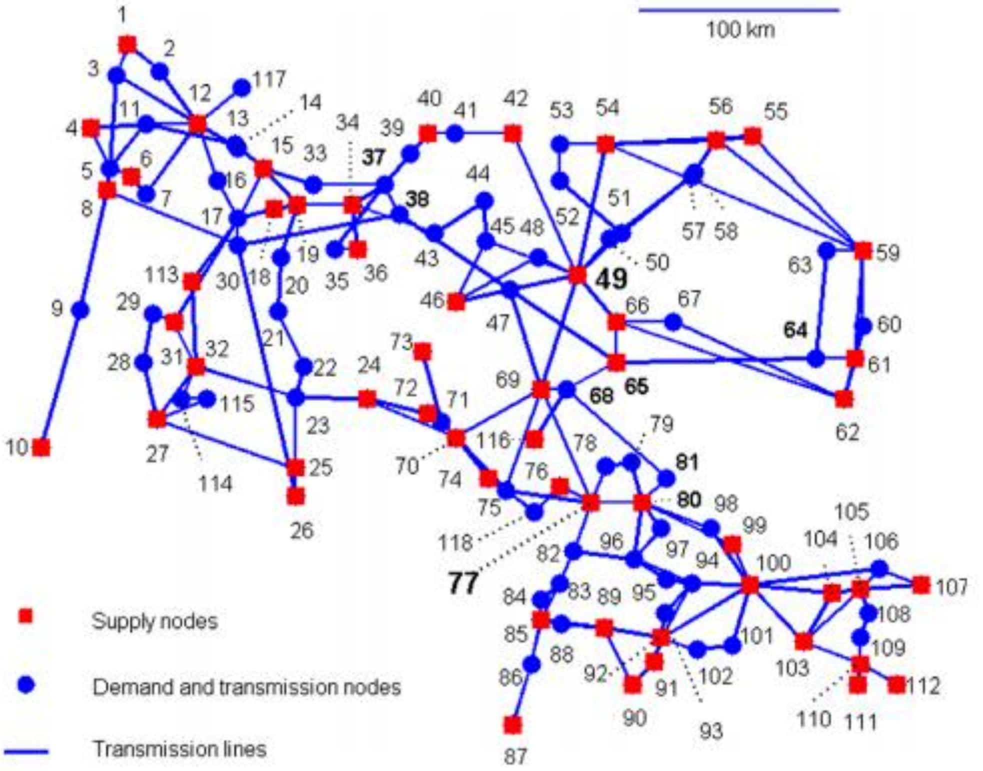


Figure 2.1: Example of a complex infrastructure system *Source:* Figure 1 in Dueñas-Osorio & Vemuru (2009)

2.1.1 What are complex systems?

Byrne (2003) notes that complexity theory offers a way to solve issues that cannot be resolved through the traditional approaches. Complexity science acknowledges the nonlinearity of time and takes the uncertainty of the future into account. De Roo (2010) has visualised the relative position of complexity theory to linear planning theory, which is visualised in figure 2.2. In this figure, the dichotomy of technical and communicative rationality is complemented by an entire new dimension, the nonlinear. In this new dimension, chaos and complexity theory can be used to tackle complexity (De Roo, 2010), such as complex systems.

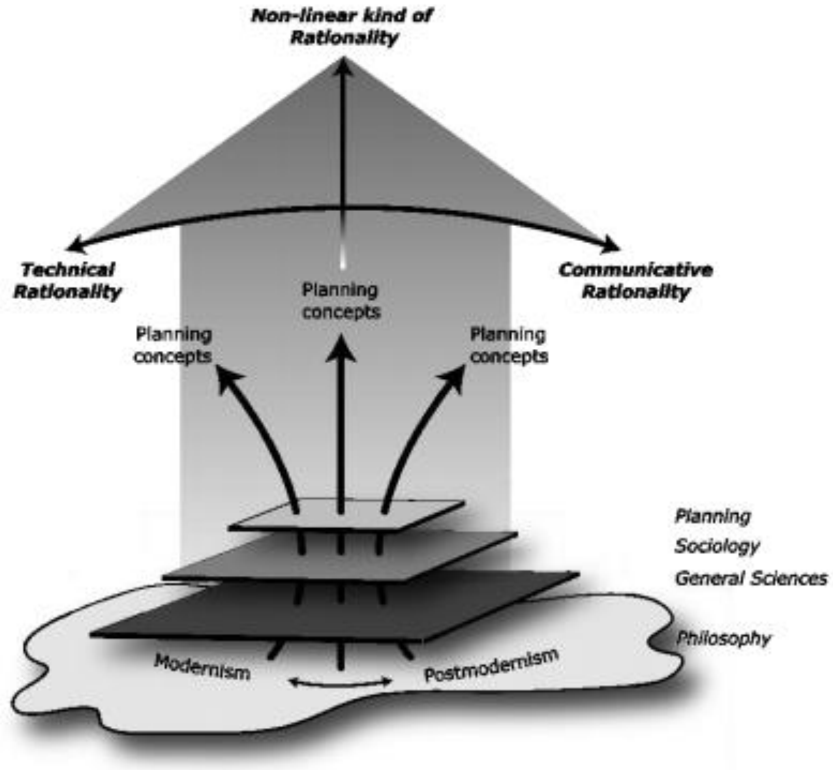


Figure 2.2: The inclusion of non-linear development over time. *Source:* Figure 2.6 in De Roo (2010)

Complex systems are characterized by being able to change radically in form while retaining their function (Byrne, 2003). Therefore, complex systems can be seen as robust systems (Byrne, 2003; Duit & Galaz, 2008). Duit and Galaz (2008) identify Complex Adaptive Systems (CAS) which adds adaptivity to complex systems. CAS can be understood as an interconnected network of multiple agents that show adaptive capacity as a response to changes in the environment as well as the system itself (Pathak et al., 2007). Adaptive capacity can be understood as the ability of systems to respond in a proper way to changes. Rauws et al. (2014) define four different properties of a CAS approach which are non-linear development, contextual interferences, self-organization and coevolution. These can be seen as the key principles of complex systems.

2.1.2 How to deal with increasing complexity in infrastructure planning?

Complex systems are hard to deal with due to their unpredictability and uncertainty and dealing with such systems seems like a heavy burden. Nevertheless, Wall et al. (2015) introduce Dynamic Adaptive Planning (DAP) in their article about the Dynamic Adaptive Approach dealing with ‘deep uncertainties’ (Walker et al., 2013). Deep uncertainties are defined as “we know only that we do not know" (Wall et al., 2015:2). One way to deal with these uncertainties is called dynamic adaptive planning (Kwakkel et al., 2014; Wall et al., 2015). DAP has shown its appearance in infrastructure planning such as in the implementation of innovative urban transport infrastructures (Marchau et al., 2008). Moreover, due to the long-time scale of infrastructure projects, DAP is extraordinary applicable for big infrastructure projects.

Wall et al. (2015) introduce a framework with a five-step model of dynamic adaptive planning which is shown in figure 2.3. (also, Haasnoot et al., 2013) In this framework, five processes have been identified to deal with uncertainties, which are explained in the next section. For infrastructure planning, monitoring flows of traffic is a good example of the applicability of the framework. If the traffic flow reaches a trigger point due to unpredicted causes, the trigger responses are available and ready to be implemented. Therefore, using the framework provides adaptive capacity for infrastructure systems to be robust in the future as well.

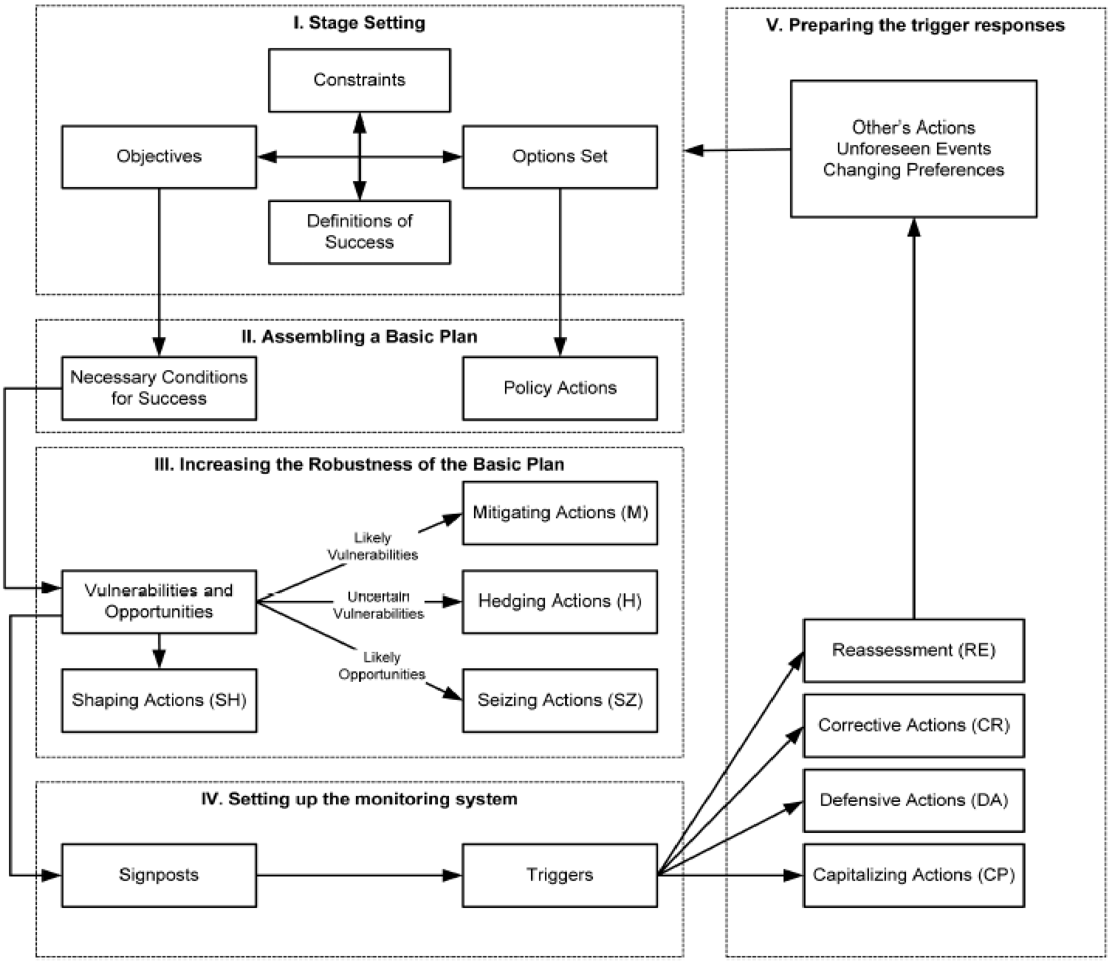


Figure 2.3: Five-step process of dynamic adaptive planning. *Source:* Figure 1 in Wall et al. (2015)

2.1.3 The Dynamic Adaptive Planning framework

In this section, the five different steps of the Dynamic Adaptive Planning (DAP) framework are explained with regards to the region of Zwolle. DAP is a new paradigm to deal with deep uncertainty based on a strategic vision (Haasnoot et al., 2013). The region of Zwolle has been chosen for since this is also the subject of case study in chapter 4.2 and, therefore, introducing the case by elaborating on the DAP framework is a stepping stone to the case study. The results of the case study can be translated to practical planning practice by complementing this framework.

Step I

The five-step process (Wall et al., 2015) is started with the 'Stage setting' step during which objectives, constraints, the options set and the definitions of success are defined. For the region of Zwolle objectives could be, 'dealing with an increased demand of the transportation network by offering a higher capacity of the links and a decrease of travel time to the cities of Utrecht and Amsterdam'. The constraints to these objectives could for example include the costs and spatial restrictions (Wall et al., 2015). The options set includes: doing nothing, intensifying existing links and creating new links. Lastly, the definition of success is based on being able to deal with an increase of passengers while decreasing the travel time.

Step II

The second step, 'Assembling a basic plan', contains the conditions for success, following from the objectives, and policy action following from the options set. The former would in the region of Zwolle include: 1. population growth does not exceed expectations, 2. enough financial support to intensify the links, 3. alternative routing is available in case of malfunctioning (Derrible & Kennedy, 2010). The latter would include intensifying the existing links as well as creating a new highway from Zwolle to Amsterdam, which was introduced as missing link earlier on.

Step III

During the third step, 'Increasing the robustness of the basic plan', the vulnerabilities and opportunities of the basic plan are discussed. This is done through analysing potential problems which could prevent as well as chances that could improve the conditions for success. In the region of Zwolle, the vulnerabilities are: 1a. much higher or lower demand on transportation network due to changes in expected population growth, 2a. financial support is lower than expected or cut off during the process and 3a. there is no alternative routing in case of malfunctioning. The opportunities are: 1b. slightly higher travel demand resulting in an even greater extension of the transportation network, 2b. more financial support from other regions to intensify links and finally 3b. alternative routing is gaining political support and implemented abundantly. To deal with the vulnerabilities, several differing actions, which have to be defined, are prepared based on the likeliness to occur. An example of such an action could be sketching routes for alternative links. While these alternative links do not have to be implemented in the contemporary situation, they might be needed in the future. Therefore, by having plans for those routes already, the plan is more adaptive to potential changes.

Step IV & V

The fourth step, 'Setting up the monitoring system', introduces signposts and subsequent triggers. Signposts are signs of vulnerabilities being monitored while trigger points are certain levels of those signs being exceeded. In the case of Zwolle an example of a signpost could be a baby boom, increasing the expected population significantly and, therefore, reaching a trigger point. When this trigger point is reached, the fifth and final step, 'Preparing the trigger responses' is activated. These are capitalizing actions, defensive actions, corrective actions and reassessment (Wall et al., 2015) with the latter including a redefinition of the stage setting. For the region of Zwolle, these actions have to be investigated first in order to define them. The entire DAP process for the region of Zwolle is summarized in figure 2.4. Throughout the next section, the possibility of infrastructure networks to be adaptive is studied to link this five-step process and to planning practice by analysing how infrastructure networks can be adaptive.

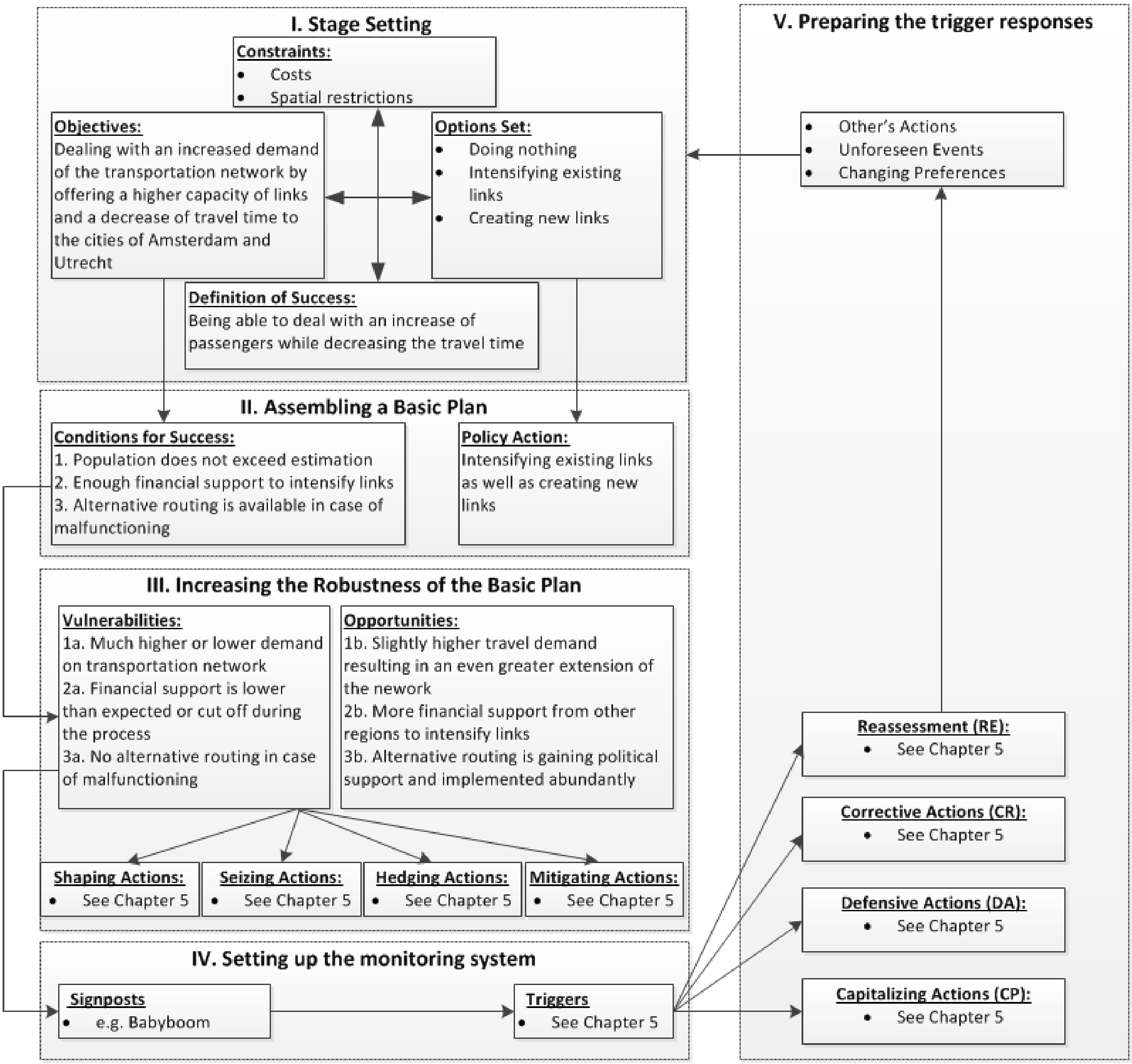


Figure 2.4: Five-step process of dynamic adaptive planning for the region of Zwolle Source: Author, based on Wall et al. (2015)

2.1.4 How can infrastructure networks be adaptive?

For infrastructure networks to be adaptive, being able to deal with deep uncertainties (Wall et al., 2015) is crucial. As explained in the previous section, the DAP approach can provide a framework to realise this. However, infrastructure networks have to be adaptive to new technologies as well. This can be seen as accommodating new modes of transports and adapting current modes of transport to new innovations. In other words, infrastructure networks have to be adaptive in all its functions. This requires adaptive capacity (Duit & Galaz, 2008) of the planning systems dealing with infrastructure networks. An unidentified part of the infrastructure networks here are the physical networks itself. Understanding the physical networks is crucial in order to understand how the networks can be adaptive. Therefore, the next section provides a deeper understanding of networks using graph theory, a theory which potentially increases the understanding of networks, as the guiding structure.

2.2 Graph theory in (rail)road networks

Besides complexity, the location of cities within a network seems to be an important factor as well. Assuming that cities located centrally within the network have more potential growth than cities located on the edge makes sense. To study this, graph theory can be used as a theory to understand the function of location within the network in terms of potential growth. Therefore, using both aspects from the complexity theory as well statistics from graph theory may prove to be a solid basis to explain location-based growth in the future, in terms of population and economic growth. Throughout this section, the implications of graph theory have been outlined starting with a concise introduction on graph theory.

2.2.1 What is graph theory?

Graph theory is a mathematical theory to study the relations between objects. Graph theory was introduced first to solve well-known Seven Bridges of Königsberg problem during the eighteenth century (Derrible & Kennedy, 2009). The theory proved that there was no solution to cross all the seven bridges consecutively (Derrible & Kennedy, 2011). To apply graph theory to the Seven Bridges of Königsberg, the land masses are considered as vertices while the bridges are considered as edges (Derrible & Kennedy, 2011). Vertices and edges, as will be discussed later on, are the core of graph theory. Graph theory is applicable broadly but, as mentioned before, originated from an urban transportation problem (Derrible & Kennedy, 2011) and is mostly applied to metro networks in contemporary literature (e.g. Derrible, 2012; Derrible & Kennedy, 2011; Gatusso & Miriello, 2005).

2.2.2 Why graph theory?

The simplicity of graph theory does not seem to be a good match with the complications caused by the interdependency of issues in spatial planning. For transportation planning graph theory seems to be more suitable despite the lack of information from a mathematical theory with dots and lines. Nevertheless, is it a challenge to apply graph theory to networks which are more complex than metro networks. In those networks, there are not only stations and connections between them but there are living and changing cities connected by numerous modes of infrastructure. First, a more detailed look into graph theory and its possibilities is needed.

2.2.3 Variables of graph theory

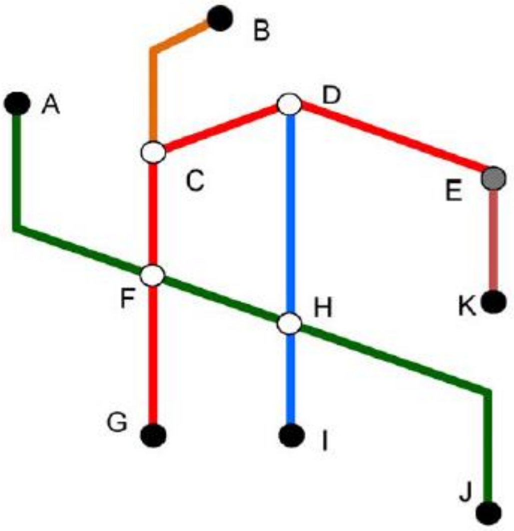
Vertices

Derrible and Kennedy (2009) describe vertices (also commonly referred to as nodes) in the context of a network as either all the stations or just the transfer stations and terminals in a network. For the latter, stations without a transfer opportunity or stations that are no terminal are excluded. Vertices are representing spatial positions within the network where there is access to the transportation mode of the network (Gattuso & Miriello, 2005). The two kinds of vertices are transfer stations and end stations, or termini (Vuchic, 2005). Vertices can be given a value for a certain characteristic of the specific vertex. An example of this is the number of edges going to the vertex. Vertices that are not connected to other vertices seem rather pointless. Therefore, they can be linked with edges, which are explained briefly next.

Edges
Derrible and Kennedy (2009) describe edges, also commonly referred to as links, as the non-directional lines between vertices. Together, edges and vertices form lines, which are representing the routes (Gattuso & Miriello, 2005). The number of lines appears, unsurprisingly, to increase with a higher number of nodes in a network (Roth et al., 2012). There are two types of edges that can be distinguished, the single and multiple edges, which is dependent on the number of edges between two vertices. Moreover, an appropriate number of edges are crucial for networks to function properly. Too few edges increase the pressure on the existing edges while too many edges make the network too complex and excessively pricey.

Matrices
The relation between the vertices and edges in a network are usually drawn in a matrix. A matrix is a clear way to show the number of edges between each different vertex where the vertices are presented in rows and columns and the number of edges as the elements of the matrix. It shows which vertices have a lot of connections to other vertices and which have less (Derrible & Kennedy, 2009). Therefore, matrices provide valuable information about the connections and the location of vertices within a network. Matrices are also used to show which vertices are isolated from the other vertices. Moreover, matrices can also be used to compare different networks and to distinguish the differences between certain characteristics within these networks (Derrible & Kennedy, 2009). An example of a matrix comparing different networks is an evaluation matrix, which is used to compare statistics of multiple networks in a clear way (Gattuso & Miriello, 2005).

An adjacency matrix (Derrible, 2012) is a kind of matrix that provides information about the relative location of nodes to others. A frequently used way to do this is by giving a certain combination of nodes the value ‘1’ if the edge exists and the value ‘0’ if it does not exist. Zhang et al. (2013), present the idea of applying the adjacency matrix to transit planning. The tracks that are directly connecting two stations in a network can be replaced by the edges and are given the value ‘1’. The vertices are given a unique number to identify them in the matrix. This means that the axes of the matrix are representing the stations and the value ‘1’ in the matrix represents an existing connection. Overlapping lines are not given any special attention in this system. Derrible (2012), illustrates this kind of matrix by using the Lyon subway system as an example as shown in figure 2.5.



	A	B	C	D	E	F	G	H	I	J	K
A	0	0	0	0	0	1	0	0	0	0	0
B	0	0	1	0	0	0	0	0	0	0	0
C	0	1	0	1	0	1	0	0	0	0	0
D	0	0	1	0	1	0	0	1	0	0	0
E	0	0	0	1	0	0	0	0	0	0	1
F	1	0	1	0	0	0	1	1	0	0	0
G	0	0	0	0	0	1	0	0	0	0	0
H	0	0	0	1	0	1	0	0	1	1	0
I	0	0	0	0	0	0	0	1	0	0	0
J	0	0	0	0	0	0	0	1	0	0	0
K	0	0	0	0	1	0	0	0	0	0	0

Figure 2.5: Schematic graph of Lyon metro system and its adjacency matrix. *Source:* Figure 2 in Derrible (2012)

2.2.4 Graph theory in network evolution

Graph theory can be applied while looking at the evolution of networks. Levinson (2005), notes that there has been little research in the process of transport network growth at the micro level. To explain the transport network growth and the emerging of certain points in a network, the author uses location nodes to clarify why the points are emerging there. Subsequently, the links emerge to connect those nodes to each other. Whenever links cross, new nodes, which are highly accessible, are created. Therefore, it is inevitable that nodes would be created at places near water crossings or at centrally located areas. On the other hand, the size of the nodes has not been determined by being created and is highly dependent on different factors as well. The author notes that transport has been the dominant reason for the existence of the twenty largest metropolitan areas in the United States.

The construction of new links as well as the expansion of links can be troublesome in some situations. Whether two nodes will be connected by a new link is dependent on the nodes as well as on the kind of network. For example, in a highway network neighbouring nodes are more likely to get a new link than in an airplane network. To predict which links will be expanded The Network Expansion Model (Levinson, 2005) can be used as tool which is based on empirical factors.

In the case of network evolution, graph theory is applied to identify and understand changes in the network. There are many different indicators and variables that can be used to describe networks and their evolution (Roth et al., 2012) Whether the location of nodes can be one of those and can be used to predict growth in the future remains uncertain. Therefore, this study suggests, more empirical research has to be done to figure this out.

2.2.5 Which derivatives of graph theory are relevant in spatial planning?

There are a lot of ways to use the available information about networks obtained from graph theory, to explore certain characteristics of the network. For example, the ratio between the number of links and vertices illustrates how well connected the vertices are. While there is a lot of information that can be derived from graph theory, only a limited part of this information is relevant for spatial planning. Therefore, the relevant information related to this research that can be derived from graph theory is studied. Whether the information is relevant with regards to this research is determined based on its applicability for inter city networks.

Node weight

Gattuso and Miriello (2005) describe that the weight of a node can be valued by analysing the number of concurrent nodes it is linked to, which is called the local degree. The node weight is then equal to the local degree if this is one or a factor two of the local degree if it is greater than one. Therefore, nodes with a lot of links to other nodes are valued higher than nodes that are connected to less. In spatial planning the node weight can be of significant importance in defining which nodes, or places, are doing well. However, the node weight does not distinguish the importance of different links, which provides more valuable information.

Line weight

The value of the different lines is called the line weight. Gattuso and Miriello (2005) define this as the weights of the nodes of the line. This means that the line weight is the sum of all the node weights on a line. The relative line weight is the line weight of a line compared to the line weight of other lines in the network. This can be useful for spatial planning to define which lines, or (rail)roads, are crucial in a network.

Loops/Cycles

Loops or cycles are opportunities to take different routes within the network. The number of network loops is equal to the difference between links and nodes plus one (Gattuso & Miriello, 2005). The extra edges in a network create cycles for alternative paths from one vertex to another (Derrible & Kennedy, 2011). Loops or cycles are especially important for the robustness of the network. For example, if one edge is congested or closed for a while, having loops and possibilities to go around that edge is crucial to keep the network from collapsing.

Complexity in networks

The complexity of a network has to be interpreted differently from the complexity in planning theory and these are not related. The complexity in networks is defined as the ratio between the number of links and the number of vertices (Gattuso & Miriello, 2005). Or in other words, the average number of connections per vertex (Derrible & Kennedy, 2011). This means that if there are relatively many links compared to nodes, the network is more complex. Complexity can be relevant in spatial planning because it is a good indicator of the state of a network. Older networks are usually more complex than newer networks where only the essential links have been established.

Connectivity

Connectivity derived from graph theory can be interpreted in two ways. First, there is the connection indicator, which is the ratio between the actual number of links and the highest number of possible links in a planar graph with an equal number of nodes (Gattuso & Miriello). This connectivity of a network has a value between '0' and '1'. The value '1' indicates a completely interconnected network and a value close to 0 indicates a lot of unused potential connections (Kansky, 1963). Or in other words, it is the ratio of actual to potential links (Derrible & Kennedy, 2011). For spatial planning this indicator is important to explore if the connectivity within a network is sufficient and if there are any missing links which can be established in the future.

Secondly, connectivity can be interpreted as structural connectivity (Derrible & Kennedy, 2009) where the importance of connections, or transfers, in the system is measured. For this indicator, the number of transfer possibilities is important. An advantage of this indicator is the emphasis on the so-called hubs, where more than two lines come together. For spatial planning these hubs are interesting places where a lot of traffic and people come together.

Directness

To calculate the directness of a network, the number of lines has to be known as well. For spatial planning, the directness of a network is mostly relevant for public transit because line transfers for road are not really seen as an obstacle. Nevertheless, the directness of transit lines is very important for networks since certain places and lines can be used more efficiently with a higher directness.

Network centrality & betweenness centrality

Derrible (2012) describes the importance of network centrality in network science and that it is at the core of public transport. The centrality degree is dependent on the number of connections that a node has. The centrality degree shows a different view on accessibility which is more useful for public transport (Curtis & Scheurer, 2010). This statistic provides only limited information about the network. Therefore, the betweenness centrality can be calculated, which, in this case, provides more valuable information than just the centrality. The betweenness centrality indicates which nodes are most frequently used in every possible trip within a network and therefore measures the importance of every node within the network. Or the number of shortest paths between every pair of nodes passing through the specific node (Zhang et al., 2013). A node with a high betweenness is, therefore, a very important part of the network.

The betweenness centrality of the nodes within the network change whenever a new node is added to the network. Derrible (2012) explained this phenomenon by using the Lyon metro as an example to illustrate the changing betweenness after adding an imaginary node to the network. This is called the democratization of the network. Comparing the betweenness within a network or between different networks is a good way to show which nodes have high betweenness and therefore the most potential to grow and become even more important. On the other side, nodes with a low betweenness, which are usually end stations, don't have much potential as long as they remain end stations. Considering the robustness of a network, networks with a more homogeneous betweenness distribution tend to be more robust since they are less dependent on one particular node (Zhang et al., 2013).

To summarise, a couple of relevant derivatives for spatial planning are outlined throughout the previous section and their applicability is elaborated. These discussed derivatives are: *Node weight, Line weight, Loops/Cycles, Complexity in networks, Connectivity, Directness and Network centrality & betweenness centrality.* These six derivatives have been introduced as most relevant for spatial planning. In the next section, the question of how these derivatives can be applied in spatial planning in explored.

2.2.6 How are those derivatives of graph theory applicable for spatial planning?

The derivatives that have been explained briefly in the previous section are adapted in known studies, in such a way that they are applicable to metro networks only. However, in this research, the opportunity to apply graph theory to a larger network has been investigated. It is, therefore, necessary to explain the function of these derivatives in a different context. Furthermore, applying graph theory to a larger network also changes the role and size of the vertices and nodes within the network.

Application of graph theory to larger networks

For transport planning, looking at a city on itself is usually just a part of the whole. The adjacent areas and cities are very important to the network of the city as well. While the application of graph theory in planning has mainly been focused on metro networks within metropolitan areas (Derrible, 2012; Derrible & Kennedy 2009; 2010; 2011; Gattuso & Miriello, 2005). There may also be a possibility to apply graph theory to a network going beyond the metropolitan boundaries, such as a network consisting out of an entire region or country. This is only possible by translating the variables of graph theory to a bigger scale as well. This new scale of using graph theory provides new views on regional and national networks and can possible be used for interurban transport planning and also for spatial planning.

Cities as vertices

In his article, Levinson (2012), compares fifty metropolitan areas in terms of accessibility to jobs. In this inter-network study, the author provides a ranking from one to fifty of all those metropolitan areas. Such a ranking may, with a different kind of variable, be a useful way to study entire countries instead of just the difference between cities. An example of a possibly relevant value for a city is the betweenness centrality. Derrible (2010) mentioned that nodes with high betweenness tend to be busier than nodes with lower betweenness. Therefore, a valuation based on betweenness may provide new information about cities within a nationwide network. Cities located near cities with a high betweenness may profit from this and show more potential growth. On the other side, cities with a low betweenness should be less likely to show potential growth. To see if these two phenomena can be linked, empirical research has to be done.

The idea of a vertex as a city as a whole instead of just a station provides a lot of opportunities for new ways of applying graph theory to spatial planning. For example, a city which has a high node weight can be expected to have more potential than a city with a low node weight. However, seeing cities as vertices changes the perception of edges as well. If edges should connect different cities instead of stations within a city, they can no longer be urban metro lines. Instead they have to go to a higher level of interurban edges. This can be related to the different levels of institutional design as described by Alexander (2005). He identifies the macro, meso and micro level in which the planner is mostly involved in the meso level. The change indicated in this chapter can be seen as a shift from a micro perspective to a meso perspective.

Inter city (rail)roads as edges

While edges are commonly seen as short-distance metro connections within a city, there have been some different interpretations as well. In their article, Zhang et al. (2013) study the biggest urban rail transit networks (URTNs) in the world. The focus of the article is mainly looking at the basic topological characteristics of these URTNs by calculating a lot of statistics for these networks. Choosing the railroads as the edges creates the possibility of looking beyond the city borders for studying networks. While it is not being mentioned in the article explicitly, the boundaries of such a network can go beyond the border of the city.

The idea of edges being (rail)roads between cities rather than metro connections within cities has not been given a lot of attention. While there are certain characteristics of ‘city-networks’ that are less valuable to ‘country-networks’, a lot of these characteristics can be translated from stations to cities and from metro lines to (rail)roads. By doing this, a whole new level of applying graph theory to spatial planning can be created. An example of translating graph theory to inter city (rail)roads can be by giving a line weight to highways or railroads depending on which cities they pass. By doing this, missing links or superfluous lines can be identified.

Application of derivatives in inter city networks

Most of the derivatives described in section 2.2.5 were aimed at metro networks within a city or metropolitan area and do not provide exactly the same information in a inter city network. Therefore, some of the derivatives have to be either explained in a different context or transformed to provide relevant information in a inter city network as well. Throughout the next section, the applicability of six derivatives of graph theory are tested for inter city networks.

Firstly, the node weight of a city instead of a station is almost the same as it was before. Although, a node with a high node weight in a metro network was usually just a popular transfer place (Gattuso & Miriello, 2005), a city with a high node weight is much more than that. A well-connected city is very likely to be more attractive as a settling location for both people and businesses. However, the node weight doesn't tell much about the kind of nodes it connects to. For example, a regional train to a small village should not be valued the same as an international train to metropolitan areas. Therefore, the line weight (Gattuso & Miriello. 2005) can provide information about the type of edge between cities. By doing this, regional trains can be distinguished from international trains and crucial and busy highways can be distinguished from superfluous highways.

Secondly, loops or cycles are very important in inter city networks in order to keep the nodes, in this case cities accessible (Gattuso & Miriello, 2005). If a road is very congested and there are no other ways to reach the city, the whole network can collapse. Moreover, a city which is known to have congested roads and overcrowded trains around it, can potentially repel businesses or people from establishing there. To prevent this, it is desirable to have loops and cycles in the network so that overcrowded edges can be avoided.

Thirdly, the complexity of a national network does not really provide much information about the different cities (nodes) relatively. However, the complexity is still a good way to compare different networks (Gattuso & Miriello, 2005), which are different inter city networks in this case. For example, it can be expected that the complexity of a network in an inter city network in a country in western Europe is much higher than the complexity of the an inter city network of a city in a country in Africa because there is simply more money to build more (rail)roads. Moreover, creating new connections or building new cities will have impact on the complexity as well. Therefore, comparing the complexity of different inter city networks can be used to identify the extent to which the networks are developed.

Fourthly, the connectivity can provide a lot of valuable information about the network. The connection indicator (Gattuso & Miriello, 2005) shows how far developed the network is as a whole. If the connection indicator is low this could be a sign that there are missing links in the network. The structural connectivity (Derrible & Kennedy, 2009) can be important to tell apart important connections within the network and thereby identifying hubs which can be seen as very interesting places for potential spatial development as they are likely to attract more people and businesses in the future.

Fifthly, the directness in national networks is especially relevant for railroads, which are, in this case, somewhat similar to the metros as described by Derrible and Kennedy (2009). Since transfers on highways are not seen as an obstacle in the contemporary road networks, the directness does not offer much valuable information for roads. For trains, however, the number of transfers to certain locations is crucial. For example, it can be assumed that suburbs with a direct connection to a business district are very likely to be more attractive as settlement location for people than suburbs with a poor connection to the business district. Empirical research has to be done to discover whether this is just an assumption or if it is actually a valid theory.

Lastly, the network centrality and the betweenness centrality as described by Derrible (2012) are fairly different in national networks compared to urban networks. For highways, the betweenness centrality indicates which nodes are busy by having a lot of cars passing by every day. While cars passing by does not tell much about the city itself, the possibility of travelling to a lot of directions and cities easily can be seen as an attractive factor for the city and hence show potential growth. For railroads, the betweenness centrality is even more important. Where a high betweenness centrality within cities usually shows busy places with a lot of transfer possibilities, a high betweenness centrality within a country is likely to show busy cities which are highly accessible form other cities. Moreover, because of the high accessibility of those cities, it is very likely to assume that cities with a high betweenness centrality have more potential growth. To find out whether this is actually true, empirical research has to be done.

2.2.7 Comparing the different derivatives

In table 2.1., all of the introduced variables and derivatives of graph theory are summarised. Moreover, the function of those variables and derivatives are noted as well. Furthermore, the usability of the derivatives is compared with the *Network centrality and betweenness centrality* being the most useful. Therefore, this is the derivative which is used and adapted for this research. Other derivatives may, in other empirical studies, prove to be just as useful to identify important cities in networks. This is, however, not studied in this research and requires further research which this study recommends.

In the next section, the trends in infrastructure planning are discussed. Relating this to graph theory, these trends can be seen as planning policies to translate opportunities of the network into practice. The potential locations for opportunities of the network can be identified using derivatives of graph theory. Moreover, the graph theory perspective and trends in infrastructure planning can be seen as complementary where graph theory focuses on the network level (macro) and trends in infrastructure planning often focus on the meso and micro level (Alexander, 2005). Therefore, these trends as well as their relation to graph theory are elaborated in the next section.

Variables and derivatives of graph theory	**Indicator**	**Function in inter city network**	**Usability to identify important cities within the network**
Vertices	**v**	City	-
Nodes/Edges	**e**	Railroad/highway	-
Matrices	**-**	-	-
Node weight	**Pi**	City weight	Reasonable
Line weight	**Pj**	(Rail)road weight	Not very
Loops/Cycles	**μ**	Accessibility of cities	Not very
Complexity	**β**	Unchanged	Not
Connectivity	**γ**	Identifying hubs	Not very
Directness	**τ**	Identifying important railroads	Not very
Network centrality and betweenness centrality	**Cb**	Recognize important cities	Very

Table 2.1: Usability of graph theory derivatives for inter city networks. *Source:* Author, based on graph theory literature (e.g. Derrible & Kennedy 2009)

2.3 New trends in infrastructure planning

It is a noticeable problem that the planning of new transport infrastructure has come to a deadlock (Struiksma et al., 2008). Hence, in the Dutch transport infrastructure a paradigm shift seems to be inevitable. The problems with the current Dutch transport infrastructure planning are caused by several trends which increased the complexity of infrastructure planning. Struiksma et al. (2008) distinguishes four trends which led to an increase of this complexity. These are: the huge interests involved, the growing scarcity of space, the changing roles of government and other parties and the increasing influence of environmental regulations.

Since these trends are likely to happen, there have to be innovative responses to make infrastructure planning more adaptive to the complex problems. There have been some approaches which can deal with this increased complexity in infrastructure planning. These approaches are, however, still limited and have to be shaped perfectly in order to work. Graph theory may prove to be an addition to these approaches and contribute to them. In this chapter, the new trends in infrastructure planning will be discussed. Moreover, for every trend the potential relation to graph theory will be discussed as well.

2.3.1 Sustainable mobility

Sustainable mobility (van Wee et al., 2013; Banister, 2000) can be seen as an inevitable turn in transportation planning due to the call for innovative ideas regarding infrastructure planning and the aspire of a sustainable world. Banister (2008) mentions the sustainable mobility paradigm as an answer to the lack of flexibility of conventional transport planning. Furthermore, the sustainable mobility approach requires interventions for the reduction of the need to travel, the encouragement of a modal shift and the encouragement of more efficiency in the transport system. To accomplish this, Banister (2008) distinguishes four approaches.

First, there is substitution, to reduce the need to travel. This requires a trip to be replaced by something else so that the trip no longer has to be made. An example for this is internet shopping, which is a substitution for a trip into the city for shopping. Not surprisingly, most of the substitutions are connected to ICT developments and are, therefore, rather uncertain for the future.

Secondly, there is the modal shift, which is also some kind of substitution. However, in this case the substitution considers different modalities that are more sustainable. To achieve this, there have to be transport policy measures. An example for this is new infrastructure for public transport or bikes as an incentive to those modalities or an increase of parking costs and tolls to stimulate people to make use of different modalities. Moreover, new walking and cycling infrastructure are a requisite for a modal shift towards more sustainable modalities (Song et al., 2017). Another example to stimulate a modal shift is by improving the areas around railway stations to stimulate the use of public transport (van Wee et al., 2013). With regards to graph theory, improving the possible directions from the railway station may also increase the use of public transport and strengthen the modal shift.

Thirdly, there is a distance reduction, which requires a relocation of activities. To accomplish this, land-use policy measures are required. An example for this is mixed use development which can in be terms of buildings, space and infrastructure. The latter requires an integrated multi-modal approach focusing on public transport oriented development.

Lastly, there is efficiency increase, which can be done by technological innovations. This has directly impact on the efficiency of transport through assuring that the best available technology is used. This can be done, for example, through making use of the cleanest, least polluting cars or by stimulating the use of green public transport.

These four approaches to achieve sustainable mobility show some similarities with graph theory related ideas. Banister (2008), notes that public acceptability and community involvement are key to the successful implementation of changes. Gaining public support for transportation planning can be a problem due to the complexity and future oriented approach it often has. On the other hand, graph theory can, because of its simplicity, function as an understandable alternative to involve the community to the process of planning and stimulate a modal shift (Song et al., 2017). For example, presenting data from graph theory to explain why a missing link should be built, may convince the local community of the value it has for the area. Furthermore, combining new links with area oriented development can solve more problems than just an increase of the accessibility of the area. Therefore, using graph theory to simplify networks can present a suitable way to involve the local community in the complex world of spatial planning.

Essential to achieve sustainable mobility is understanding daily travel patterns and daily urban systems (Timmermans et al., 2003). These daily urban systems vary from person to person and place to place. By understanding the unique context of a place and the people living there, sustainable mobility (Banister, 2000) can provide a tailor-made solution to improve the mobility for all places. An example of this is comparing two similar villages, one is located in northern Canada and one in the Netherlands. While the people in the village in the Netherlands are possibly accustomed to using the bicycle, and walking as their main modality, the people in the village in Canada may have never ridden a bike and use a snow scooter instead. Moreover, for people in a thinly populated area like northern Canada it might be common for a home work distance to be around three hours while this would be very unlikely in the Netherlands. The reason for emphasizing this is to reveal the importance of the context for mobility. Since the cases in this research are located in the Netherlands, the outcomes of the research are different for all places and the variables used might make less sense in other countries. Therefore, it is important to keep the definition of mobility for the specific place in mind as well as understanding what may be different in other places. This is context that may be lost when using graph theory as a method to present a complex reality.

2.3.2 Integrated infrastructure planning

To achieve an integrated transport system, a shift from the contemporary small-scoped planning approach towards an integrated, strategy driven planning approach is necessary (Arts et al., 2016). Subsequently, in their article Arts et al. (2016) provide several examples of the best practices amongst European countries of infrastructure planning. Arts et al. (2016) distinguish six dimensions for their conceptual model with vitality being in the centre of those six. Those are: the spatial dimension, the network dimension, the time dimension, the value dimension, the institutional dimension and the implementation as can be seen in figure 2.6 (Arts et al., 2016).

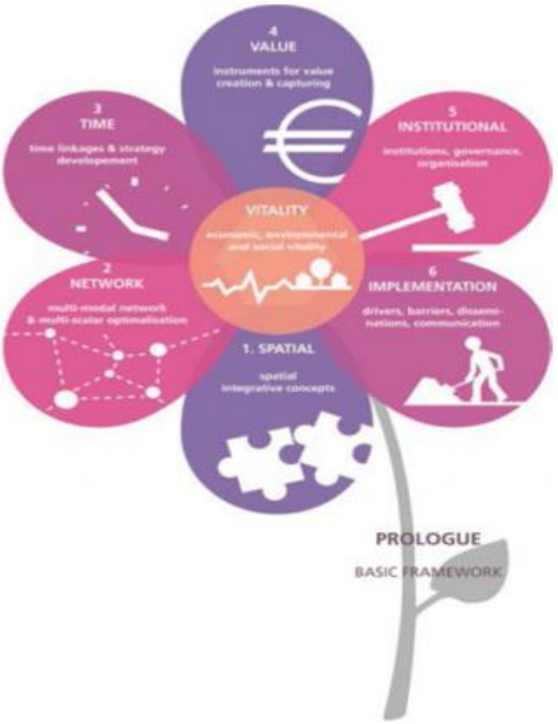


Figure 2.6: the NUVit conceptual model Source: Figure 1 in Arts et al. (2016)

For this research, particularly the spatial dimension and the network dimension share a lot of characteristics with the new approach to graph theory. The spatial and network dimension can be seen a change from uni to multi-functional and uni- to multimodal respectively. The change from uni to multi-functional is quite similar to the change from line to area-oriented approach in transportation planning. The change from uni- to multimodal is comparable to the change in graph theory from a unimodal metro network to a multi modal network between cities. Furthermore, multimodality is becoming a recognized method to decrease car dependency by stimulating other modalities (Buehler & Hamre, 2014; van Wee et al., 2013). This should be taken into account when planning for new roads to stimulate multimodal road use.

2.3.3 Line to area-oriented approach

In their article, Heeres et al. (2012) mention that in the Netherlands the planning and realization of road infrastructure has traditionally been separated from other aspects of spatial planning. Considering the high interdependencies between infrastructure and other parts of spatial planning, this is highly inconvenient. Due to new insights about the areas surrounding infrastructure projects and about the integration of planning processes, the different aspects of planning should no longer be seen as independent but rather as interwoven. Therefore, a road can no longer be seen as only a connection from point A to point B. The other spatial sectors, which include: housing, business, recreation, water, nature and agriculture (Priemus, 2007), have to be included in the decision making about infrastructure projects. Hence, it is inevitable to adapt the line approach towards an area-oriented approach which takes all the spatial policy sectors into account (Heeres et al., 2012). Hence, various developments in the direction towards area-oriented approach in planning can be identified in the Netherlands (Struiksma et al., 2008).

The area-oriented approach is a result of multiple interrelated trends in the Netherlands which led to the malfunction of the traditional road planning in dealing with contemporary dynamics (Heeres et al., 2012). Therefore, it was no surprise that a new, innovative approach was necessary to move with the times. Heeres et al. (2012) distinguish two forms of integration being internal and external. Where the latter is mostly reliant on cross-sectoral coordination between the different spatial policy sectors, the first-mentioned aimed mainly at integrating different levels of infrastructure planning. The internal integration program intended to develop an integrated traffic and transport policy at different institutional levels.

This transformation from line towards area-oriented approach shows some similarities to transforming graph theory from city-network to nation-network. The nodes can no longer be seen as just a metro station but are actually living and changing cities where all spatial policy sectors come together. Moreover, the links are no longer mono-modal lines between two stations but are actually a part of the area in which the link is located. Furthermore, the links are now part of a multi-modal network in which different kinds of modalities with different kinds of infrastructures can be used to travel from A to B.

2.3.4 Transit-oriented development

Transit-oriented development (TOD) is based on the idea of accommodating incremental urban activities near urban rail stations in relatively high density (Yang et al., 2016). Moreover, TOD is seen as a way to achieve sustainable transportation and deal with problems caused by urban sprawl (Wey et al., 2016). TOD fits well with graph theory in terms of connectivity and betweenness centrality since these derivatives can indicate places where TOD could be successful. Thus, potential locations for TOD within a network could be defined using graph theory as a framework. Furthermore, if local or regional TOD can be connected efficiently to the national transportation network, it would improve the entire network system. Therefore, TOD can be seen as a way of dealing with urban sprawl while improving the mobility within a network. Figure 2.8 shows an example of TOD in Taiwan with multiple Development areas based on an existing Mass Rapid Transit (MRT) line.

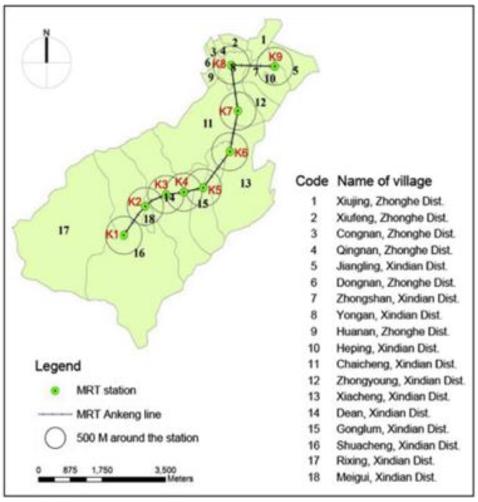


Figure 2.7: Transit-oriented Development in Taiwan *Source:* Figure 3 in Wey et al. (2016)

Now all of the perspectives introduced in chapter 2.1 have been discussed, the perspectives are placed in a conceptual model in the next section showing the relation between the perspectives as well as the general point of view of the research with regards to these perspectives and the next chapters.

2.4 Conceptual Model

Figure 2.8 shows the Conceptual Model in which all the parts of the theoretical framework have been visualised. In this model, infrastructure planning is the beginning, being divided into new trends, graph theory and planning theory as a response to increasing complexity. From here, the derivatives of graph theory and approaches regarding complexity theory are the source of a case study, which is elaborated upon in chapter 3. The results of the case study lead to a generalizable concept, which together with a case comparison and an analysis of the new trends leads to the results and expectations. From here, a framework is build based on the Dynamic Adaptive Approach and on graph theory. The position of the research question and sub questions within this framework have been added for clarification.

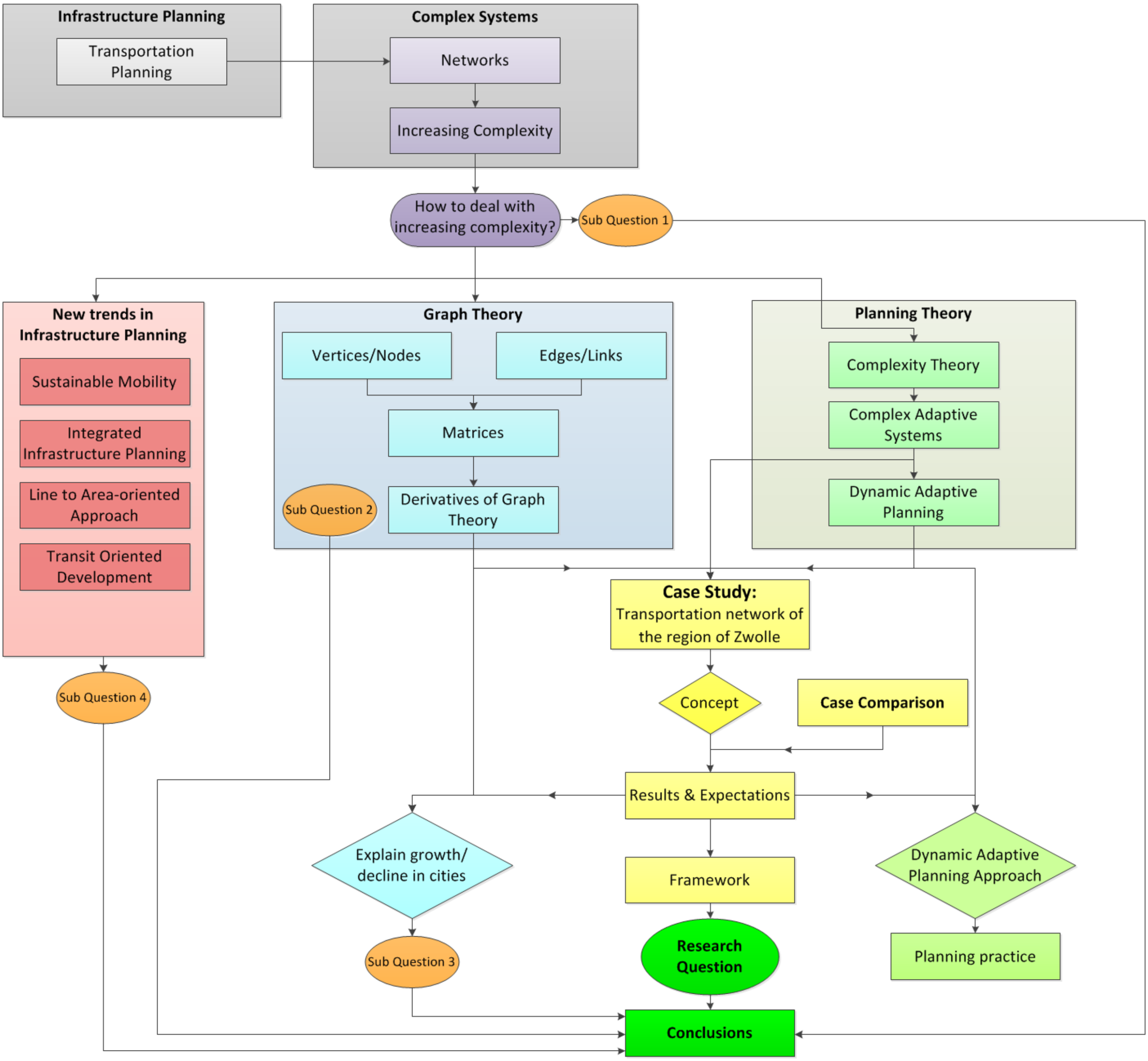


Figure 2.8: Conceptual Model *Source:* Author

3. Methodology

In chapter 1.2, a research question and several sub questions have been identified. To answer those questions, the sub questions have to be put apart and a suitable method to answer each of those has to be identified. While some of the issues identified, were studied extensively in the previous chapter, other issues require a more empirical method to be understood. Therefore, this chapter provides a distinction of the used methods as well as an explanation why these methods are especially suitable for this research. Moreover, the selection for the methods and the preference of those methods over other methods is elaborated upon. These methods come together in a research strategy containing three methods, which is summarised in figure 3.2. Subsequently, a more in depth analysis of the chosen methods is given. However, first a more detailed scientific position of this research has been outlined to identify the position of the research within the planning debate.

3.1 Scientific position of the research

Within scientific research, a distinction can be made between qualitative and quantitative research (O'Leary, 2014). The latter is characterised by statistics, variables and mainly based on facts, which leads to a verified or falsified hypotheses. The former is characterised by meanings, values and concepts often obtained through research based on interviews with experts. This distinction between qualitative and quantitative can be compared to the Aristotle and Plato dualism (Allmendinger, 2009) based on the orientation on the object or the subject respectively. This can also be linked to the contemporary planning debate of the modernism and postmodernism dualism (De Roo, 2003).

For this research, which is mainly an exploration of the use of graph theory for networks, experts are few in number since not much research has been done in this specific part of transportation planning. Therefore, a more quantitative method seems more suitable for this research due to the absence of comprehensive debates, meanings and concept. Nevertheless, obtaining values and concepts are eventually an essential part of answering the research question and can, therefore, be seen as an inevitable part of the process. Moreover, due to the lack of data on the subject of study, not all sorts of quantitative research can be used for this research. A tailor-made approach seems to be required to match the difficult characteristics of this research. This approach would require a mixed method, a combination of quantitative as well as qualitative research.

Lijphart (1975) made a distinction within scientific methods between experimental and non-experimental methods in which the latter includes the statistical, comparative and case study method, each based on the amount of cases (N) available. Considering the extensiveness of networks and the high number of variables within networks, a small N is more appropriate for this research. Therefore, a single case study can become a concept to generalise elsewhere (Rose, 1991). In this case a case study of one network can be used to explain certain characteristics of the network. Subsequently, comparing cases, using the most similar systems design (Sartori, 1991), can be used to verify or falsify the dependent variable. A summarizing explanation of this has been visualised in Figure 3.1, in which the starting point is the choice of a scientific method, leading step-by-step towards the dependent variable.

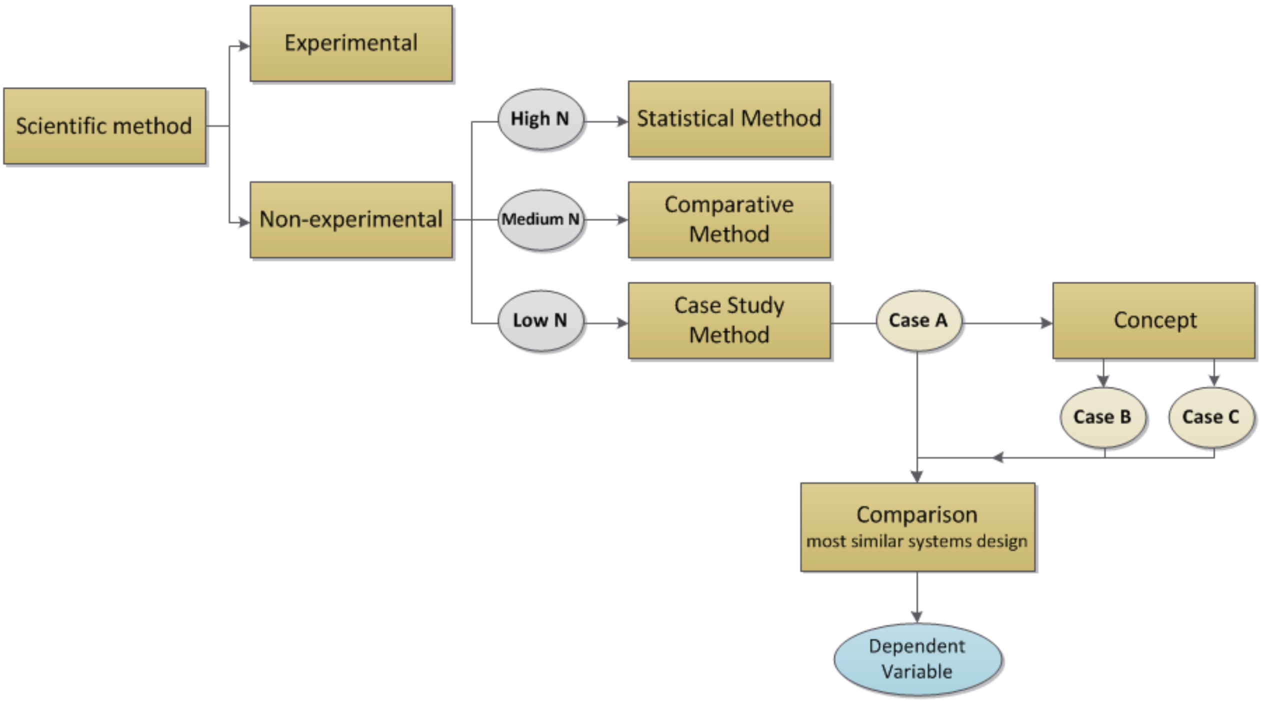


Figure 3.1: Summary of research methods *Source:* Author, based on Lijphart (1975), Rose (1991) & Sartori (1991)

3.2 Data collection and research methods

The collection of data for this research can predominantly be distinguished into three, complementing methods which form the research strategy together. First, there is the literature study, of which the results are presented in chapter two, providing the theoretical framework and the subsequent conceptual framework. Secondly, a case study approach is used to create a concept which can be generalised for other networks (Rose, 1991). Lastly, a case comparison approach has been chosen to identify the dependent variable and compare the studied case to similar other cases. These methods were chosen for as a result of the availability of mainly statistical data about networks and the abundance of literature on transportation planning. Moreover, due to the novelty of the topic, an interview or survey based research would be less suitable due to the potential lack of data. While an interview based research would require interviews with the few experts around the world, a survey based research would not be suitable due to the public unawareness about this topic among society. Finally, a statistical approach is found unsuitable due to the preferred focus on just a small amount of cases (Lijphart, 1975), which are networks in this research. Consequently, the literature study, case study and case comparison are found most suitable for this research. The specific order of the applied methods was a deliberate decision. While the literature study was done first to provide a theoretical framework and a conceptual model, the choice to do the case study before the case comparison follows from figure 3.1. Throughout the next sections, these methods will be further elaborated independently.

3.2.1 Literature study

In retrospect, the literature study has been divided into three separate parts leading towards the conceptual model (2.4). These are: complexity in transportation planning (2.1), graph theory and its derivatives (2.2) and new trends in infrastructure planning (2.3) respectively. This division was a result of the distinction between planning theory, graph theory and future developments with regards to transportation planning. The literature study has predominantly been done by studying literature in articles read before this research as well as looking for online articles, books and documents to complement this. Regarding graph theory, the literature study was based on Derrible and Kennedy (2009) initially, leading to a larger amount of literature by going through the referred and cited papers as well as using Google Scholar and WorldCat. Moreover, the literature about new trends in infrastructure planning is a combination of literature from other courses as well as online research into these trends. The available literature was from multiple perspectives, authors with different backgrounds and with a complementary character. An example of this is the different kind of journals in which the used articles were published, ranging from mathematical papers about graph theory to planning journals about trends in planning. Consequently, in the theoretical framework a more comprehensive view on the subject of study was obtained leading to the conceptual model, which is the framework for the next sections.

3.2.2 Case study and case selection

To gain more knowledge about the implications of graph theory on transportation planning, a case study approach has been used. Case studies have been an important tool for natural as well social scientists for a long time (McCorcle & Bell, 1986). A case study is a qualitative method requiring intensive knowledge about one or a few cases (Clifford et al., 2010). Case studies can reveal structures and concepts which can be used to create models and test hypotheses (Harvey, 1969). An advantage of this method for this research, is the possibility to choose the case deliberately based on the results of analysing a network using the derivatives of graph theory. On the other hand, a disadvantage of case studies is they require intensive knowledge (Clifford et al., 2010) and can be seen as highly subjective in terms of case selection and interpretation. Nevertheless, a case study approach has been chosen for as a source of data.

The primary case selected for this research is the transportation network of the region of Zwolle. The choice for this specific case is a deliberate choice based on the favourable position in the network with regards to graph theory as well as the population growth the region has shown throughout the last decade (CBS, 2016a). These statistics as well as the favourable position, leading to the selection of this case are further elaborated upon in chapter 4. Moreover, statistics regarding population growth and passenger numbers in the Netherlands are widely present and available to public (CBS, 2016a; ArcGIS, 2016), which enables a comprehensive data analysis as the basis for the case study.

3.2.3 Case comparison and case selection

Comparing of cases can be done for multiple reasons. Berting (1979 in Booth, 2011) identifies the following reasons to compare: to develop theory, to explain or interpret social phenomena, to describe social reality, to understand the effects of policy intervention and to evaluate policy process. This research is mainly focusing on developing theory and explaining social phenomena and, therefore, these can be seen as the primary reasons of comparison.

For comparing the different cases, the “Most Similar Systems” Design (Przeworski & Teune, 1970) has been used. Przeworski and Teune (1970:32) note that “such studies are based on the belief that systems as similar as possible with respect to as many features as possible constitute the optimal samples for comparative inquiry”. With regards to the earlier mentioned case study, a small number of ‘Most Similar Systems’ have been identified. These are initially selected based on the population of the municipality, access to highways and railroads and being a node in the network. Thereafter, the selection is reduced by taking a closer look at the position of the nodes within the network where nodes near the border and near other big cities were filtered out. Finally, a comparison between Zwolle and the two cases leftover, which are Apeldoorn and 's-Hertogenbosch, is done based on a wide range of criteria to identify the most similar as well as the most relevant case. This case turned out to be 's-Hertogenbosch.

3.2.4 Outline of research design

To summarise the research strategy, it has been visualised in Figure 3.2, where the initial literature study is outlined on the left going through the explained steps of the research to the right.

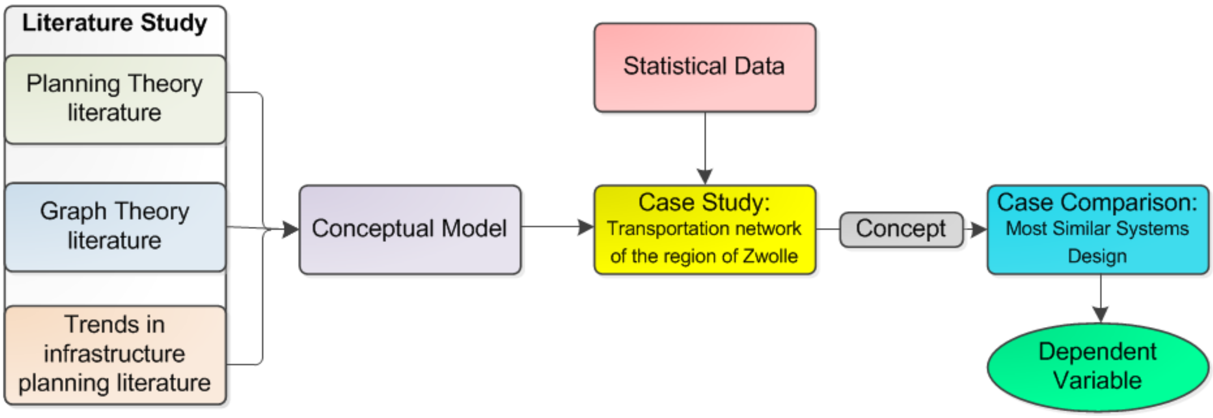


Figure 3.2: Research strategy design. *Source:* Author

3.3 Data analysis

Analysing the data gained from the literature is summarised in the conceptual model (2.4). This is a requisite for the case study. Subsequently, the specific case data combined with the conceptual data has to be analysed for the case study and the following case comparisons. Thereafter, the Dynamic Adaptive Planning model (Wall et al., 2015) is used to translate the results of the case study and case comparisons to planning practice. Finally, the results of the research are analysed based on the research question and sub questions (1.2).

3.3.1 Case and comparative data

The data for the case study are predominantly about the network of the case. To study these networks, maps are used as a source to understand and identify the important places in the network. The gathered data from these maps includes cities, roads and railroads. Moreover, to give a value to each of these cities, statistical data are used to gather information about the size and importance of cities, the number of daily passengers and the travel time between cities. In Figure 3.3 an outline of the data analysis as well as the data sources is visualised. For the data analysis, a distinction can be made between three types of data concerning network data, city data and comparative data. For each type of data different sources are required. Therefore, the same distinction is used for the data sources resulting in sources like traveller's numbers, scanning maps for cities and comparing cities using the DESTEP method (Van Vliet, 2013). This method includes the comparison based on demographics, economic, social, technological, ecological and political factors (Van Vliet, 2013). The sources are consulted based on the relevance of the data. For example, daily number of passengers is very relevant to networks and these data are, therefore, acquired extensively using multiple sources. The collected data are processed using Excel as calculating and working tool and thereafter visualised in tables and figures. The data are collected from statistical data bases such as CBS and passenger railway operators such as NS. These data are collected at the same time to prevent miscomparing. The collection of the data is elaborated further in chapter 4.1.

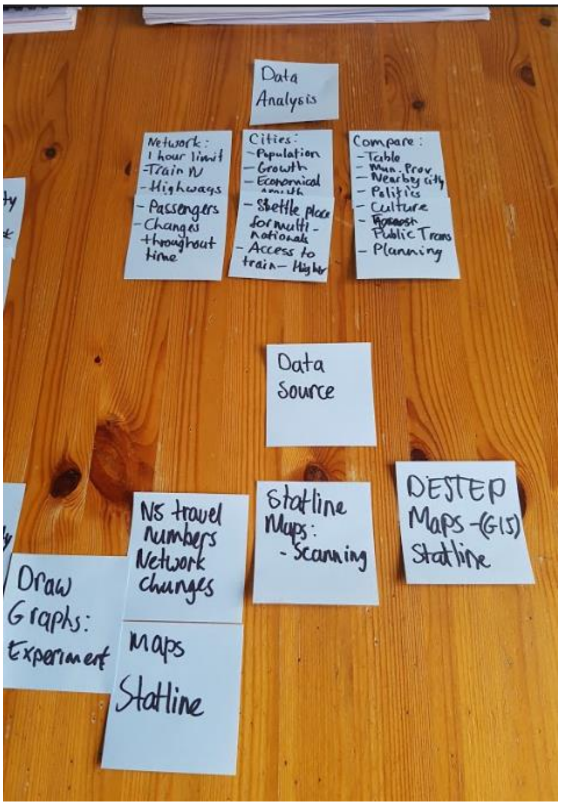


Figure 3.3: Outline of data analysis and data source. *Source:* Author

3.3.2 Dynamic Adaptive Planning

To process the gathered information, the earlier explained Dynamic Adaptive Planning model (Wall et al., 2015) and partially completed framework is complemented based on the results of the case study. The model is essentially a method to implement the results of the case study and comparisons to make it applicable for planning practice. The dependent variable serves as a key concept to make it applicable by explaining the potential of a certain area based on its location in the network. Furthermore, the Dynamic Adaptive Planning approach can translate graph theoretical results into common planning practice (e.g. combing railroads with bicycle lanes for important links in a network).

3.3.3 Results

The results of this research ought to be an explanation of how graph theory can be used as a framework for inter city networks using Zwolle as a case study while also accounting for the increasing complexity. This framework can either be found or not depending on the availability and usability of data. The extent of this framework is, however, considerable in potential if it can be applied to different types of networks all around the world. Therefore, the results of this research are just an exploration of the possibilities to apply graph theory to inter city networks. With regards to explaining potential growth, graph theory can either be used to explain this phenomenon or not be used. However, it is a likely outcome that more research has to be done to achieve a 'true' answer for this statement. Since this subject is still in its infancy, an exploration of the possibilities is the highest achievable result of this research. In retrospect, it can be concluded that a framework has been identified throughout the next chapters and, therefore, results are found. These results are, however, subjective and can still be improved.

4. Data

In this chapter, the collected data are presented and used to get to the results. In chapter 3.3.1 the methods of data analysis as well as the data sources have been mentioned. However, a more extensive outline of the data collection is perceived necessary and presented in chapter 4.1. Thereafter, in chapter 4.2 a framework is introduced to apply graph theory to inter city transportation networks. Subsequently, in chapter 4.3 a comprehensive case study, providing a framework is done. This case study is done initially with railroad networks but also contains a road network. The different outcomes using different methods are outlined in chapter 4.3.4. To test the values resulting from the case study in a another network, a comparative study is done in chapter 4.4.

4.1 Data collection

As explained in the previous section, the collection of data is divided into three different parts. These parts are networks, cities and comparing between cities. For each of these parts, a different method of collecting data has been applied based on the kind of data required. Throughout the next section, each of these parts, and their respective data, are explained separately.

4.1.2 Network data

To analyse physical networks, a boundary has to be set to the network due to the connecting nature of networks. In theory, the whole planet could be seen as one big physical network which is almost completely connected. However, the boundary of the network has been set at one hour travelling from the central place in the network to limit the scope of the network. This boundary is set based on the daily urban system (Arts et al., 2016; Timmermans et al., 2003) of the respective city. To decide how far this actually is from the centre, travel-time calculators have been consulted as a tool to check the travel time. The travel time calculators used for trains are valid until the 11th of December 2016. After this date, the timetable of the whole Dutch rail network has been adjusted slightly. This might have some influence on the results and can be the subject of further research. For all of the travel time data, the old timetables are used to prevent miscomparing.

4.1.3 City data

Data about the different cities within the network is required to distinguish the importance of the different nodes in the network. Since not all cities are of equal importance for a network, this distinction is inevitable. The distinction between cities is done based on either the number of inhabitants of the municipality in which the node is located or the daily number of passengers for the respective node. For the specific city of the case study a wider collection of data is done including the population growth over the last couple of years.

4.1.4 Comparable data

For comparable data, it is important that the source of all of the data for one variable is the same. This is because of the different measurements that can be used by different providers of statistics. Therefore, it is important to use the same source and prevent 'miscomparing' (Sartori, 1991). The comparable data is used to identify a most similar case to Zwolle. Based on the number of inhabitants, a small selection of cities is selected. Furthermore, being a railway node as well as a highway node are preconditions to be suitable for the selection. Thereafter, more detailed criteria such as location in the network and similar DESTEP conditions (Van

Vliet, 2013) to the case of the case study are used to define the most suitable case for comparison.

4.2 A framework to apply graph theory to inter city transportation networks

In this chapter, a framework is introduced to apply graph theory to the case of the case study. The structure of the framework is explained briefly and can be applied to similar cases elsewhere. Therefore, the case study can be seen as an example of the application of those guidelines for one specific case. The guidelines are constructed in three subsequent steps which are elaborated in the next section and summarised in table 4.1.

The first step is defining the size of the network by finding all nodes within the respective time limit (step 1a). For this case the time limit is set at one hour +15% to include the daily urban system (Arts et al., 2016) and in this specific case to include the city of Amsterdam. After defining the number of nodes in the network, it is important to distinguish larger nodes from smaller ones by looking at the population of the cities the nodes represent. This is especially important for inter city networks since large cities should not always be valued equally as small cities. Therefore, distinguishing the nodes into three categories indicates the importance of the different cities in the network. Based on these data, a first graph map can be drawn in which the nodes are located according to their geographical location (step 1b).

The second step includes the abstracting of the graph map into a clear structured graph in which no distinction can me made among the nodes (step 2a). The nodes are longer located based on their geographical location but in a structured manner to provide clarity. Moreover, the names of the nodes are replaced by letters to ensure the abstract nature of the graph. Subsequently, a matrix can be drafted in order to indicate whether a pair of nodes is connected or not (step 2b). In this matrix, a value of '1' indicates there is a link between the nodes and a value of '0' indicates no link. The total number of each row and column should then be equal to the number of links of the respective node. This matrix can also be adjusted to indicate if a direct line between the two nodes exists instead of a direct link.

The third step is calculating the betweenness of the studied node (step 3). This is the most complicated step and involves an accurate method to prevent mistakes. Calculating the betweenness centrality is a tool to understand the value of certain nodes within the network (see chapter 2.2.6). To do this, there are multiple methods of calculating the betweenness depending on the size and importance of the nodes in the network. The most basic method is drawing a half matrix with all the possible node pairs excluding the node representing the city of study (node X). Such a matrix then looks like AB, AC, BC etc. An explanation of this is drawn in table 4.5. Thereafter, a calculation is done for the fastest route between all the respective pairs. If the fastest route passes the node X it is given a value '1', if it passes the node X in some cases it is given the value '0.5' and if the fastest route never passes the node X a value of '0'. The fastest route can be calculated in multiple ways such as counting the route with the least number of nodes it passes or by using an online travel planner (NS-Reisinformatie, 2016). The betweenness centrality of node X can then be found by calculating the share of fastest routes going through X of the total number of node pairs (e.g. 5 out of 20 fastest routes go through X so the betweenness centrality is 0.25). The betweenness centrality can then be compared to the betweenness centrality of nodes in other networks to compare their relative values. A more detailed explanation of betweenness centrality is given is chapters 2.2.5 and 2.2.6 (or e.g. Derrible, 2012; Zhang et al., 2013).

An extension to calculating the betweenness centrality is to account for the importance of different nodes within the network since small cities are of less importance in an inter city network than large cities (e.g. Amsterdam is more important in the network of Zwolle than Almelo while both are equal nodes in the network). To do this, this study introduces the 'node pair value' which is a multiplication of a node weight for each pair of nodes (e.g. node A has a value of 2 and node B a value of 3 so their combined node pair value is 6). This calculation is a combination of the node weight (Gattuso & Miriello, 2005) and the betweenness centrality to emphasize the importance of different nodes within the network. The value for each of the nodes can be defined by their daily number of passengers or population, indicating their size and importance in the network. In the next section, the guidelines of the framework are applied to the case of the region of Zwolle. This is done initially for the railroad network and later on for the road network as well.

What?	How?	Why?
Step 1a: Defining the network size and nodes. **Step 1b:** Drawing the nodes and links in a graph.	Identify all the nodes within the time limit. Categorize the nodes based on population. Draw a map using the nodes geographical location	To give an overview of the network and emphasizing the important cities in the network
Step 2a: Draw an abstract graph. **Step 2b:** Draft a matrix based on the drawn graph.	Abstract the graph by removing the geographical accuracy of the nodes and by representing the nodes with letters. Thereafter, a matrix can be drafted to indicate which nodes are linked	To make a clear, structured graph which can be used efficiently for the matrix and can be used as a basis in the next step.
Step 3: Calculate the betweenness centrality.	By pairing up all the nodes and calculating the fastest route between the pairs. The pair is then given a value based on whether the fastest route passes node 'X'	To indicate the importance of node 'X' in the network and looking at the share of fastest routes passing node X. The betweenness centrality value can then be used as comparative value to other networks.

Table 4.1: Guidelines to apply graph theory to inter city transport networks *Source:* Author

4.3 Case Study: The transportation network of the region of Zwolle

In order to study the importance of Zwolle in its transportation network, a case study is done following the framework containing guidelines to apply graph theory to inter city networks identified in the previous section.

4.3.1 The railroad network of the region of Zwolle

Based on data from OpenStreetMap (2016) and NS-Reisinformatie (2016) a one-hour train travel map for Zwolle is visualised in figure 4.1. This figure presents the nodes in the region of Zwolle of around one hour travel time and their respective links. Moreover, the location of the nodes in the map approximately represents the relative location of the nodes. The travel time window of about one hour was exceeded partly to include the Dutch capital Amsterdam which has a travel time of 68 minutes and is of significant importance for the region of Zwolle. 68 minutes corresponds more or less with the 70-90 minutes indicated by the law of constant travel time (BREVER-wet) (Hupkes, 1979) indicated as maximum daily travel time. The fastest travel time from Zwolle, using as few transfers as possible has been studied using the NS timetable valid until 11th of December 2016 (NS-Reisinformatie, 2016). Moreover, the size of the nodes in the map is based on the number of inhabitants of the respective nodes including a categorization of small, medium and large nodes. Small nodes have less than 100000 inhabitants, medium nodes have between 100000 and 250000 inhabitants and large nodes more than 250000 inhabitants. Or noted otherwise: small < 100000 < medium < 250000 < large. All of these data are explained in table 4.2.

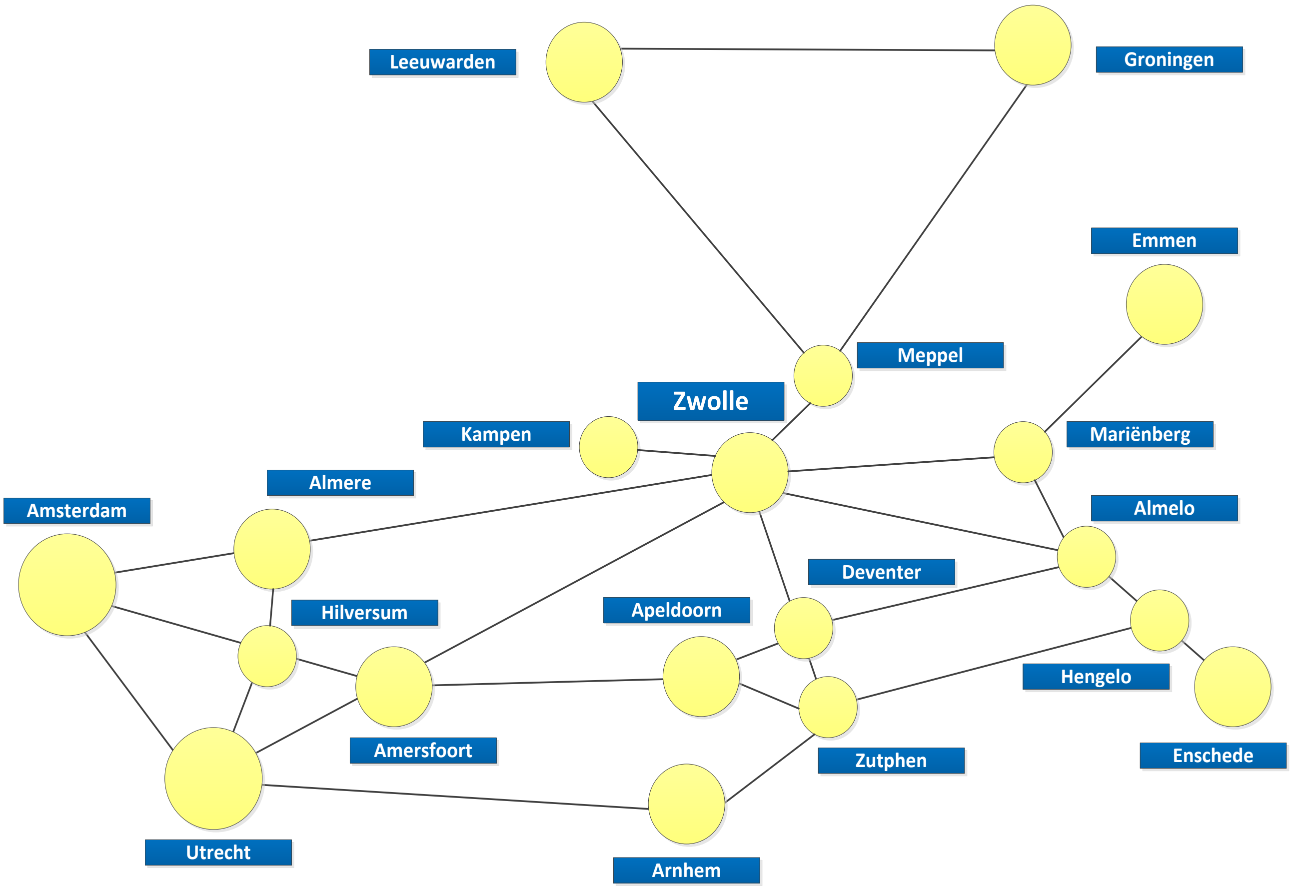


Figure 4.1: One-hour train travel map of the region of Zwolle *Source:* Author, based on OpenStreetMap (2016)

Node	Municipality	Travel time to Zwolle	Inhabitants (2016)	Node size in map
Almelo	Almelo	41 minutes	72425	SMALL
Almere	Almere	40 minutes	198145	MEDIUM
Amersfoort	Amersfoort	34 minutes	153602	MEDIUM
Amsterdam	Amsterdam	68 minutes	833624	LARGE
Apeldoorn	Apeldoorn	40 minutes	159025	MEDIUM
Arnhem	Arnhem	61 minutes	153818	MEDIUM
Deventer	Deventer	24 minutes	98869	SMALL
Emmen	Emmen	55 minutes	107584	MEDIUM
Enschede	Enschede	68 minutes	158351	MEDIUM
Hengelo	Hengelo	56 minutes	81075	SMALL
Groningen	Groningen	57 minutes	200952	MEDIUM
Hilversum	Hilversum	50 minutes	87830	SMALL
Kampen	Kampen	10 minutes	51950	SMALL
Leeuwarden	Leeuwarden	54 minutes	107897	MEDIUM
Mariënberg	Hardenberg	25 minutes	59687	SMALL
Meppel	Meppel	17 minutes	32794	SMALL
Utrecht	Utrecht	53 minutes	338967	LARGE
Zutphen	Zutphen	38 minutes	46997	SMALL
Zwolle	Zwolle	-	124896	MEDIUM

Table 4.2: Inhabitants per municipality and travel time to Zwolle *Source:* CBS (2016b) & NS-Reisinformatie (2016)

4.3.1.1 Graph analysis of railroads in the region of Zwolle

In the graph analysis, the cities are represented as nodes which are indicated by letters. Table 4.3 shows which letter represents which city in the graph. The letters are chosen according to their location in the abstracted graph map. This is chosen for to prevent any linkage of nodes to cities in the graph map which may lead to presumptions.

Node/City	Letter in Graph
Almelo	**P**
Almere	**B**
Amersfoort	**E**
Amsterdam	**A**
Apeldoorn	**H**
Arnhem	**M**
Deventer	**K**
Emmen	**Q**
Enschede	**S**
Hengelo	**R**
Groningen	**N**
Hilversum	**C**
Kampen	**F**
Leeuwarden	**G**
Mariënberg	**O**
Meppel	**J**
Utrecht	**D**
Zutphen	**L**
Zwolle	**I**

Table 4.3: Letters representing nodes in railroad graphs in the network of Zwolle *Source:* Author

Figure 4.2 shows the graph map for railroads in the region of Zwolle, which is used throughout the next sections. The figure is an abstraction of figure 4.1 in which the geographical location and node size are no longer taken into account. The links represent existing railroad connections, which are split into different lines in chapter 4.2.2. Moreover, table 4.4 shows a matrix of the existence of links between the nodes. Value ‘1’ represents a direct link and value ‘0’ represents no direct link.

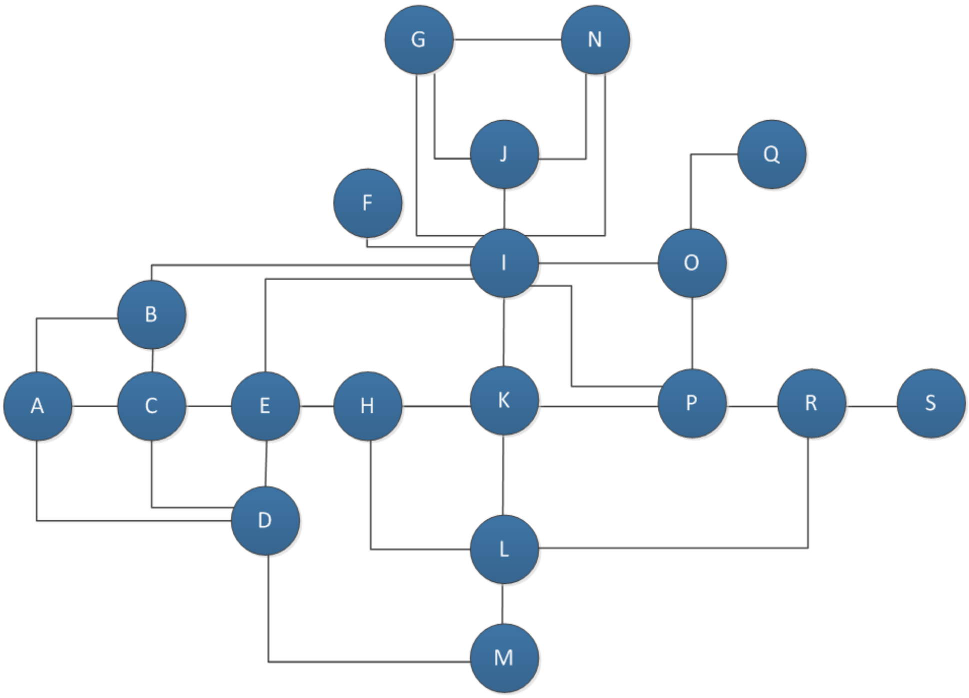


Figure 4.2: Graph map of railroads in the region of Zwolle *Source:* Author

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**Total**
A	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
B	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**3**
C	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**
D	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**4**
E	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	**4**
F	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
G	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	**3**
H	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	**3**
I	0	1	0	0	1	1	1	0	0	1	1	0	0	1	1	1	0	0	0	**9**
J	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	**3**
K	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	**4**
L	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0	**4**
M	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**2**
N	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	**3**
O	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	**3**
P	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	0	**4**
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
R	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	**3**
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Total	**3**	**3**	**4**	**4**	**4**	**1**	**3**	**3**	**9**	**3**	**4**	**4**	**2**	**3**	**3**	**4**	**1**	**3**	**1**	

Table 4.4: Direct railroad links between nodes in the region of Zwolle *Source:* Author

4.3.1.2 Calculating the betweenness centrality for Zwolle

Based on the map and graph in figure 4.2, the derivatives of graph theory can be calculated for the network. In chapter 2.2.7 the betweenness centrality (C_b) has been indicated as a useful derivative to identify important cities within the network. Table 4.5 shows the calculation of the C_b of Zwolle ('I') in the network by indicating if the fastest route between a pair of two nodes (node pairs) which always goes directly through 'I' (green), sometimes goes through 'I' (orange) or never goes through 'I' (red). To clarify this, an example is given for two node pairs in figure 4.3. For the node pair 'AJ' the fastest route is from A to B to I to J, which is highlighted in 4.3a. Since this fastest route passes through 'I', the value for AJ is '1' and marked as green in the table. In figure 4.3b the fastest route between node pair 'AL' is given, following the route from A to D to M to L, which does not include 'I'. Therefore, the node pair AL has a value of '0' and is red in the table.

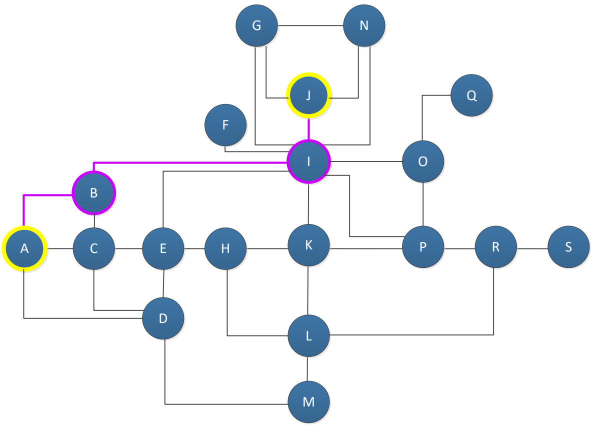


Figure 4.3a: Fastest route between node A & J

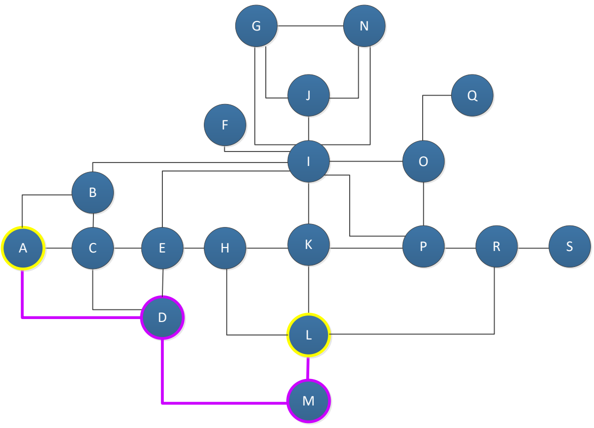


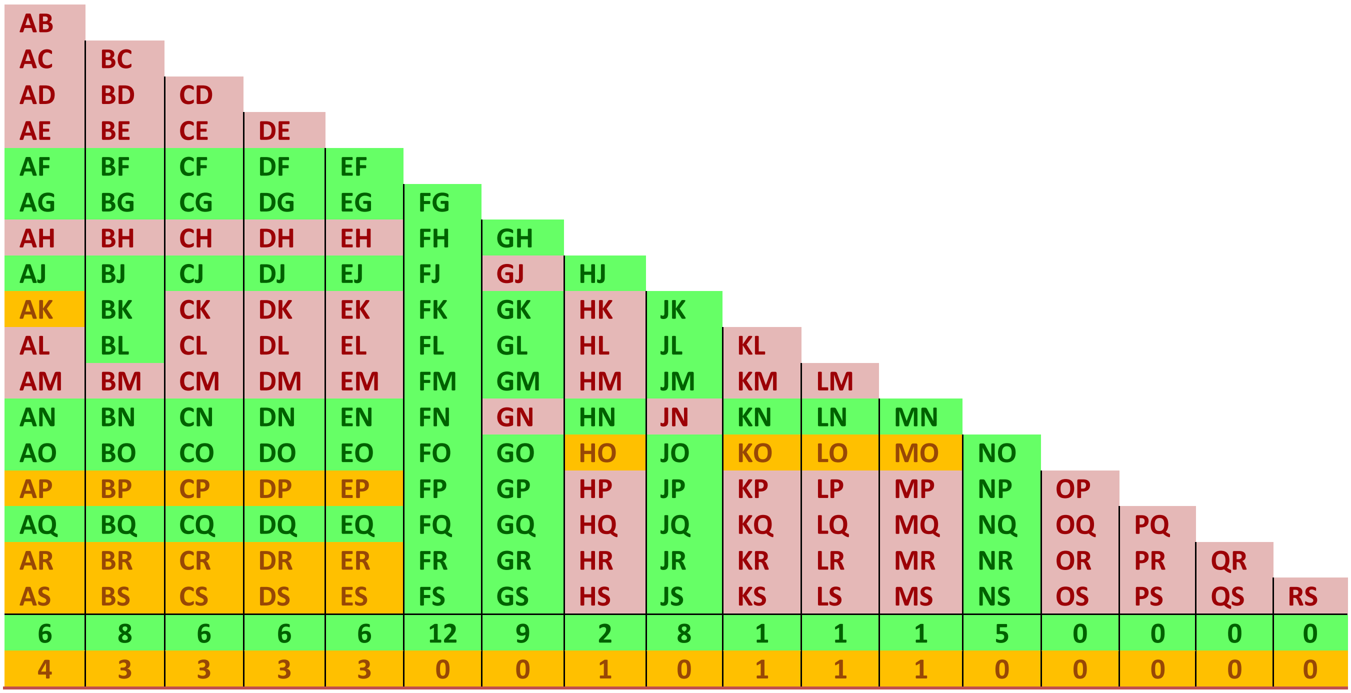
Figure 4.3b: Fastest route between node A & L

Source: Author

In table 4.5 the C_b of Zwolle in the network can be calculated by counting the total number of green node pairs, which is 71 and the total amount of orange node pairs, which is 20. The green and orange pairs are given value 1 and 0.5 respectively leading to a total C_b of 81 for Zwolle in its one-hour rail travel network. Derrible (2012) then calculates the share of the total by dividing the C_b of a node by the C_b of the whole network to define the relative betweenness centrality (C'_b). However, in this study it is chosen to calculate the share of the C_b related to the total number of pairs. This is chosen since this selection is only a part of the network and the C_b for stations located on the edge of the network does not match their real C_b. It does not match because the stations located beyond the stations on the edge are left out of the map since they are outside the time limit, but still exist (e.g. Haarlem located on the west side of Amsterdam is outside the time limit from Zwolle). Consequently, the results for inter city networks deviate from metro networks. However, metro network and inter city networks are not being compared within this study so this does not affect the validity of the results. While Derrible (2012) uses metro networks which are located within one or a few cities, railroad networks are connected almost infinitely around the world containing the excess of national and continental borders. Therefore, metro networks are defined as closed systems and the studied network can be seen as a small part of an open system (Kast & Rosenzweig, 1972), requiring an adapted approach to define the relative betweenness centrality.

Consequently, the relative betweenness centrality (C'_b) is here defined as the share of pairs that go through 'station x'. This can be calculated through dividing the value of C_b by the total number of pairs ((N-1)(N-2)/2). The share of the pairs going through 'I' can then be calculated by:

$$C'_b = C_b / (N-1)(N-2)/2 =$$
$$C'_b = 81 / (19-1)(19-2)/2 =$$
$$C'_b = 81/ 306/2 = 0.53$$



AB																
AC	BC															
AD	BD	CD														
AE	BE	CE	DE													
AF	BF	CF	DF	EF												
AG	BG	CG	DG	EG	FG											
AH	BH	CH	DH	EH	FH	GH										
AJ	BJ	CJ	DJ	EJ	FJ	GJ	HJ									
AK	BK	CK	DK	EK	FK	GK	HK	JK								
AL	BL	CL	DL	EL	FL	GL	HL	JL	KL							
AM	BM	CM	DM	EM	FM	GM	HM	JM	KM	LM						
AN	BN	CN	DN	EN	FN	GN	HN	JN	KN	LN	MN					
AO	BO	CO	DO	EO	FO	GO	HO	JO	KO	LO	MO	NO				
AP	BP	CP	DP	EP	FP	GP	HP	JP	KP	LP	MP	NP	OP			
AQ	BQ	CQ	DQ	EQ	FQ	GQ	HQ	JQ	KQ	LQ	MQ	NQ	OQ	PQ		
AR	BR	CR	DR	ER	FR	GR	HR	JR	KR	LR	MR	NR	OR	PR	QR	
AS	BS	CS	DS	ES	FS	GS	HS	JS	KS	LS	MS	NS	OS	PS	QS	RS
6	8	6	6	6	12	9	2	8	1	1	1	5	0	0	0	0
4	3	3	3	3	0	0	1	0	1	1	1	0	0	0	0	0

Table 4.5: Betweenness centrality on a basis of node distance. *Source:* Author

Slower through 'I'	**Value = 0**
Faster through 'I'	**Value = 1**
Equal through 'I'	**Value = 0.5**

4.3.1.3 A different way to calculate the betweenness centrality for Zwolle

In figure 4.5 the fifteen relevant lines in the train network of Zwolle are drawn. While the frequency and number of stops on intermediate stations may differ, these were identified as the most important lines, highlighting the termini and transfer stations properly. On a side note, regional trains were only added to the network if they have a unique transfer station which is not located within fifteen minutes of another station. This is why for example Meppel (J) is shown in the figure and Lelystad (within fifteen minutes from Almere (B)) is left out. Moreover, for clarity, several different train stations in Amsterdam (Amsterdam Centraal and Amsterdam Zuid) are merged into one node in the figure. Table 4.6 indicates whether there is a direct connection between the nodes. Comparing this to table 4.4, there is an obvious increase of the value '1' due to the direct lines connecting nodes with no direct link between them (e.g. 'A' & 'N' are not directly linked but are connected by the orange line and, therefore, the combination has a value '1' in table 4.6). This adds the value of a direct connection over an indirect connection (including one or more transfers). Moreover, introducing the value of lines explains why some connections between nodes are slower through ‘I’ in travel time while passing through less nodes (e.g. the fastest connection between ‘A’ and ‘K’ is the green line while the connection including the fewest nodes is A-B-I-K). Hence, introducing the different lines in the network offers a new perception of travel routing through the network.

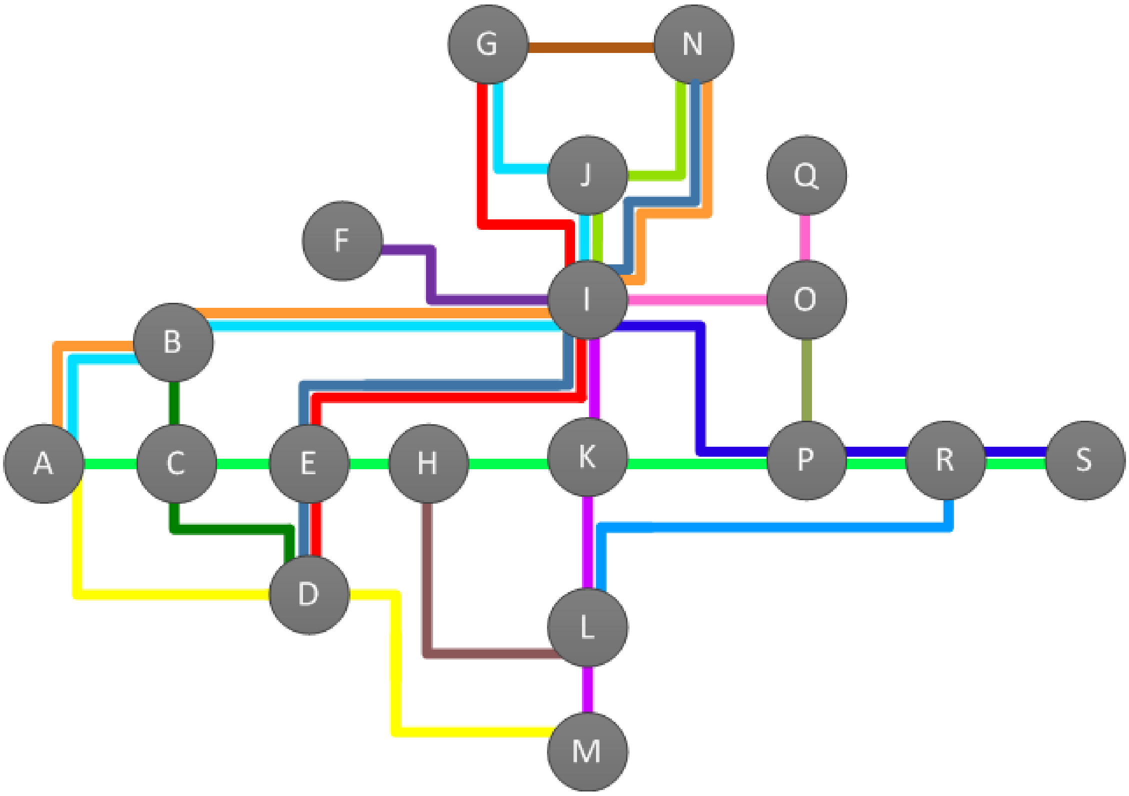


Figure 4.4: Link map of rail lines in the region of Zwolle Source: Author based on OpenStreetMap (2016)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	Total
A	0	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	0	1	1	**14**
B	1	0	1	1	0	0	1	0	1	1	0	0	0	1	0	0	0	0	0	**7**
C	1	1	0	1	1	0	0	1	0	0	1	0	0	0	0	1	0	1	1	**9**
D	1	1	1	0	1	0	1	0	1	0	0	0	1	1	0	0	0	0	0	**8**
E	1	0	1	1	0	0	1	1	1	0	1	0	0	1	0	1	0	1	1	**11**
F	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
G	1	1	0	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	**7**
H	1	0	1	0	1	0	0	0	0	0	1	1	0	0	0	1	0	1	1	**8**
I	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	**16**
J	1	1	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	**5**
K	1	0	1	0	1	0	0	1	1	0	0	1	1	0	0	1	0	1	1	**10**
L	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	**5**
M	1	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	**5**
N	1	1	0	1	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	**7**
O	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	**3**
P	1	0	1	0	1	0	0	1	1	0	1	0	0	0	1	0	0	1	1	**9**
Q	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	**2**
R	1	0	1	0	1	0	0	1	1	0	1	1	0	0	0	1	0	0	1	**9**
S	1	0	1	0	1	0	0	1	1	0	1	0	0	0	0	1	0	1	0	**8**
Total	**14**	**7**	**9**	**8**	**11**	**1**	**7**	**8**	**16**	**5**	**10**	**5**	**5**	**7**	**3**	**9**	**2**	**9**	**8**	

Table 4.6: Direct railroad lines between nodes in the region of Zwolle *Source:* Author

By taking the direct lines into account, a new approach to calculating the C_b can now be used. The direct lines are obviously faster than indirect links even though the route may go through more nodes. To check this, the shortest route in terms of travel duration provided by the passenger railway operator itself is used (NS-Reisinformatie, 2016). Consequently, the fastest route in terms of travel time can now be defined and verified. In table 4.7 this is done. The most significant difference is that the pairs that include either 'O' or 'B' are now faster through 'I' while the other pairs are now slower. However, the new C_b of node 'I' is with 78 quite comparable to the first one. This can be calculated by counting the green values in the table. Just like the former table, a share of pairs going through 'I' can then be found by calculating the share of the total number of pairs:

$$C'_b = C_b / (N-1)(N-2)/2 =$$
$$C'_b = 78/\ (19-1)(19-2)/2 =$$
$$C'_b = 78/\ 306/2 = 0.51$$

This value on itself does not mean much. Therefore, a comparison of the different outcomes for the C'_b using different methods is elaborated in chapter 4.3.4.

🟥 AB																	
🟥 AC	🟥 BC																
🟥 AD	🟥 BD	🟥 CD															
🟥 AE	🟥 BE	🟥 CE	🟥 DE														
🟩 AF	🟩 BF	🟩 CF	🟩 DF	🟩 EF													
🟩 AG	🟩 BG	🟩 CG	🟩 DG	🟩 EG	🟩 FG												
🟥 AH	🟥 BH	🟥 CH	🟥 DH	🟥 EH	🟩 FH	🟩 GH											
🟩 AJ	🟩 BJ	🟩 CJ	🟩 DJ	🟩 EJ	🟩 FJ	🟥 GJ	🟩 HJ										
🟥 AK	🟩 BK	🟥 CK	🟥 DK	🟥 EK	🟩 FK	🟩 GK	🟥 HK	🟩 JK									
🟥 AL	🟩 BL	🟥 CL	🟥 DL	🟥 EL	🟩 FL	🟩 GL	🟥 HL	🟩 JL	🟥 KL								
🟥 AM	🟥 BM	🟥 CM	🟥 DM	🟥 EM	🟩 FM	🟩 GM	🟥 HM	🟩 JM	🟥 KM	🟥 LM							
🟩 AN	🟩 BN	🟩 CN	🟩 DN	🟩 EN	🟩 FN	🟥 GN	🟩 HN	🟥 JN	🟩 KN	🟩 LN	🟩 MN						
🟩 AO	🟩 BO	🟩 CO	🟩 DO	🟩 EO	🟩 FO	🟩 GO	🟩 HO	🟩 JO	🟩 KO	🟩 LO	🟩 MO	🟩 NO					
🟥 AP	🟩 BP	🟥 CP	🟥 DP	🟥 EP	🟩 FP	🟩 GP	🟥 HP	🟩 JP	🟥 KP	🟥 LP	🟥 MP	🟩 NP	🟥 OP				
🟩 AQ	🟩 BQ	🟩 CQ	🟩 DQ	🟩 EQ	🟩 FQ	🟩 GQ	🟥 HQ	🟩 JQ	🟥 KQ	🟥 LQ	🟥 MQ	🟩 NQ	🟥 OQ	🟥 PQ			
🟥 AR	🟩 BR	🟥 CR	🟥 DR	🟥 ER	🟩 FR	🟩 GR	🟥 HR	🟩 JR	🟥 KR	🟥 LR	🟥 MR	🟩 NR	🟥 OR	🟥 PR	🟥 QR		
🟥 AS	🟩 BS	🟥 CS	🟥 DS	🟥 ES	🟩 FS	🟩 GS	🟥 HS	🟩 JS	🟥 KS	🟥 LS	🟥 MS	🟩 NS	🟥 OS	🟥 PS	🟥 QS	🟥 RS	
6	11	6	6	6	12	9	3	8	2	2	2	5	0	0	0	0	

Table 4.7: Betweenness centrality on a basis of travel time. *Source:* Author, based on NS-Reisinformatie (2016)

🟥 **Slower through 'I'**	**Value = 0**
🟩 **Faster through 'I'**	**Value = 1**

4.3.1.4 Adding value to the nodes

The difference between the shares using either method of calculating the betweenness centrality is relatively small. Both of the values are slightly above 0.5 which equals a share of 50%, indicating the importance of Zwolle (node I) in this network. Moreover, calculating the betweenness centrality using both the timetables and graph theory provides a more solid foundation to explain the importance of Zwolle in the network. To emphasize the importance of certain nodes in the network the node weight (P_i), as described by Gattuso and Miriello (2005) can be used. The P_i can be linked to the daily number of passengers for the nodes which is shown in table 4.8. The number of daily passengers are based on data from the NS, the other passenger railway operators (e.g. Arriva) have not published their number of daily passengers. Therefore, some of these data are incomplete or unavailable in the cases of Mariënberg and Emmen. The node weight of these cases is based on the number of possible transfers as well as the node weight of comparable cities in terms of population (e.g. the value for Mariënberg is based on a comparison with Kampen based on a comparable population of the municipalities). To justify these node weights, more travel data has to be studied over a longer period of time.

Node/City	Letter in Graph	Daily Passengers	Node weight
Almelo	P	10618*	2
Almere	B	23784	2
Amersfoort	E	39675	3
Amsterdam	A	167427	3
Apeldoorn	H	14628*	2
Arnhem	M	39164*	3
Deventer	K	19739	2
Emmen	Q	Unknown**	1
Enschede	S	18508	2
Hengelo	R	13437	2
Groningen	N	19706*	2
Hilversum	C	24105	2
Kampen	F	4136	1
Leeuwarden	G	9682*	1
Mariënberg	O	Unknown**	1
Meppel	J	5638	1
Utrecht	D	176552	3
Zutphen	L	11732*	2
Zwolle	I	41618*	3

Table 4.8: Node weight based on Daily Passengers. *Source:* Author, based on ArcGIS (2016)

* Station shared with other passenger railway operator

** No data on daily passengers

Now, each pair of nodes can be given a value by multiplying their respective node weights (e.g. Deventer – Leeuwarden = 'K' * 'G' = 2 * 1 = 2, resulting in: 'KG' = 2). Based on the values of the pairs, the C_b can be calculated once more, now accounting for the node weight based on the number of daily travellers. This leads to a total pair weight value (node weights of all the pairs combined) of 572, out of which 188 are green, 93 are orange and 293 are red. The calculation of the green and orange pairs is elaborated and clarified in table 4.9. This table provides a framework to calculate the C_b based on the values of 'node pair weight' which can be applied to other networks as well.

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R
B	6																
C	6	4															
D	9	6	6														
E	9	6	6	9													
F	3	2	2	3	3												
G	3	2	2	3	3	1											
H	6	4	4	6	6	2	2										
J	3	2	2	3	3	1	1	2									
K	6	4	4	6	6	2	2	4	2								
L	6	4	4	6	6	2	2	4	2	2							
M	9	6	6	9	9	3	3	6	3	6	6						
N	6	4	4	6	6	2	2	4	2	4	4	6					
O	3	2	2	3	3	1	1	2	1	2	2	3	2				
P	6	4	4	6	6	2	2	4	2	4	4	6	4	2			
Q	3	2	2	3	3	1	1	2	1	2	2	3	2	1	2		
R	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	
S	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	4

Total	96	60	56	75	66	21	20	36	17	28	26	30	16	7	10	4	4	572
Green	21	22	14	21	21	21	17	6	15	4	4	6	16	0	0	0	0	188
Orange	24	12	12	18	18	0	0	2	0	2	2	3	0	0	0	0	0	93
Red	51	26	30	36	27	0	3	28	2	22	20	21	0	7	10	4	4	291

Table 4.9: Betweenness centrality based on node pair weight and node distance. *Source:* Author

Slower through 'I'	**Value = 0**
Faster through 'I'	**Value = 1**
Equal through 'I'	**Value = 0.5**

The new C_b can now be calculated by 188 + 0.5 * 93 = 234.5. The share of 'node pair value' going through 'I' can now be found by calculating its share of the total number of pair weight value. However, the total pair weight value of the network has already been calculated and is 572. The following calculation is used to find the share:

$$C'_b = C_b / 572 =$$
$$C'_b = 234.5 / 572 = 0.41$$

The difference between the relative betweenness centrality with or without node weight is considerably. Consequently, distinguishing between more and less important nodes in the network seems to be crucial in order to get a more realistic view on the importance of nodes in an inter city network. Therefore, using the node pair weight provides more valuable information for inter city networks since the importance of certain cities is emphasized. However, defining the node weight for every node is done intuitively and more possibilities for node value as well as tracking changes in daily number of passengers could lead to different results for the betweenness centrality. The comparison between the different outcomes for the different methods to calculate the C'_b is elaborated in chapter 4.3.4. In this chapter, a conclusion is drawn to decide which method provides the most realistic outcome.

For the C_b based on travel time, introducing the pair weight value has some implications as well. Table 4.10 shows that the C_b is now 209, which is significantly lower than the pair weight value C_b based on nodes. This is due to the relative high pair weight values of the orange pairs including ‘P’, ‘R’ & ‘S’ which are all red when based on travel time.

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R
B	6																
C	6	4															
D	9	6	6														
E	9	6	6	9													
F	3	2	2	3	3												
G	3	2	2	3	3	1											
H	6	4	4	6	6	2	2										
J	3	2	2	3	3	1	1	2									
K	6	4	4	6	6	2	2	4	2								
L	6	4	4	6	6	2	2	4	2	2							
M	9	6	6	9	9	3	3	6	3	6	6						
N	6	4	4	6	6	2	2	4	2	4	4	6					
O	3	2	2	3	3	1	1	2	1	2	2	3	2				
P	6	4	4	6	6	2	2	4	2	4	4	6	4	2			
Q	3	2	2	3	3	1	1	2	1	2	2	3	2	1	2		
R	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	
S	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	4

Total	96	60	56	75	66	21	20	36	17	28	26	30	16	7	10	4	4	**572**
Green	21	34	14	21	21	21	17	8	15	6	6	9	16	0	0	0	0	**209**
Red	75	26	42	54	45	0	3	28	2	22	20	21	0	7	10	4	4	**363**

Table 4.10: Betweenness centrality on based node pair weight and travel time. *Source:* Author, based on NS-Reisinformatie (2016)

Slower through ‘I’	**Value = 0**
Faster through ‘I’	**Value = 1**

Just like the former table, the share of ‘node pair value’ going through ‘I’ can then be found by calculating its share of the total number of pair weight value. However, the node pair value is already calculated and is 572. The following calculation is used to find the share:

$$C'_b = C_b / 572 =$$
$$C'_b = 209 / 572 = 0.37$$

The result of 0.37 is a relatively high drop compared to the pair weight value C'_b based on node distance only (0.41 vs 0.37). This is most likely the result of the orange pairs with a high node pair value which are now red. A more detailed analysis of the results of the different methods is given in chapter 4.3.4.

4.3.2 Changes in the railroad network throughout time

Throughout the years, several changes have occurred within the network leading to changes with regards to graph theory as well as the timetable. One important change in the network is the establishment of the Hanzelijn (Rijksoverheid, 20010 connecting Zwolle and Amsterdam going through Almere. Therefore, taking a closer look at the results of this new link is interesting to explain growth or decline based on the establishment of new links. In figure 4.6 the old network without the Hanzelijn is visualised. The figure still includes Almere and Amsterdam although these cities are outside the time limit now. It is chosen to include those nodes to make it easier to compare the two networks in terms of C_b value. Excluding these two cities would disable the opportunity for a valid comparison. Table 4.11 shows a matrix of the existence of links between the nodes. Value ‘1’ represents a direct link and value ‘0’ represents no direct link. This is highly comparable with table 4.2 except for the fact that ‘B’ and ‘I’ are no longer connected.

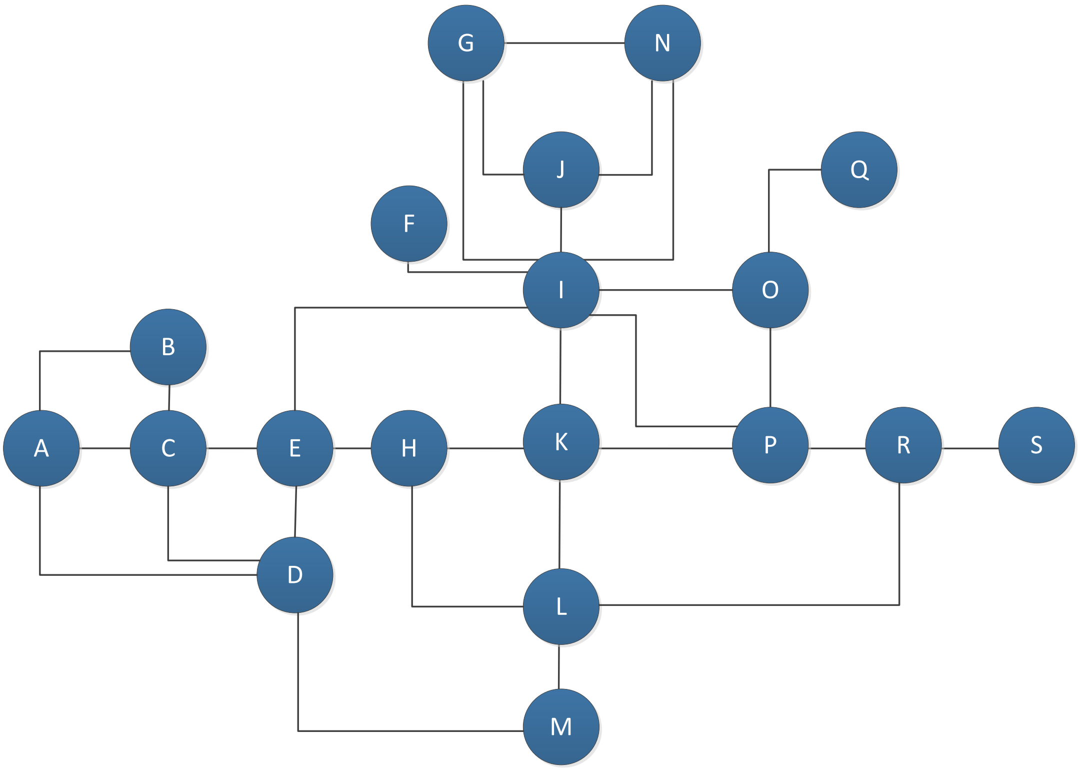


Figure 4.5: Graph map of railroads in the region of Zwolle before the establishment of the Hanzelijn *Source:* Author

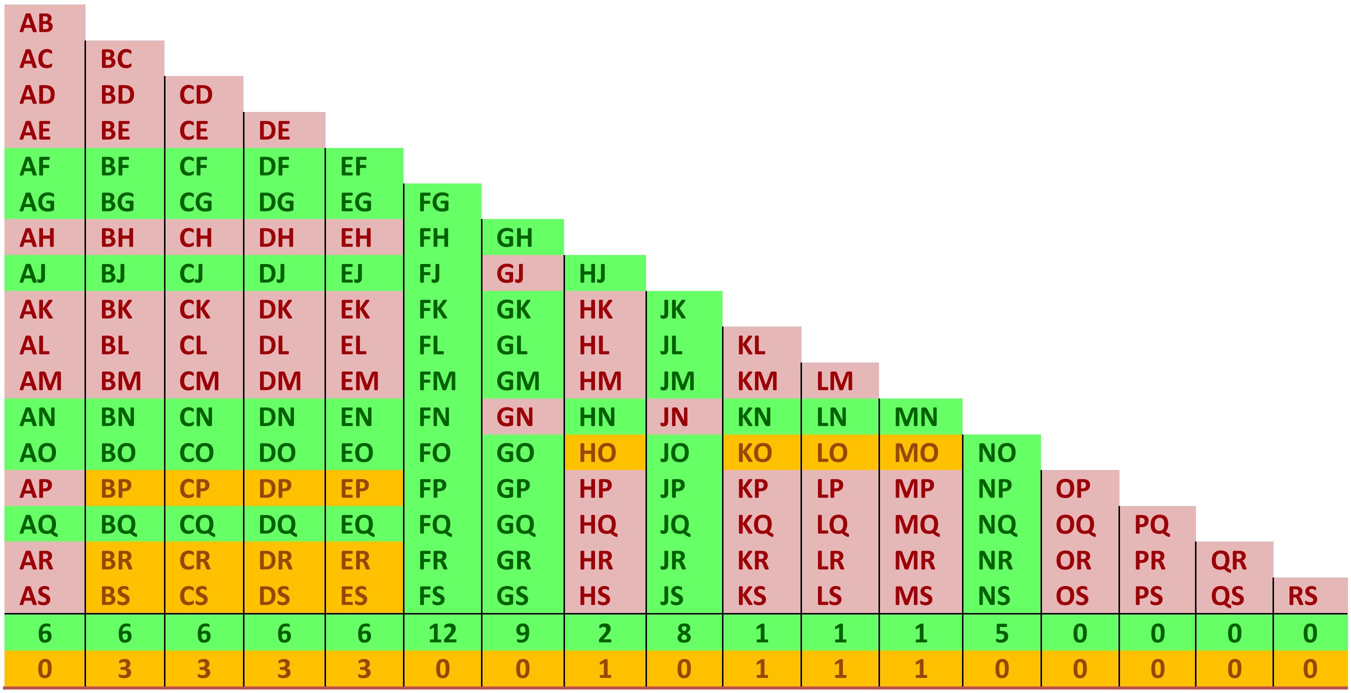
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	Total
A	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
B	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**
C	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**
D	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**4**
E	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	**4**
F	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
G	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	**3**
H	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	**3**
I	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	0	0	0	**8**
J	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	**3**
K	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	**4**

L	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0	**4**
M	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**2**
N	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	**3**
O	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	**3**
P	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	0	**4**
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
R	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	**3**
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Total	**3**	**2**	**4**	**4**	**4**	**1**	**3**	**3**	**8**	**3**	**4**	**4**	**2**	**3**	**3**	**4**	**1**	**3**	**1**	

Table 4.11: Direct railroad links between nodes in the region of Zwolle before the Hanzelijn *Source:* Author

Following from the new graph map and table, the betweenness centrality (C_b) can be calculated once more. Due to the lack of availability of old timetables, this can be done only through analysing the node distance. The C_b for the network before the Hanzelijn is explained in table 4.12 in which it stand out there are less green and orange pairs with the value 'A' or 'B'. The total number of green pairs is now 69 and the amount of orange pairs is 16. This leads to a total C_b of the node 'I' in this network of 77. Moreover, using the same calculation as earlier, the relative share of C_b is now:

$$C'_b = C_b /(N-1)(N-2)/2 =$$
$$C'_b = 77/ (19-1)(19-2)/2 =$$
$$C'_b = 77/ 306/2 = 0.50$$



🟥 **AB**																
🟥 **AC**	🟥 **BC**															
🟥 **AD**	🟥 **BD**	🟥 **CD**														
🟥 **AE**	🟥 **BE**	🟥 **CE**	🟥 **DE**													
🟩 **AF**	🟩 **BF**	🟩 **CF**	🟩 **DF**	🟩 **EF**												
🟩 **AG**	🟩 **BG**	🟩 **CG**	🟩 **DG**	🟩 **EG**	🟩 **FG**											
🟥 **AH**	🟥 **BH**	🟥 **CH**	🟥 **DH**	🟥 **EH**	🟩 **FH**	🟩 **GH**										
🟩 **AJ**	🟩 **BJ**	🟩 **CJ**	🟩 **DJ**	🟩 **EJ**	🟩 **FJ**	🟥 **GJ**	🟩 **HJ**									
🟥 **AK**	🟥 **BK**	🟥 **CK**	🟥 **DK**	🟥 **EK**	🟩 **FK**	🟩 **GK**	🟥 **HK**	🟩 **JK**								
🟥 **AL**	🟥 **BL**	🟥 **CL**	🟥 **DL**	🟥 **EL**	🟩 **FL**	🟩 **GL**	🟥 **HL**	🟩 **JL**	🟥 **KL**							
🟥 **AM**	🟥 **BM**	🟥 **CM**	🟥 **DM**	🟥 **EM**	🟩 **FM**	🟩 **GM**	🟥 **HM**	🟩 **JM**	🟥 **KM**	🟥 **LM**						
🟩 **AN**	🟩 **BN**	🟩 **CN**	🟩 **DN**	🟩 **EN**	🟩 **FN**	🟥 **GN**	🟩 **HN**	🟥 **JN**	🟩 **KN**	🟩 **LN**	🟩 **MN**					
🟩 **AO**	🟩 **BO**	🟩 **CO**	🟩 **DO**	🟩 **EO**	🟩 **FO**	🟩 **GO**	🟧 **HO**	🟩 **JO**	🟧 **KO**	🟧 **LO**	🟧 **MO**	🟩 **NO**				
🟥 **AP**	🟧 **BP**	🟧 **CP**	🟧 **DP**	🟧 **EP**	🟩 **FP**	🟩 **GP**	🟥 **HP**	🟩 **JP**	🟥 **KP**	🟥 **LP**	🟥 **MP**	🟩 **NP**	🟥 **OP**			
🟩 **AQ**	🟩 **BQ**	🟩 **CQ**	🟩 **DQ**	🟩 **EQ**	🟩 **FQ**	🟩 **GQ**	🟥 **HQ**	🟩 **JQ**	🟥 **KQ**	🟥 **LQ**	🟥 **MQ**	🟩 **NQ**	🟥 **OQ**	🟥 **PQ**		
🟥 **AR**	🟧 **BR**	🟧 **CR**	🟧 **DR**	🟧 **ER**	🟩 **FR**	🟩 **GR**	🟥 **HR**	🟩 **JR**	🟥 **KR**	🟥 **LR**	🟥 **MR**	🟩 **NR**	🟥 **OR**	🟥 **PR**	🟥 **QR**	
🟥 **AS**	🟧 **BS**	🟧 **CS**	🟧 **DS**	🟧 **ES**	🟩 **FS**	🟩 **GS**	🟥 **HS**	🟩 **JS**	🟥 **KS**	🟥 **LS**	🟥 **MS**	🟩 **NS**	🟥 **OS**	🟥 **PS**	🟥 **QS**	🟥 **RS**
🟩 **6**	🟩 **6**	🟩 **6**	🟩 **6**	🟩 **6**	🟩 **12**	🟩 **9**	🟩 **2**	🟩 **8**	🟩 **1**	🟩 **1**	🟩 **1**	🟩 **5**	🟩 **0**	🟩 **0**	🟩 **0**	🟩 **0**
🟧 **0**	🟧 **3**	🟧 **3**	🟧 **3**	🟧 **3**	🟧 **0**	🟧 **0**	🟧 **1**	🟧 **0**	🟧 **1**	🟧 **1**	🟧 **1**	🟧 **0**	🟧 **0**	🟧 **0**	🟧 **0**	🟧 **0**

Table 4.12: Betweenness centrality on a basis of node distance before the Hanzelijn. *Source:* Author

🟥 **Slower through 'I'**	**Value = 0**
🟩 **Faster through 'I'**	**Value = 1**
🟧 **Equal through 'I'**	**Value = 0.5**

The C’$_b$ value is not drastically lower without the establishment of the Hanzelijn. However, it has increased slightly with the new connection. These values are also compared in chapter 4.3.4. Moreover, the increase of C’$_b$ with the establishment of the Hanzelijn concerns the cities of Amsterdam and Almere, which are both important nodes in the network. To emphasize the importance of certain nodes in the network the node weight (P_i), as described by Gattuso and Miriello (2005) can be used once more. The P_i can be linked to the daily number of passengers such as used in chapter 4.2.1. For simplicity, the same number of daily passengers is used even though these data are obtained after the establishment of the Hanzelijn. Therefore, the values may deviate slightly from the actual values. To verify the positive impact of the Hanzelijn, the daily number of passengers of Zwolle and Almere has to be monitored for the years after the establishment. The values are shown in table 4.13

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R
B	6																
C	6	4															
D	9	6	6														
E	9	6	6	9													
F	3	2	2	3	3												
G	3	2	2	3	3	1											
H	6	4	4	6	6	2	2										
J	3	2	2	3	3	1	1	2									
K	6	4	4	6	6	2	2	4	2								
L	6	4	4	6	6	2	2	4	2	2							
M	9	6	6	9	9	3	3	6	3	6	6						
N	6	4	4	6	6	2	2	4	2	4	4	6					
O	3	2	2	3	3	1	1	2	1	2	2	3	2				
P	6	4	4	6	6	2	2	4	2	4	4	6	4	2			
Q	3	2	2	3	3	1	1	2	1	2	2	3	2	1	2		
R	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	
S	6	4	4	6	6	2	2	4	2	4	4	6	4	2	4	2	4

Total	**96**	**60**	**56**	**75**	**66**	**21**	**20**	**36**	**17**	**28**	**26**	**30**	**16**	**7**	**10**	**4**	**4**	**572**
Green	21	14	14	21	21	21	17	6	15	4	4	6	16	0	0	0	0	**180**
Orange	0	12	12	18	18	0	0	2	0	2	2	3	0	0	0	0	0	**69**
Red	75	34	30	36	27	0	3	28	2	22	20	21	0	7	10	4	4	**323**

Table 4.13: Betweenness centrality based on node pair weight and node distance before the Hanzelijn. *Source:* Author

Slower through ‘I’	**Value = 0**
Faster through ‘I’	**Value = 1**
Equal through ‘I’	**Value = 0.5**

The new C_b can now be calculated by 180 + 0.5 * 69 = 214.5. Just like table 4.9, the share of ‘node pair value’ going through ‘I’ can then be found by calculating the share of the total number of pair weight value. However, the total pair weight value has already been calculated and is 572. The following calculation is used to find the share of pair weight value going through 'I':

$$C'_b = C_b / 572 =$$
$$C'_b = 214.5 / 572 = 0.38$$

Consequently, the relative betweenness centrality is now lower than 0.4. Compared to the contemporary share (0.41, see table 4.9), the C'_b has increased with almost 10% with the introduction of the Hanzelijn. The comparison between the different outcomes for the C'_b is elaborated in chapter 4.3.4. The Hanzelijn opened in December 2012 (ProRail, 2012). Subsequently, the hypothesis that graph theory can be linked to spatial growth in Dutch cities can now be tested. To test this, the growth rate of the daily number of passengers in Zwolle is compared after the establishment of the Hanzelijn. The growth of the daily number of passengers in Zwolle between 2013 and 2014 has been 5.2 percent and in 2015 the number of passengers grew with 2.5 percent (ArcGIS, 2016). Although this proves a significant increase of passengers, the data about the population growth, which are shown in table 4.14, show no sign of an increased growth rate. This can be due to several reasons such as the efficacy time of such an operation, the decrease of housing development due to the economic crisis and other non-network related factors which are not discussed within this study. Therefore, more research into the effects of new railroads to the population growth of a city has to be done to understand the resulting changes in growth rates. Moreover, the time scale of the study has to be more than a just few years to see major changes in the growth rate as well as to understand these changes.

Year	Population at the beginning of the year	Population at the end of the year	% Growth
2005	111900	113078	**1.05**
2006	113078	114635	**1.38**
2007	114635	116365	**1.51**
2008	116365	117703	**1.15**
2009	117703	119030	**1.13**
2010	119030	120355	**1.11**
2011	120355	121527	**0.97**
2012	121527	122562	**0.85**
2013	122562	123159	**0.49**
2014	123159	123861	**0.57**
2015	123861	124896	**0.84**

Table 4.14: Yearly growth of the population of Zwolle *Source:* CBS (2016c)

However, another comparison can now be done, comparing the growth and of the daily passengers and the population growth in general. This is done in table 4.15. Since the total number of daily passengers as well as the percentage of daily passengers is higher than their counterparts on population growth, it can be concluded that more people from other places are now travelling through Zwolle. Therefore, the node of Zwolle is growing faster than the city itself. Hence, relatively, the node of the railway station of Zwolle is growing faster than Zwolle emphasising the potential growth of the city as well.

Year	Population growth	% Population growth	Daily passenger growth	% Daily passenger growth
2014	702	**0.57**	1997	**5.17**
2015	1035	**0.84**	1027	**2.53**

Table 4.15: Yearly growth of the population & daily passengers for Zwolle *Source:* CBS (2016c) & ArcGIS (2016)

In the next section, the framework is applied to the road network of Zwolle to explore if the framework is applicable to other modalities as well as studying the different outcomes and implications the framework has for the road network of Zwolle.

4.3.3 The road network of the region of Zwolle

To test if the step-by-step guidelines can be applied to other networks than railroad networks, it is applied to the road network of Zwolle. Following the same steps, the applicability of the framework is tested. However, first a small introduction on the location of Zwolle in the road network is given.

Besides the important location of Zwolle in the railroad network, its location within the road network is also significant due to its close location to a highway intersection. The intersection is the one of the A28 and the A50, located at Hattemerbroek (Rijkswaterstaat, 2013), which is 7 kilometres or 8 minutes away from Zwolle (Distance24.org, 2016). Since Zwolle is the only relatively big city near the intersection, Zwolle is assigned as the node for this intersection. Following the steps of how to apply graph theory to inter city transport networks, the size of the network is defined first followed by a drawing of those in a map. The nodes located within the 70-minute time frame, which is also used throughout section 4.2.1, are shown in table 4.16.

Node	Intersection	Travel time to Zwolle	Road distance to Zwolle
Zwolle	A28/A50	-	-
Groningen	A28/A7	64 minutes	105 km
Hoogeveen	A28/A37	31 minutes	45 km
Meppel	A28/A32	19 minutes	26 km
Amersfoort	A28/A1	45 minutes	68 km
Utrecht	A28/A27/A12/A2*	60 minutes	90 km
Heerenveen	A32/A7	38 minutes	64 km
Leeuwarden	A32/A31	57 minutes	92 km
Joure	A7/A6	45 minutes	69 km
Emmeloord	N50**/A6	29 minutes	38 km
Apeldoorn	A50/A1	28 minutes	39 km
Arnhem	A50/A12/A15***	45 minutes	61 km
Nijmegen	A50/A73/A326	61 minutes	77 km
Almelo	A35/A1	52 minutes****	53 km
Hilversum	A1/A27	52 minutes	85 km
Amsterdam (East)	A1/A2/A9/A10*****	62 minutes	103 km
Barneveld	A1/A30	45 minutes	75 km
Veenendaal	A12/A30	56 minutes	91 km
Doetinchem	A12/A18	58 minutes	96 km
Almere	A27/A6	54 minutes	76 km

Table 4.16: Highway nodes and distance to Zwolle *Source:* Rijkswaterstaat (2013) & Distance24.org (2016)

*	Intersections around Utrecht (NE, SE, SW)
**	No official highway
***	Intersections near Arnhem
****	Regional/Highway combination
*****	Intersections on the east side of Amsterdam

The nodes in the table are visualised in figure 4.7 showing the one hour road travel map accounting for the geographical location of the respective nodes. The dotted lines in the figure represent an expressway which is a little slower than a highway.

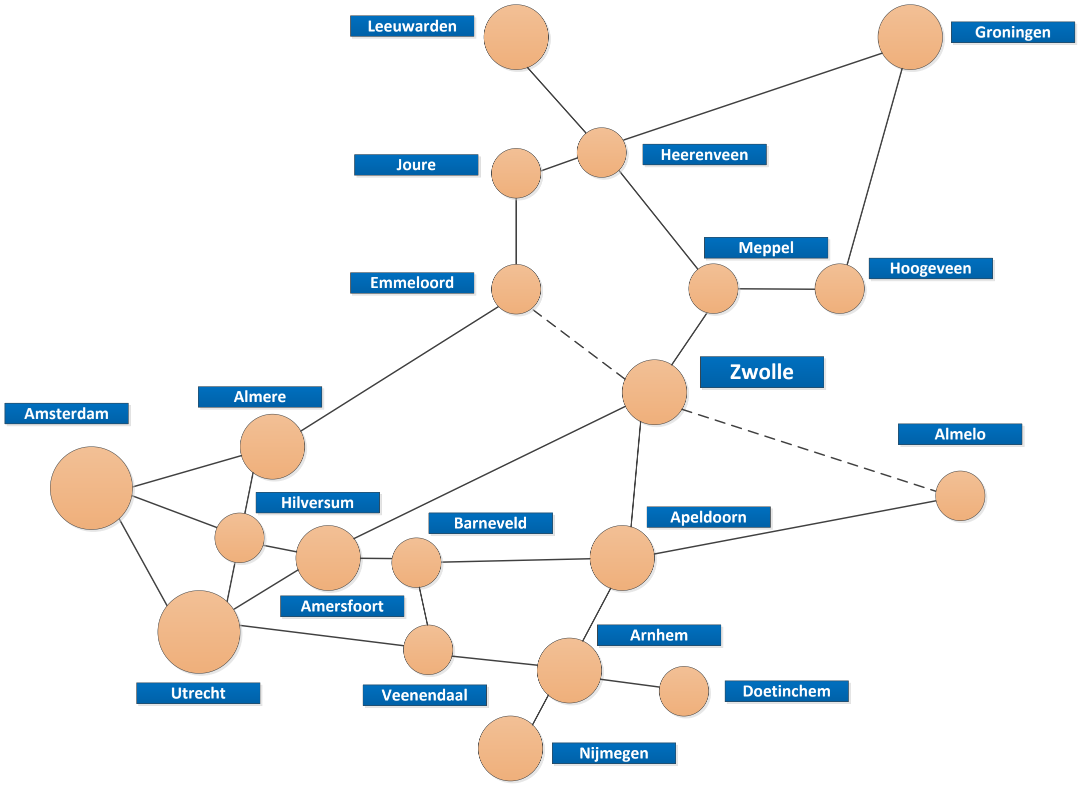


Figure 4.6: One-hour highway travel map of the region of Zwolle *Source:* Author, based on OpenStreetMap (2016)

During the second step, the nodes are drawn in an abstract map followed by a matrix showing whether there is a connection between the nodes or not. In table 4.17, the letters representing the nodes are shown.

Node/City	Letter in Graph
Almelo	S
Almere	B
Amersfoort	D
Amsterdam (East)	A
Apeldoorn	N
Arnhem	O
Barneveld	H
Doetinchem	T
Emmeloord	G
Groningen	Q
Heerenveen	K
Hilversum	C
Hoogeveen	R
Joure	F
Leeuwarden	J
Meppel	L
Nijmegen	P
Utrecht	E
Veenendaal	I
Zwolle	M

Table 4.17: Letters representing nodes in railroad graphs *Source:* Author

Figure 4.8 shows the graph map for roads in the region of Zwolle. The links represent existing highway connections and the dotted lines are expressways. Moreover, in table 4.18 a matrix is drafted showing the existence of a link between the nodes. Value ‘1’ represents a direct link and value ‘0’ represents no direct link.

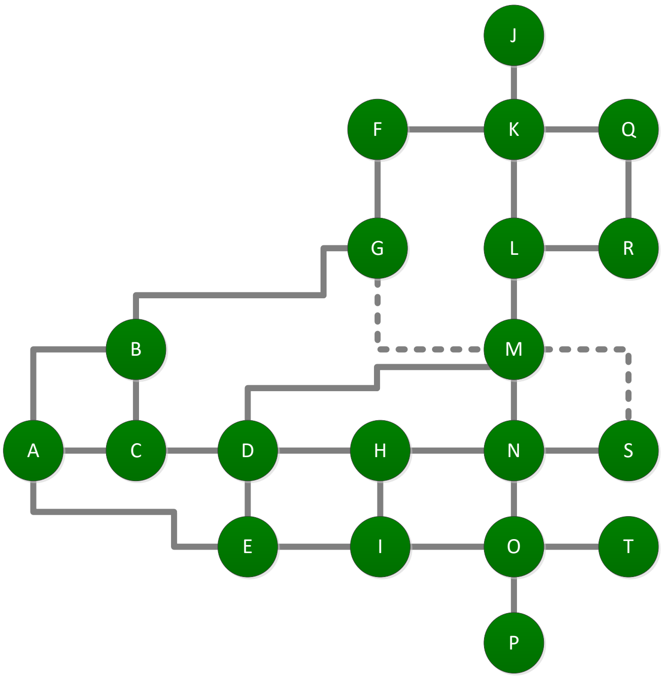
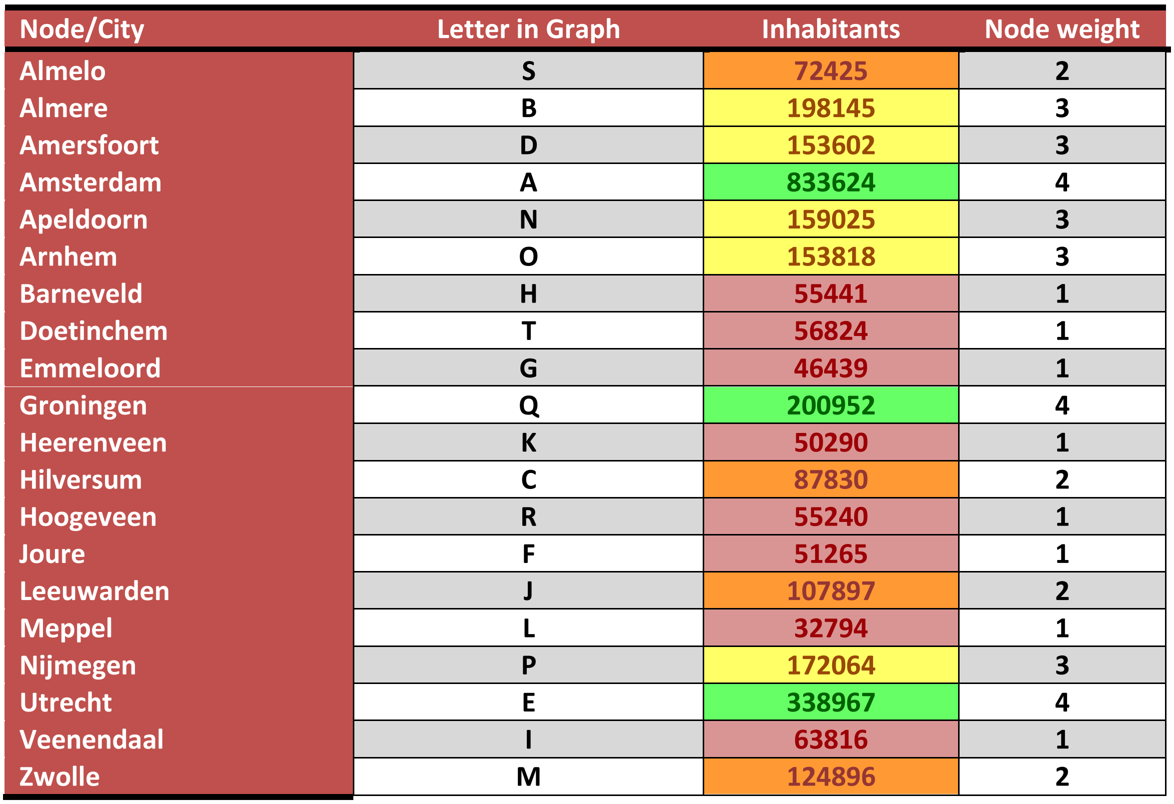


Figure 4.7: Graph map of highways in the region of Zwolle *Source:* Author

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	Total
A	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
B	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
C	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
D	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	**4**
E	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**3**
F	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	**2**
G	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**3**
H	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	**3**
I	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	**3**
J	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**
K	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	**4**
L	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	**3**
M	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0	0	0	1	0	**5**
N	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	**4**
O	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1	**4**
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
Q	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	**2**
R	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	**2**
S	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	**2**
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
Total	**3**	**3**	**3**	**4**	**3**	**2**	**3**	**3**	**3**	**1**	**4**	**3**	**5**	**4**	**4**	**1**	**2**	**2**	**2**	**1**	

Table 4.18: Direct road links between nodes in the region of Zwolle *Source:* Author

For the third step, calculating the betweenness centrality, the option is chosen to only use the node pair value instead of calculating the C_b without weighing the node pair first. This is chosen for since this has provided the most valuable information so far because it weighs the importance of the nodes in the network. However, due to the lack of data on road travellers, the number of inhabitants of the municipality the node is located in is chosen as the source for the node weight. The node weight for roads is divided into four categories since the number of inhabitants per municipality differs strongly. Therefore, four categories are seen as more appropriate than three to represent these differences. The categories are: less than 70000 inhabitants (red, node weight '1'), between 70000 and 135000 inhabitants (orange, node weight '2'), between 135000 and 200000 inhabitants (yellow, node weight '3') and more than 200000 inhabitants (green, node weight '4'). The nodes, their respective letters in the graph and the node weight are shown in table 4.19. The node weight may in some cases not completely correspond with the municipality the node is in. However, a deliberate choice is made for all the nodes to assign them to the municipality containing the closest 'big' city or town in the area (e.g. node 'C' is located quite far outside Hilversum yet assigned to Hilversum since it is the closest city).



Node/City	Letter in Graph	Inhabitants	Node weight
Almelo	S	72425	2
Almere	B	198145	3
Amersfoort	D	153602	3
Amsterdam	A	833624	4
Apeldoorn	N	159025	3
Arnhem	O	153818	3
Barneveld	H	55441	1
Doetinchem	T	56824	1
Emmeloord	G	46439	1
Groningen	Q	200952	4
Heerenveen	K	50290	1
Hilversum	C	87830	2
Hoogeveen	R	55240	1
Joure	F	51265	1
Leeuwarden	J	107897	2
Meppel	L	32794	1
Nijmegen	P	172064	3
Utrecht	E	338967	4
Veenendaal	I	63816	1
Zwolle	M	124896	2

Table 4.19: Node weight based on inhabitants. *Source:* Author, based on CBS (2016b)

Every node pair can be given a value now, which is shown in table 4.20. All the node pairs are given a green value if the fastest route passes node 'M' and a red value if the fastest route does not pass 'M'. To calculate the fastest route between every node pair, the travel time is used instead of the node distance. This is chosen for because the intersections in a highway are no barrier and the taken route is mostly chosen based on the shortest travel distance.

	A	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R	S
B	12																	
C	8	6																
D	12	9	6															
E	16	12	8	12														
F	4	3	2	3	4													
G	4	3	2	3	4	1												
H	4	3	2	3	4	1	1											
I	4	3	2	3	4	1	1	1										
J	8	6	4	6	8	2	2	2	2									
K	4	3	2	3	4	1	1	1	1	2								
L	4	3	2	3	4	1	1	1	1	2	1							
N	12	9	6	9	12	3	3	3	3	6	3	3						
O	12	9	6	9	12	3	3	3	3	6	3	3	9					
P	12	9	6	9	12	3	3	3	3	6	3	3	9	9				
Q	16	12	8	12	16	4	4	4	4	8	4	4	12	12	12			
R	4	3	2	3	4	1	1	1	1	2	1	1	3	3	3	4		
S	8	6	4	6	8	2	2	2	2	4	2	2	6	6	6	8	6	
T	4	3	2	3	4	1	1	1	1	2	1	1	3	3	3	4	6	2

Total	148	102	64	87	100	24	23	22	21	38	18	17	42	33	24	16	12	2	793
Green	8	6	4	27	8	12	12	9	9	24	12	12	15	15	15	4	6	0	198
Red	140	96	60	60	92	12	11	13	12	14	6	5	27	18	9	12	6	2	595

Table 4.20 Betweenness centrality based on node pair weight and travel time for roads. *Source:* Author based on Distance24.org (2016)

Slower through 'M'	**Value = 0**
Faster through 'M'	**Value = 1**

The C_b for roads in the region of Zwolle based on travel time can now be calculated by counting the green node pair value: 198. The share of 'node pair value' going through 'M' is found by calculating its share of the total number of node pair value. The total node pair value of the network is already calculated and is 793. The following calculation is used to find the share:

$$C'_b = C_b / 793 =$$
$$C'_b = 198 / 793 = 0.25$$

Therefore, it can be concluded that the C_b for roads (0.25) is much lower than the C_b for trains (0.37). The reason for this is likely caused by the different size of the node Zwolle with regards to the number of links. While Zwolle can be seen as an important hub for the railroad network, it is only located near one of the many intersections in the network. Moreover, due to the different values used to define the node weight, the values may not be completely comparable. However, defining the node weight for the road as well as the railroad network has been done as fairly as possible. In the next section, all of the C_b values of the case study are compared, related and the shortcomings of the methods are elaborated.

4.3.4 Comparing diverging C_b values for the network of the region of Zwolle

Throughout the case study, multiple methods, situations and variables are used to examine the railroad and road network of Zwolle. This led to divergent values for the C_b based on the chosen variables and methods. In table 4.21, all of the results are outlined and the methods of calculation, situation and modality are mentioned to enable a fair comparison between the values. The variables in this table are the modality, situation, fastest route calculation and node weight calculation, out of which all combinations lead to different C'_b outcomes.

Calculation #	Modality	Situation	Fastest route calculation	Node weight calculated	C'_b outcome	Table
1	Train	Current situation	Node distance	No	**0.53**	4.5
2	Train	Current situation	Travel time	No	**0.51**	4.7
3	Train	Current situation	Node distance	Yes	**0.41**	4.9
4	Train	Current situation	Travel time	Yes	**0.37**	4.10
5	Train	Before Hanzelijn	Node distance	No	**0.50**	4.12
6	Train	Before Hanzelijn	Node distance	Yes	**0.38**	4.13
7	Road	Current situation	Travel time	Yes*	**0.25**	4.20

Table 4.21: Comparing the different C_b values for the region of Zwolle. *Source:* Author

* Different calculation for node weight

To be able to compare in a fair way, only one of the variables can be different between the compared situations (e.g. for #1 and #5 only the situation is different while for #1 and #4 the fastest route and node weight calculation are different). Calculation #1 shares three out of four variables with calculation #2, calculation #3 and calculation #5. Therefore, the implications of the different C'_b outcomes for each of these 'calculation pairs' is elaborated in table 4.22. This is done for every possible pair of calculations sharing three out of four variables.

While this table shows some interesting differences, which can be explained based on the experiences throughout this research, there are a lot of uncertainties due to the limited generalisations that can be drawn from a single case study. However, there are some notable results most of which are also indicated in the table. The most important of these are;

- The method used to calculate the fastest route is of minor importance with the calculation based on travel time showing the lowest outcome for the C'_b for Zwolle.
- Calculating the node weight decreases the C'_b for Zwolle with around 25% indicating the importance of distinguishing between large cities and smaller ones.
- The result of the establishment of the Hanzelijn for the C'_b is an increase of 0.03 or around 6~10%.
- The different outcomes for the C'_b between the road network and the railroad network are significant where the C'_b outcome for railroads is almost 33% higher indicating the important role of Zwolle in the railroad network.
- While the results for Zwolle do indicate some interesting differences between methods and variables, comparing the different outcomes between Zwolle and another city would provide a lot more information about the applicability of these methods. Since the node weight calculation proved to have major impact showing a more realistic point of view, this method seems to be most suitable to compare two different cities.

Calculations	Different variable	Difference in C'_b outcome	What does it tell?
1 & 2	Fastest route calculation	**0.02**	The small difference in outcome tells that the method the fastest route is calculated does have implications on the results but those are only minor
1 & 3	Node weight calculated	**0.12**	Using the node weight of pairs has major impact on the outcome of the C'_b. Weighing the nodes results in an outcome which is almost 25% lower than the outcome without weighing the nodes in the case of Zwolle.
1 & 5	Situation	**0.03**	This relatively small difference is the result of the establishment of the Hanzelijn for the C'_b of Zwolle which slightly increased.
2 & 4	Node weight calculated	**0.14**	Using the node weight of pairs has major impact on the outcome of the C'_b. Weighing the nodes results in an outcome which is more than 25% lower than the outcome without weighing the nodes in the case of Zwolle. Based on the values for travel time instead of node distance (1 & 3) shows an even higher fall of C'_b outcome for Zwolle
3 & 4	Fastest route calculation	**0.04**	The small difference in outcome tells that the method the fastest route is calculated does have implications on the results but those are only minor. However, the outcomes based on travel time diverge more than the results on node distance (1 & 3)
3 & 6	Situation	**0.03**	This relatively small difference is the result of the establishment of the Hanzelijn for the C'_b of Zwolle which slightly increased (equal to 1 & 5).
4 & 7	Modality	**0.12**	The different outcome of the C'_b for railroads and highways is almost 33% indicating the node in the railroad network appears to be more important than the road network.

Table 4.22: Comparing the different calculations sharing three variables. *Source:* Author

4.4 Case comparison

4.4.1 Case selection

To select to most suitable case for comparison, the 'most similar systems design' (Przeworski & Teune, 1970) is used to identify the dependent variable in the potential growth of networks. Therefore, some criteria are set to identify cases similar to the region of Zwolle, which is studied in the case study. First, being located in the Netherlands as well as having a population amount between 100.000 and 160.000 are chosen to select a reasonable number of cases as a basis in which Zwolle fits perfectly. Moreover, a train station as well as direct to a highway are preconditions to be in the selection. Subsequently, a highway intersection nearby is a precondition as well since it is a requirement for being a node. The resulting selection process is explained in table 4.23 resulting in a selection of eleven cities after the first selection round.

Municipality	Inhabitants	Train station	Highway access	Highway intersection nearby	Suitable for selection
Alkmaar	107106	YES	YES	NO	NO
Alphen a/d Rijn	107396	YES	NO	NO	NO
Amersfoort	152481	YES	YES	YES	YES
Apeldoorn	158099	YES	YES	YES	YES
Arnhem	152293	YES	YES	YES	YES
Delft	101030	YES	YES	YES	YES
Dordrecht	118899	YES	YES	YES	YES
Ede	111575	YES	YES	YES	YES
Emmen	107775	YES	YES	NO	NO
Enschede	158553	YES	YES	NO	NO
Haarlem	156645	YES	YES	YES	YES
Haarlemmermeer	144152	YES*	YES	YES	YES
's-Hertogenbosch	150889	YES	YES	YES	YES
Leeuwarden	107691	YES	YES	NO	NO
Leiden	121562	YES	YES	NO	NO
Maastricht	122397	YES	YES	YES	YES
Venlo	100536	YES	YES	YES	YES
Westland	104302	NO	NO	NO	NO
Zoetermeer	124025	YES	YES	NO	NO

Table 4.23: Comparable cities to Zwolle *Source:* CBS (2016d) & OpenStreetMap (2016)
*Train station of Hoofddorp

After the first selection round, a closer look is taken at the location of the cities within the network. By doing this, more important nodes are distinguished from less important nodes. The first criterion for this is a central location within the train network, decided by being at least 25 kilometres away from the Dutch border. The second criterion has to do with its location with regards to big cities which is defined by not being located to another city within 25 kilometres. The results of the second selection round are explained in table 4.24 leaving two possibilities for comparative research which are Apeldoorn and 's-Hertogenbosch.

Municipality	Distance to border	Distance to big city	Suitable for selection
Amersfoort	70 km	20 km	NO
Apeldoorn	40 km	26 km	YES
Arnhem	22 km	16 km	NO
Delft	65 km	8 km	NO
Dordrecht	34 km	19 km	NO
Ede	39 km	17 km	NO
Haarlem	100 km	18 km	NO
Haarlemmermeer	90 km	16 km	NO
's-Hertogenbosch	30 km	30 km	YES
Maastricht	8 km	67 km	NO
Venlo	11 km	49 km	NO

Table 4.24: Distance of comparable cities to the border and other big cities *Source:* Author based on Distance24.org (2016)

After the selection process based on the location of the nodes within the network, a more in depth case comparison between Zwolle and the two remaining cities is required for a well deliberated choice for comparison. Therefore, the next criteria are not selected based on boundary conditions but are compared to their relative values to Zwolle instead. The selected criteria are 'growth of daily train passengers' (ArcGIS, 2016), 'number of possible train directions' (OpenStreetMap, 2016), 'overlap with Zwolle network' (NS-Reisinformatie, 2016), inhabitants (CBS, 2016d), 'province capital' (CBS, 2003), 'largest political party' (Verkiezingskaart.nl, 2012) and 'city rights' (Cox, 2005). These criteria provide an overview of the growth and the importance of the node within the network as well as demographical information. The selection is elaborated in table 4.25 based on these criteria and their respective sources. In the table, the green background indicates most suitable for comparison, orange background indicates a little less suitable for comparison and the red background indicates less suitable than the other city for comparison.

City	Zwolle	Apeldoorn	‘s-Hertogenbosch
Growth of daily train passengers	+8%	+4%	+3%
Number of possible train directions	8	3	4
Overlap with Zwolle network		Considerable	Limited
Inhabitants	124896	158099	150889
Province capital	YES	NO	YES
Largest political party (2012 elections)	PVDA	PVDA	VVD
City rights (year)	1230	Not available	1184

Table 4.25: Comparison between Zwolle and Apeldoorn & ‘s Hertogenbosch *Source:* Author, based on mentioned sources

The result of the comparison between Zwolle and the two cities results in the choice for the region of ‘s-Hertogenbosch as comparable network. In retrospect, the result of the comparison selection is advantageous for the study since it gives a view on the southern part of the Dutch network complementing the view on the northern part of the network in the case study of Zwolle. Therefore, the case study together with the case comparison provide a more holistic view of the Dutch (rail)road network.

4.4.2 The case of ‘s-Hertogenbosch

To identify similarities and differences between the networks of Zwolle and ‘s-Hertogenbosch, the same three step framework to apply graph theory to inter city networks is used. For clearness, the three, subsequent steps of the framework (chapter 4.2) are mentioned in table 4.26. Similar to the case study, these steps are followed for ‘s-Hertogenbosch. However, due to previous experiences, some steps are shortened or partly skipped.

Step 1a: Defining the network size and nodes. **Step 1b:** Drawing the nodes and links in a graph.
Step 2a: Draw an abstract graph. **Step 2b:** Draft a matrix based on the drawn graph.
Step 3: Calculate the betweenness centrality.

Table 4.26: Guidelines to apply graph theory to inter city transport networks Source: Author

Like the network of Zwolle, the railroad network of ‘s-Hertogenbosch can also be drawn in a one-hour train travel map, with a margin of about 10% (around 66 minutes), this is visualised in figure 4.8. In this figure, the nodes are places on their geographical location. Moreover, due to the different geographical location of ‘s-Hertogenbosch compared to Zwolle, this includes a number of new cities since only five of the cities are represented in both the network of Zwolle as well as the network of ‘s-Hertogenbosch. The nodes, their respective travel time to ‘s-Hertogenbosch and the number of inhabitants per municipality resulting in the node size, are presented in table 4.27.

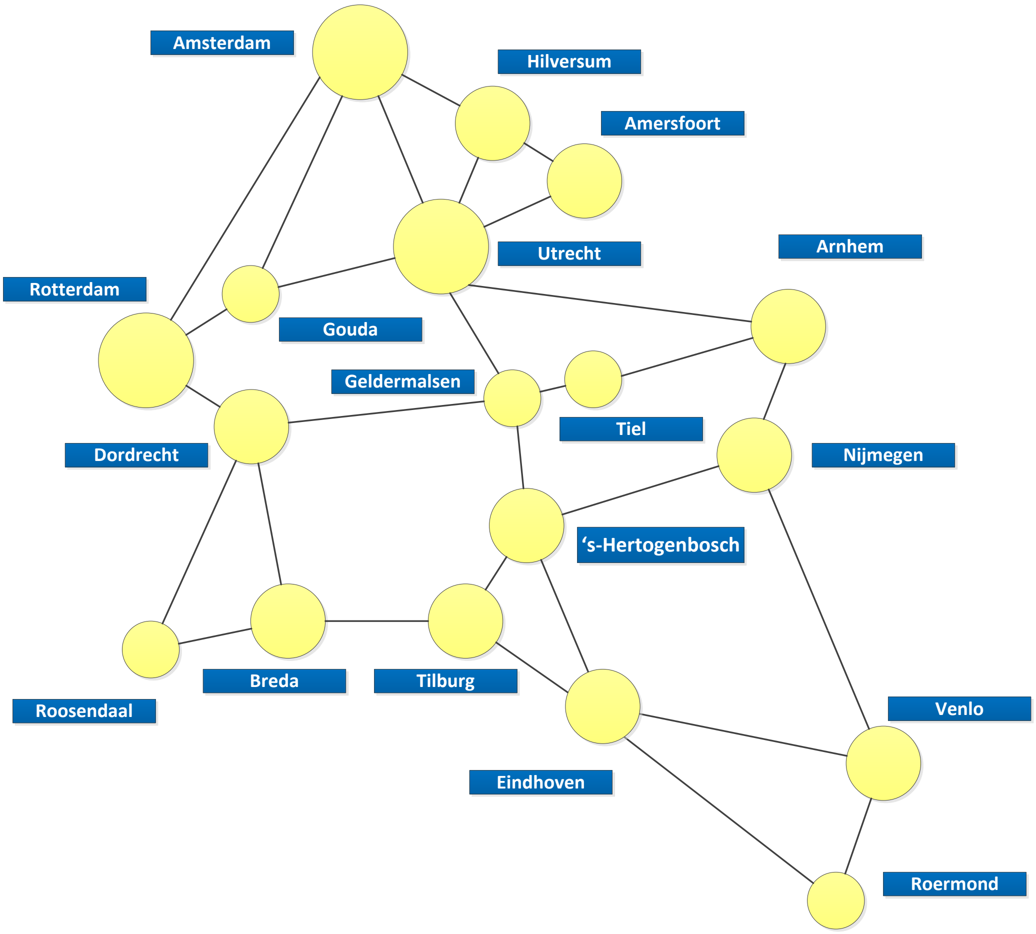


Figure 4.8: One-hour train travel map of the region of ‘s-Hertogenbosch *Source:* Author, based on OpenStreetMap (2016)

Node/Municipality	Travel time to ‘s-Hertogenbosch	Inhabitants (2016)	Node size in map
Amersfoort	55 minutes	152481	MEDIUM
Amsterdam	58 minutes	833624	LARGE
Arnhem	53 minutes	152293	MEDIUM
Breda	15 minutes	181611	MEDIUM
Dordrecht	61 minutes	118899	MEDIUM
Eindhoven	19 minutes	224755	MEDIUM
Geldermalsen	16 minutes	26346	SMALL
Gouda	54 minutes	71189	SMALL
‘s-Hertogenbosch	-	151608	MEDIUM
Hilversum	51 minutes	87830	SMALL
Nijmegen	28 minutes	172064	MEDIUM
Roermond	52 minutes	57010	SMALL
Roosendaal	51 minutes	76960	SMALL
Rotterdam	64 minutes	629606	LARGE
Tiel	33 minutes	41510	SMALL
Tilburg	32 minutes	212941	MEDIUM
Utrecht	28 minutes	338967	LARGE
Venlo	64 minutes	100536	MEDIUM

Table 4.27: Inhabitants per municipality and travel time to ‘s-Hertogenbosch *Source:* CBS (2016b) & NS-Reisinformatie (2016)

During the second step, an abstract map is drawn complemented by a matrix identifying links between the nodes. In table 4.28 the letters representing every city are shown.

Node/City	Letter in Graph
Amersfoort	**N**
Amsterdam	**F**
Arnhem	**O**
Breda	**E**
Dordrecht	**D**
Eindhoven	**L**
Geldermalsen	**J**
Gouda	**C**
Hilversum	**H**
Nijmegen	**P**
Roermond	**R**
Roosendaal	**B**
Rotterdam	**A**
s Hertogenbosch	**K**
Tiel	**M**
Tilburg	**G**
Utrecht	**I**
Venlo	**Q**

Table 4.28: Letters representing nodes in railroad graphs in the network of ‘s-Hertogenbosch *Source:* Author

The node map for railroads in the region ‘s-Hertogenbosch is shown in figure 4.10 and the matrix is drafted in table 4.29**.** In this matrix, the value of ‘1’ represents a direct link and the value ‘0’ no direct link once again. Comparing the node map of ‘s-Hertogenbosch to Zwolle, a dissimilarity can be seen between the respective cities. While the network of Zwolle seems to be focused on Zwolle with a lot of links in all directions, the focus in the network of 's-Hertogenbosch is more evenly distributed with Utrecht being the biggest node in terms of most links.

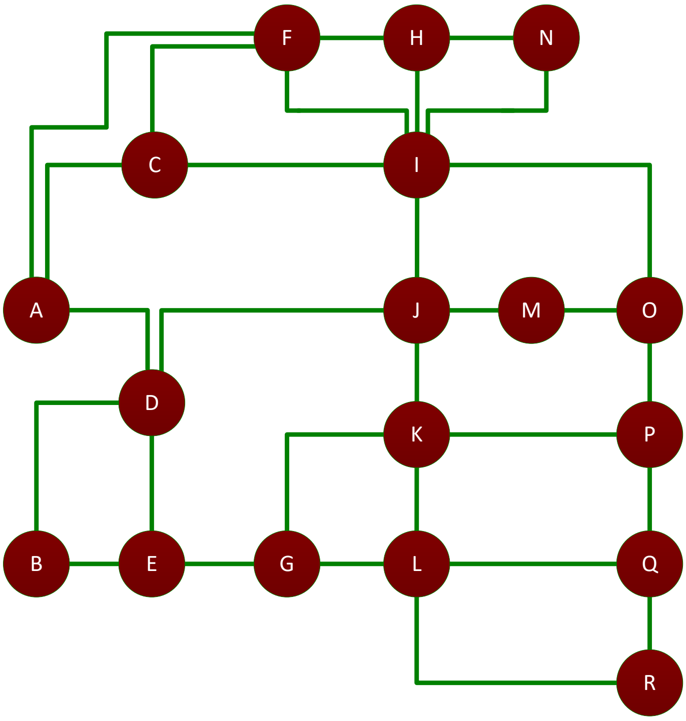


Figure 4.9: Graph map of railroads in the region of 's-Hertogenbosch *Source:* Author

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	Total
A	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**3**
B	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**
C	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	**3**
D	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	**4**
E	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**3**
F	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	**4**
G	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	**3**
H	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	**3**
I	0	0	1	0	0	1	0	1	0	1	0	0	0	1	1	0	0	0	**6**
J	0	0	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0	0	**4**
K	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	**4**
L	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	1	**4**
M	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	**2**
N	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	**2**
O	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	**3**
P	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	**3**
Q	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	**3**
R	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	**2**
Total	**3**	**2**	**3**	**4**	**3**	**4**	**3**	**3**	**6**	**4**	**4**	**4**	**2**	**2**	**3**	**3**	**3**	**2**	

Table 4.29: Direct railroad links between nodes in the region of 's-Hertogenbosch *Source:* Author

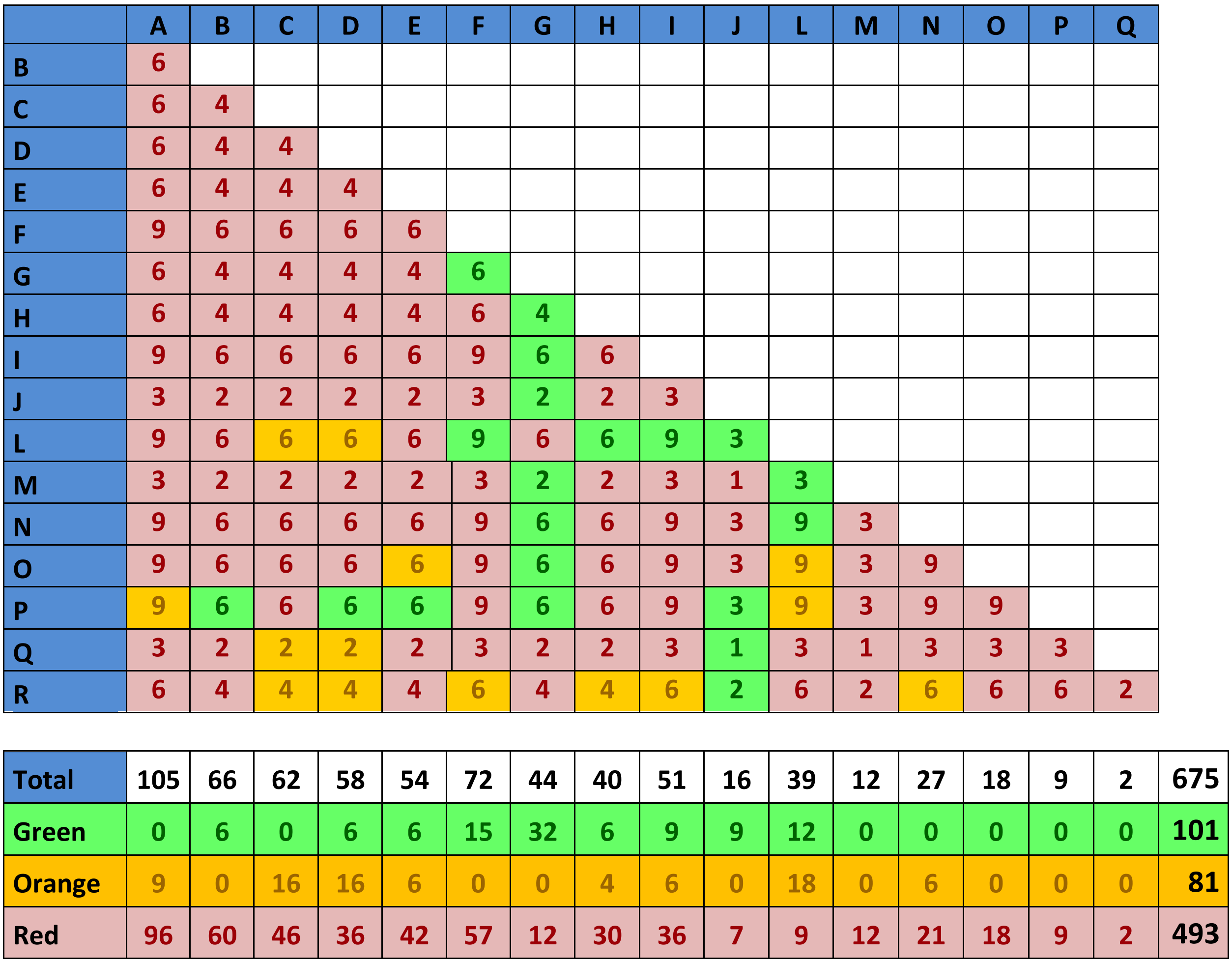
For calculating the betweenness centrality, the case study of Zwolle has shown that the betweenness centrality based on the node pair value offers most insight in the importance of nodes in the network (chapter 4.3.4). This is due to the distinction between important and less important nodes. Therefore, calculating the betweenness centrality the 'original way', without weighing the node pairs, is skipped for the case of 's-Hertogenbosch. Consequently, the node weight for each node is calculated based on the number of daily passengers which is shown in table 4.29. Nodes with less than 10000 daily passengers are given a node weight value of 1, nodes with a number of daily passengers between 10000 and 35000 are given a node weight value of 2 and nodes with more than 35000 daily passengers are given a node weight value of 3. Similar to Zwolle, some of the data about daily passengers are incomplete due to the absence of passenger data from other passenger railway operators Nodes including other passenger railway operators on the boundary of a node weight value are checked for a reasonable node weight.

Node/City	Letter in Graph	Daily Passengers	Node weight
Amersfoort	N	39675	3
Amsterdam	F	167427	3
Arnhem	O	39164*	3
Breda	E	30554	2
Dordrecht	D	23172*	2
Eindhoven	L	60450	3
Geldermalsen	J	5909*	1
Gouda	C	21298	2
Hilversum	H	24105	2
Nijmegen	P	43195*	3
Roermond	R	13274	2
Roosendaal	B	10399	2
Rotterdam	A	85246	3
's-Hertogenbosch	K	43172	3
Tiel	M	3445	1
Tilburg	G	32158	2
Utrecht	I	176552	3
Venlo	Q	4370*	1

Table 4.30: Node weight based on Daily Passengers for the network of 's-Hertogenbosch. *Source:* Author, based on ArcGIS (2016)

* Station shared with another passenger railway operator

Each of the node pairs can now be given a value according to a multiplication between the node weights of the respective nodes. In table 4.31, each of the node pairs is given the respective value. Moreover, in this table, the node of 's-Hertogenbosch (K) is left out. Now the betweenness centrality can be calculated by checking for each pair if the fastest route between the nodes always passes node 'K' (green), the fastest route is equal through node 'K' or an alternative route (orange) or is slower through node 'K' (red). Green pairs are once again given value '1', orange pairs value '0.5' and red pairs value '0'. The total pair weight for the network is 675, out of which 101 is green, 81 orange and 493 red.



	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P	Q
B	6															
C	6	4														
D	6	4	4													
E	6	4	4	4												
F	9	6	6	6	6											
G	6	4	4	4	4	6										
H	6	4	4	4	4	6	4									
I	9	6	6	6	6	9	6	6								
J	3	2	2	2	2	3	2	2	3							
L	9	6	6	6	6	9	6	6	9	3						
M	3	2	2	2	2	3	2	2	3	1	3					
N	9	6	6	6	6	9	6	6	9	3	9	3				
O	9	6	6	6	6	9	6	6	9	3	9	3	9			
P	9	6	6	6	6	9	6	6	9	3	9	3	9	9		
Q	3	2	2	2	2	3	2	2	3	1	3	1	3	3	3	
R	6	4	4	4	4	6	4	4	6	2	6	2	6	6	6	2

Total	105	66	62	58	54	72	44	40	51	16	39	12	27	18	9	2	675
Green	0	6	0	6	6	15	32	6	9	9	12	0	0	0	0	0	101
Orange	9	0	16	16	6	0	0	4	6	0	18	0	6	0	0	0	81
Red	96	60	46	36	42	57	12	30	36	7	9	12	21	18	9	2	493

Table 4.31: Betweenness centrality based on node pair weight and node distance for ‘s-Hertogenbosch. *Source:* Author

Slower through ‘K’	Value = 0
Faster through ‘K’	Value = 1
Equal through ‘K’	Value = 0.5

The C_b can now be calculated by 101 + 0.5 * 81 = 141.5. The share of ‘node pair value’ going through ‘K’ can now be found by calculating its share of the total number of pair weight value. However, the total pair weight value of the network has already been calculated and is 675. The following calculation is used to find the share:

$$C'_b = C_b / 675 =$$
$$C'_b = 141.5 / 675 = 0.21$$

Surprisingly, the difference between the C'_b for ‘s-Hertogenbosch and Zwolle is a lot. The main reason for this is the availability of alternative paths in the network. However, the use of the link between ‘D’ and ‘J’ (Dordrecht – Geldermalsen) is very important on the node map. In reality the connection between those nodes takes 53 minutes (NS-Reisinformatie, 2016). This emphasizes the distinction between the model and reality. Consequently, adding the betweenness centrality based on pair weight value while taking the travel time into account is inevitable for a more representative answer. Moreover, the high connectivity of the big cities in the network of 's-Hertogenbosch is unfavourable for the relative betweenness centrality for 's-Hertogenbosch.

In figure 4.11 the fifteen relevant lines in the train network of 's-Hertogenbosch are drawn. Similar to the case of Zwolle, these lines were identified as the most important lines emphasizing important nodes in the network (e.g. Rotterdam (A) & Utrecht (I)). In table 4.32 a matrix is drafted showing whether there is a direct line between two nodes or not (value '1' or '0' respectively). The connections between the nodes has increased considerably because the nodes do not have to be 'direct neighbours' in order to be linked now. By introducing the lines as extra source of data, the new fastest routes between the node pairs can be calculated by using the shortest travel time.

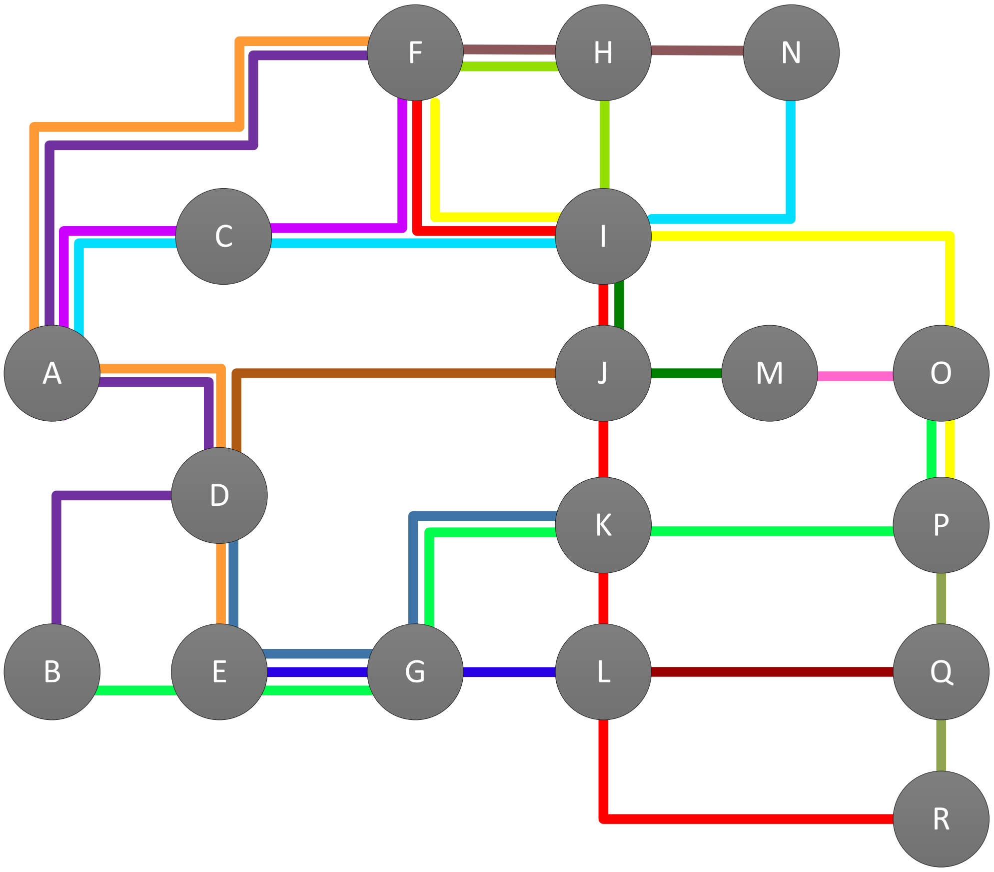


Figure 4.10: Link map of railroads in the region of 's-Hertogenbosch *Source:* Author based on OpenStreetMap (2016)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	Total
A	0	1	1	1	1	1	0	0	1	0	0	0	0	1	0	0	0	0	**7**
B	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	1	0	0	**8**
C	1	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	**4**
D	1	1	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	**7**
E	1	1	0	1	0	1	1	0	0	0	1	1	0	0	1	1	0	0	**9**
F	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	1	0	1	**14**
G	0	1	0	1	1	0	0	0	0	0	1	1	0	0	1	1	0	0	**7**
H	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	**3**
I	1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	**12**
J	0	0	0	1	0	1	0	0	1	0	1	1	1	0	0	0	0	1	**7**
K	0	1	0	1	1	1	1	0	1	1	0	1	0	0	1	1	0	1	**11**
L	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	1	1	**8**
M	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	**3**
N	1	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	**5**
O	0	1	0	0	1	1	1	0	1	0	1	0	1	0	0	1	0	0	**8**
P	0	1	0	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	**9**
Q	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	**3**
R	0	0	0	0	0	1	0	0	1	1	1	1	0	0	0	1	1	0	**7**
Total	**7**	**8**	**4**	**7**	**9**	**14**	**7**	**3**	**12**	**7**	**11**	**8**	**3**	**5**	**8**	**9**	**3**	**7**	

Table 4.32: Direct railroad links between nodes in the region of ‘s-Hertogenbosch *Source:* Author

For the C_b based on travel time there are some differences leading to more ‘green node pairs’ in general. Especially pairs including the nodes ‘E’, ‘Q’ and ‘R’ are more likely to be green based on travel time. An explanation of this can be found in the slowness of some links in the network such as the previously mentioned link between ‘D’ and ‘J’. In retrospect, the C_b based on travel time provided a much more reliability than basic node counting. Compared to metro networks, these train networks are easier affected by direct and indirect trains as well as the distinction between local and national trains. The former is due to the higher interval of trains compared to metros while the latter is due to the high amount of stops of local trains in small towns compared to national trains. The results are shown in table 4.33.

	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P	Q
B	6															
C	6	4														
D	6	4	4													
E	6	4	4	4												
F	9	6	6	6	6											
G	6	4	4	4	4	6										
H	6	4	4	4	4	6	4									
I	9	6	6	6	6	9	6	6								
J	3	2	2	2	2	3	2	2	3							
L	9	6	6	6	6	9	6	6	9	3						
M	3	2	2	2	2	3	2	2	3	1	3					
N	9	6	6	6	6	9	6	6	9	3	9	3				
O	9	6	6	6	6	9	6	6	9	3	9	3	9			
P	9	6	6	6	6	9	6	6	9	3	9	3	9	9		
Q	3	2	2	2	2	3	2	2	3	1	3	1	3	3	3	
R	6	4	4	4	4	6	4	4	6	2	6	2	6	6	6	2

Total	**105**	**66**	**62**	**58**	**54**	**72**	**44**	**40**	**51**	**16**	**39**	**12**	**27**	**18**	**9**	**2**	**675**
Green	9	14	14	12	26	24	32	12	18	9	30	3	9	0	0	0	**212**
Red	96	52	48	46	28	48	12	28	33	7	9	9	18	18	9	2	**463**

Table 4.33: Betweenness centrality based on node pair weight and node distance for ‘s-Hertogenbosch. *Source:* Author, based on NS-Reisinformatie (2016)

Slower through ‘K’	**Value = 0**
Faster through ‘K’	**Value = 1**

The C_b of ‘s-Hertogenbosch based on travel time can now be calculated by counting the green node pair weight: 212. The share of ‘node pair value’ going through ‘K’ can now be found by calculating its share of the total number of pair weight value. The total pair weight value of the network has already been calculated and is 675. The following calculation is used to find the share:

$$C'_b = C_b / 675 =$$
$$C'_b = 212 / 675 = 0.31$$

This value is almost 50% higher than the earlier calculated betweenness centrality, which is 0.21. Therefore, the changes in outcomes between the different methods in finding the fastest route between the node pairs remains considerable and should be taken into account. The comparison of the values and a comparison of the methods is given in chapter 4.4.3.2.

4.4.3 Comparing the cases

The results of the values for the betweenness centrality of Zwolle and ‘s-Hertogenbosch show some notable differences. The applied method for the case of ‘s-Hertogenbosch is the one based on the node pair value since this provided more valuable information in the case of Zwolle. Therefore, the original method is adapted for ‘s-Hertogenbosch to decrease the workload and focus on the new, more valuable method only. However, within this method, two ways of calculating the betweenness centrality are used. One of the ways focusses only on fastest route between the node pair based on the node distance while the other focusses on the shortest travel time between the pair of nodes. For both of these methods, the cases of Zwolle and ‘s-Hertogenbosch are compared. For the values of Zwolle, the values of the contemporary situation are taken. These are the values after the establishment of the Hanzelijn.

4.4.3.1 Comparing the betweenness centralities based on node distance

For clarity, the relative betweenness centrality based on node distance is shortened to C'_b-d_n. The calculated C'_b-d_n of Zwolle and ‘s-Hertogenbosch are 0.41 and 0.21 respectively. Surprisingly, the C'_b-d_n of Zwolle is almost twice as high compared to ‘s-Hertogenbosch. These differences can be linked by comparing the graph maps of the respective cities. Both of these maps are shown alongside each other in figure 4.12 On the left side, the network of Zwolle is shown in which Zwolle (I) has an important role containing most links per node with 8 links. On the right side, ‘s-Hertogenbosch (K) has a less important function in the network, containing only 4 links. Moreover, for the network of Zwolle, all node pairs containing F have to go through I since its only connection is to I. On the other hand, ‘s-Hertogenbosch does not have a similar node connected only to itself. Another interesting pattern is the availability of alternative routing. In the network of Zwolle, the only possibility to travel from south to north is by going through node I or O in which the latter is only favourable when travelling to Q. In the network of ‘s-Hertogenbosch there are numerous alternatives to travel around node K, which can be seen as loops (Gattuso & Miriello, 2005). Therefore, there are lots of possibilities to use other routes. Consequently, it is not really surprising after all that the C'_b-d_n of Zwolle is higher than the C'_b-d_n of ‘s-Hertogenbosch.

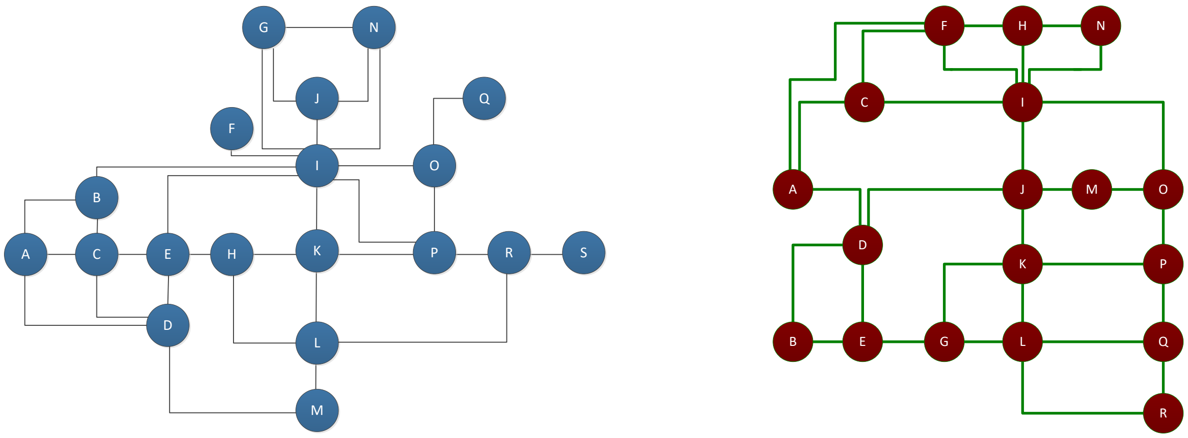


Figure 4.11: Graph map of railroads in the region of Zwolle & the region of ‘s-Hertogenbosch *Source:* Author

4.4.3.2 Comparing the betweenness centralities based on travel time

For clarity, the relative betweenness centrality based on travel time is shortened to C'_b-t_t. The C'_b-t_t for Zwolle and ‘s-Hertogenbosch are 0.37 and 0.31 respectively. While the value for Zwolle remains higher, the values for the C'_b-t_t are closer together than the values for the C'_b-d_n. The decrease of the value for Zwolle relative to the C'_b-d_n is predominantly caused by the fast, direct line connecting the nodes A and S and all nodes in between. On the other hand, the higher value of the C'_b-t_t for ‘s-Hertogenbosch compared to the C'_b-d_n is predominantly caused by the direct line between node F and R, going through ‘s-Hertogenbosch (K) as well. Moreover, a few local trains are included in the graph map of ‘s-Hertogenbosch. These routes include many stops in small villages and are, therefore, often slower than inter city trains. Consequently, the travel time is highly influenced by the availability of direct trains as well as the kind of train. The direct lines for both networks are shown in figure 4.13 showing a more comprehensive visualisation of the network than a graph map of the links only. The C'_b-t_t of Zwolle remains, however, higher than the C'_b-t_t of ‘s-Hertogenbosch. Therefore, based on this method, the importance of Zwolle in its network seems to be higher than the importance of ‘s-Hertogenbosch in its network. Since the location of Zwolle initially appeared to be more central in the network than ‘s-Hertogenbosch, this result seems reasonable. Therefore, the results of the graph approach can be seen as matching the expectations. In the next chapter, the results of the case study and comparative study are elaborated as well as a method to translate these results into planning practice.

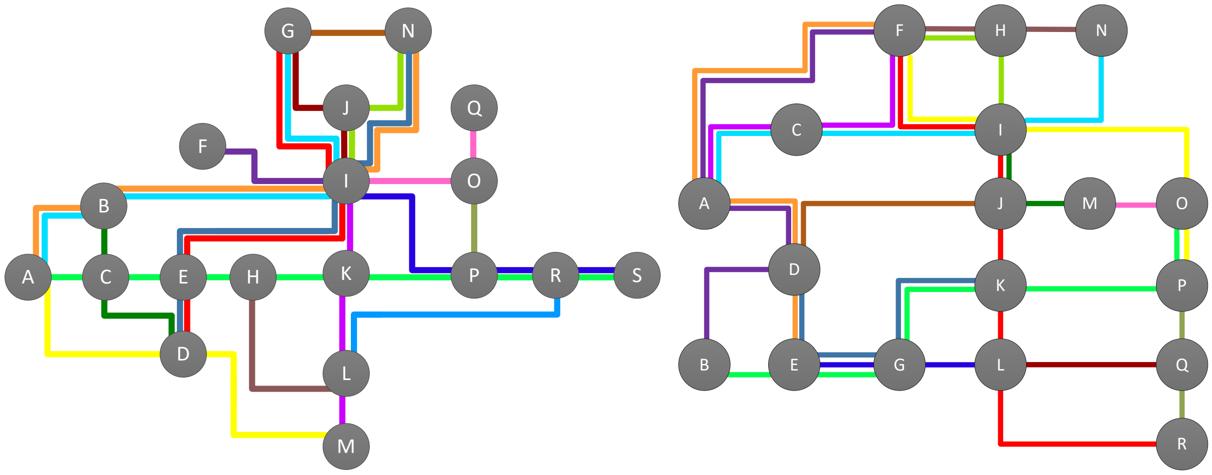


Figure 4.12: Link map of railroads in the region of Zwolle & the region of ‘s-Hertogenbosch *Source:* Author based on OpenStreetMap (2016)

After using both methods and comparing the results in chapter 4.3.4 this study suggests a node distance based on travel time is more suitable for inter city networks than based on node distance. The case of ‘s-Hertogenbosch proved the unrealistic influence a slow link between two nodes (D-J) can have on the outcome if the fastest route is calculated through node distance. Therefore, the fastest route between nodes based on travel time turned out to be the most successful method in this research. However, this may differ for other contexts.

5. Results

The results of the data analysis can be split into three categories which are discussed separately. First, the framework with guidelines about how to apply graph theory to inter city transport networks which can be used as an universal tool to study transportation networks. Secondly, the results these guidelines gave for the case study and subsequent comparative study. And thirdly, how can these results be connected and adapted into the Dynamic Adaptive Planning framework.

5.1 A framework for applying graph theory to inter city networks

In chapter 4.2 a framework is introduced containing three subsequent steps to apply graph theory to inter city transportation networks. These guidelines can be seen as a new, universal method which can be adapted for every type of network. The guidelines lead to a value for the betweenness centrality (C_b) for a city in the network. This value can be compared to other cities, other modalities or different periods within the network. During every step, there are possibilities to adjust or adapt the guidelines fitting the context accordingly (e.g. different data sources for roads relative to railroads). For clarity, table 4.1 is reintroduced to summarise the steps of the guidelines once more in table 5.1. During step one, the network boundaries are drawn and the nodes and links visualised according to their geographical location. During step two, the graph is abstracted and a matrix is drafted based on the graph. The matrix may differ if lines are used as basis for the graph instead of links. During step three, the betweenness centrality is calculated. This calculation can be done using multiple methods, some of these are used comprehensively throughout chapters 4.2 and 4.3. The most resourceful and suitable method used in this research appeared to be using the node pair value to identify important cities in the network as well using the shortest travel time to calculate the fastest route between two nodes. Alternative methods can be applied depending on what the situation demands.

What?	How?	Why?
Step 1a: Defining the network size and nodes. **Step 1b:** Drawing the nodes and links in a graph.	Identify all the nodes within the time limit. Categorize the nodes based on population. Draw a map using the nodes geographical location	To give an overview of the network and emphasizing the important cities in the network
Step 2a: Draw an abstract graph. **Step 2b:** Draft a matrix based on the drawn graph.	Abstract the graph by removing the geographical accuracy of the nodes and by representing the nodes with letters. Thereafter, a matrix can be drafted to indicate which nodes are linked	To make a clear, structured graph which can be used efficiently for the matrix and can be used as a basis in the next step.
Step 3: Calculate the betweenness centrality.	By pairing up all the nodes and calculating the fastest route between the pairs. The pair is then given a value based on whether the fastest route passes node 'X'	To indicate the importance of node 'X' in the network and looking at the share of fastest routes passing node X. The betweenness centrality value can then be used as comparative value to other networks.

Table 5.1: Guidelines to apply graph theory to inter city transport networks *Source:* Author

5.2 Case study and comparative study

Using the guidelines for the case and comparative study lead to interesting results. The railroad network of the region of Zwolle is the first network that has been studied. The results of this part of the case study alone did not provide much information since the obtained values could not be compared to anything. Therefore, the railroad network is compared to an earlier situation of the network where one new link between Almere and Zwolle (the Hanzelijn) had not been established yet. The values for the C_b of the old and new situation have been compared and, unsurprisingly, showed a slight increase of the value for Zwolle. The next part of the case study examined the road network of the region of Zwolle, in which the role of the node Zwolle appears to be much smaller with regards to the number of possible directions it has. By calculating the C_b for Zwolle for the road network, using slightly adjusted values, the role of Zwolle in the road network appeared to be lower than for the railroad network. Therefore, the assumptions about the important role of Zwolle in the railroad network were more or less strengthened by the obtained information from the case study. Moreover, different methods to calculate the C_b have been used which lead to different results which provided more insight in which method comes closest to represent the network in a realistic way. Furthermore, comparing Zwolle to another network, using the same methods and variables, would clarify the meaning of the value for Zwolle with regards to another network.

The most suitable case for comparison turned out to be ‘s-Hertogenbosch after comparing similar cities to Zwolle throughout the Netherlands using multiple criteria. The interesting aspect of ‘s-Hertogenbosch is the different location in the Netherlands having only a little overlap with Zwolle. Moreover, the location of ‘s-Hertogenbosch is interesting since it is located closely to the big cities Utrecht and Eindhoven as well as closer to the Randstad than Zwolle. The results of the comparison were in the favour of Zwolle, which turned out to have the highest C_b using two different methods to compare. When looking to both of the networks next to each other it is striking that the number of alternative routing for the network of Zwolle is much lower than for ‘s-Hertogenbosch. If someone wants to travel from north to south in the network of Zwolle, the node of Zwolle is almost inevitable while there are some possible alternatives in the network of ‘s-Hertogenbosch. In retrospect, the higher value for the centrality of Zwolle in its respective network could, therefore, be expected. With regards to the indicator, this correspondence with the initial expectations shows at least some kind of relation between the indicator and reality. The central location in its respective network appears to be the dependent variable for this. To test this hypothesis, this study recommends more research with more cases.

5.3 The Dynamic Adaptive Planning process as a framework

Using the case study and the comparative study, the DAP framework for Zwolle can be complemented based on the outcomes of these studies. Although these values are merely an indication of the relative importance of the city, modality or period in time, it does tell something about the potential of the network.

The first part of the DAP framework that has to be complemented are the actions that have to be taken during the third step to counter the vulnerabilities and increase the robustness of the plan. These are hedging, mitigating, seizing and shaping actions. Hedging and mitigating actions are taken to adverse unlikely and likely vulnerabilities respectively while seizing actions are taken when opportunities occur and shaping actions are taken proactively to reduce the chance of failure or increase the chance of success for the plan (Wall et al., 2015). The actions for the network of Zwolle while taking the case study into account are shown in table 5.2

Hedging Actions:	**Mitigating Actions:**
• Increase the robustness of links by establishing alternatives for 'vulnerable links' (e.g. links that are prone to climate change such as low bridges). • Decrease the pressure on links in case of lower demand.	• Find cheap options for alternatives in case of cut off budget. • Intensify the use of links in case of a higher demand (e.g. new timetable for trains).
Seizing Actions:	**Shaping Actions:**
• Create new links matching an increased demand (e.g. establishment of the Hanzelijn) • Upgrade monofunctional links to multifunctional links (e.g combine railroads with roads, bicycle lanes or other public transport.	• Find additional links to increase the betweenness centrality of the network • Combine infrastructure investments for the network with other investments such as housing (TOD)

Figure 5.1: Actions to counter vulnerabilities and increase the robustness of the plan for Zwolle. *Source:* Author, based on Wall et al. (2015)

During the fourth step, setting up the monitoring system, the monitored signposts and triggers are identified as an indicator for the need of trigger responses. A selection of possible signposts and the respective triggers based on this research are shown in table 5.3.

Monitoring:	**Triggers:**
Monitor: traffic volume of links increases	Trigger: If maximum capacity is reached, take corrective actions. If corrective actions fail, take capitalizing actions
Monitor: changes in the budget available for network improvements	Trigger: If budget is lower than expected, take defensive actions, if defensive actions fail, reassess the plan.
Monitor: Vulnerabilities in the network due to climate change	Trigger: If changes due to climate change reach certain limit, take defensive actions
Monitor: Opportunities for multifunctional link use	Trigger: Reassess the basic plan to permit multifunctional link use
Monitor: Increase of population in the region of Zwolle	Trigger: If population extends a certain number, take capitalizing actions
Monitor: Opportunities for lower travel time due to improved technology.	Trigger: If new technologies become available, take capitalizing actions. If capitalizing actions fail, reassess the plan.
Monitor: Betweenness centrality changes for cities in the network	Trigger: If the betweenness centrality rises or drops below a certain number, take corrective actions.

Figure 5.2: Monitoring signposts and triggers for the plan for Zwolle. Source: Author, based on Wall et al. (2015)

During the fifth step, actions are taken to prepare the trigger responses. These actions are defensive actions, corrective actions, capitalizing actions and reassessment. First, defensive actions are actions leaving the basic plan unchanged. Secondly, corrective actions are adjustments of the basic plan in response to triggers. Thirdly, capitalizing actions are actions taking advantage of opportunities that improve the performance of the basic plan. Lastly, reassessment of the basic plan is needed when the plan proved to be unsuccessful due to wrong analysis or wrong assumptions for the basic plan (Wall et al., 2015). These actions are shown in table 5.4. This concludes the DAP framework for the region of Zwolle. The actions, monitoring and triggers are merely arising from this research and are incomplete in terms of a potential framework for the region of Zwolle. Therefore, more research is recommended to complement this framework.

Defensive Actions:

- Implement increased external sources of money in case of decreased budget (e.g. external investor, more expensive use of network for consumers)
- Devise alternatives for climate prone links in the network in case of problems due to climate change

Corrective Actions:

- Increase maximim capacity through intensifying the links (e.g. higher frequency)
- Intensify, establish or decrease the need for certain links to match the desired betweenness centrality.

Capitalizing actions:

- Intensify links and establish new links to meet a higher capacity
- Combine new housing and network improvement for a larger population through sustainable mobility or TOD
- Implement new technologies in the network

Reassessment:

- Reassess the basic plan to deal with a lower budget in defensive actions are limited.
- Reassess the basic plan to permit multifunctional link use
- Reassess the basic plan to allow new technologies

Figure 5.3: Actions taken as trigger responses for the plan for Zwolle. *Source:* Author, based on Wall et al. (2015)

5.4 Relating the results to the new trends in in infrastructure planning

The results of the case study show some interesting similarities with the new trends in infrastructure planning. First, it is possible to link distance reduction from sustainable mobility (Banister, 2008) to betweenness centrality. Living in cities with a high betweenness centrality automatically reduces the distance due to the location on the route between other cities. While this statement may be jumping to conclusions a little too soon, it is an indication that the location of a node in the network is important in order to reduce the need to travel. Moreover, increasing the efficiency of a network can be done by looking for opportunities at the graph map (e.g. which link(s) has to be established to increase the betweenness centrality to a certain value and how can this be done as cheap as possible). Earlier in this study (chapter 2.3.1) it is mentioned that graph theory might be able provide an opportunity to involve the community by clarifying complex problems. In retrospect, however, these graphs and calculations proved to be rather complex themselves and, therefore, rather inappropriate to involve the community in.

For integrated infrastructure planning, the results especially provide a lot of insights on networks. Moreover, multi-modalities can be explained using graph theory on multiple levels and multiple scales. This would, however, be a rather complex network requiring deeper insight on the interaction between networks within a city and networks between cities. Nevertheless, this can be a useful tool to study networks in the future. The line to area-oriented approach does not seem to match well with the results of the data analysis. Due to limits of information that graph maps can provide, the information about the area seems to get lost in the process. Moreover, combining the network, which is part of infrastructure planning, with other spatial sectors seems rather illogical when using graph theory. Therefore, graph theory and the line to area-oriented approach can be seen as complementary instead of alike. Graph theory can provide information about the network as a whole, or macro scale and locations within this network and the line to area-oriented approach can be used as a tool to translate this to the local context, or micro scale.

Lastly, for transit-oriented development, the results of the research can be important in order to define a city with a high betweenness centrality. These cities appear to be important in the network and well connected to other cities. Hence, following from this study combined with literature about TOD (e.g. Yang et al., 2016; Wey et al., 2016), TOD around these cities is more likely to be effective if it is well adapted to the inter city network. Moreover, TOD is an example that urban sprawl can be dealt with using the transit network efficiently. Through analysing the daily number of passengers after introducing TOD, important locations for new nodes can be identified.

6. Discussion and conclusion

Throughout this chapter, the results and data are compared with the conceptual model. Moreover, a discussion is started based on the limitations of this study as well as. Thereafter, a more general conclusion with regards to the research question and sub questions is given to indicate to which extent the results lead to answers to the research question. Finally, some recommendations for future research based on the findings of this research are given which can be seen as the starting point for further research. However, first a discussion is given in which the results from the data are compared with the conceptual model.

6.1 Discussion

Within the conceptual model, there is a clear boundary between theory and data in which the conceptual model itself is the line of demarcation between those two. In retrospect, the theory section of the conceptual model proved to be a solid point of departure with regards to input to start the case study. Complemented by additional data that had to be obtained, the case study has been done in an explorative way. Therefore, distinguishing three separate aspects of infrastructure planning in the conceptual model proved to be useful to understand networks as complex systems as well as applying graph theory to identify variables within the networks. Moreover, linking the outcomes of the case study and case comparison to the new trends in infrastructure planning provides a connection between graph theory and potential growth in the future.

The results of this study are merely an exploration of the possibilities to apply graph theory to inter city networks. Due to the novelty of this topic, a lot of choices and assumptions are made throughout the research in order to get to results. Moreover, a set of guidelines to apply graph theory to inter city networks was presumed necessary to guarantee consistent and comparable results. There is within these guidelines, however, a lot of room for improvement and adjustment based on experience and expertise. Throughout the data analysis, just a few examples of the possibilities in defining a network are used. An exciting alternative might be to expand the boundaries of the network in such a way it includes the two cities for comparison. With regards to the studied cases, this can be done by increasing the maximum travel time for both cities to two hours so the overlap of the networks is significant. This would, however, mean that the network includes almost the complete country, leading to an enormous amount of data to be studied. Nevertheless, there are many possibilities to change the variables (e.g. network size, calculating variables, possible comparative studies) used within this study to complement the results of this study. A dependent variable, or in this case a success factor for networks that can link spatial growth to graph theory remains unidentified in this research.

With regards to previous work on the topic, this research showed both comparable results as well as new insights. While most of the results turned out to be somewhat predictable in terms of outcomes, the method of obtaining those results has not been used before in this context. However, the methods of applying graph theory to inter city networks are adapted from metro networks with some adjustments to distinguish the importance of cities. While the stations in metro networks represent merely a station or a stop in a neighbourhood, stations in inter city networks represent entire, ‘living’ cities. These cities are complex systems and cannot be straight up compared to other cities without losing a valuable part of its unique context. Therefore, the works on graph theory for metro network provide a basic framework which can be used when adjusted for inter city networks as well.

Taking the previous works about new trends in infrastructure into account, it can be concluded that the results from this research do not really point towards a single trend as main trend for the future. However, graph theory can be seen as a complementary tool to understand these trends on a bigger scale. Or in other words, graph maps can provide a view on the macro scale and the trends can translate this to the meso and micro scale. Moreover, the identified trends can be seen as rather abstract and linking this to the more practical aspects of graph theory to understand the importance of certain nodes and edges in networks can be useful to get a basic understanding of the network on a bigger scale. An example of this is identifying important nodes in a network which can be expanded using ideas from sustainable mobility of transit-oriented development.

6.2 Conclusion

This research aimed to provide inside in how graph theory and inter city transportation networks can be linked while accounting for the increasing complexity in these networks. In order to do so, a research question and four sub questions have been formalized in chapter 1 to discuss each of these parts separately leading to a more integrated conclusion on the research question. Throughout this conclusion, the answers to these sub questions and research question (if present) are discussed. Moreover, the results are put into a broader perspective with regards to contemporary planning discussions as well as the part of the world the results represent. Linking the results to planning theory and planning practice proved to be tough in earlier chapters due to the different scale and nature of the data.

The first sub question is: “How can transportation planning deal with increasing complexity and, therefore, be adaptive for the future?” This sub question has been studied by taking a closer look at the literature about complex adaptive systems (Duit & Galaz, 2008; Rauws et al., 2014). Following from this literature study the dynamic adaptive planning (DAP) approach (Wall et al., 2015) turned out to be a suitable method for transportation planning to take complexity into account as well as being robust and adaptive (Duit & Galaz, 2008) for future uncertainties. Therefore, the DAP approach (Wall et al., 2015) can be considered as method for transportation planners to deal with complexity and uncertainty in infrastructure networks. This can be directly linked to the contemporary planning debate in which complexity is becoming more and more important (De Roo, 2010). Moreover, the realisation that infrastructure planning cannot be carried out separately from other planning policies requires a more integral approach leading to even more complex problems (Arts et al., 2016).

The second sub question discussed the applicability of graph theory in inter city transportation networks. This question is answered mostly by experimenting with a case study leading to a framework of guidelines which prescribe how graph theory can provide a basis to understand phenomena in inter city networks. This framework is merely an exploration of the possibilities in which graph theory can be applied to inter city networks. There are numerous other ways in which the framework can be adjusted such as different derivatives of graph theory, different variables for cities, different network sizes and different methods to calculate the values for cities. Therefore, this research provided an introduction to a framework of applying graph theory which can be used and applied on many different networks. While graph theory is rarely used for transportation planning in contemporary planning practice, the insides from graph theory on metro networks combined (e.g. Derrible, 2012; Derrible & Kennedy, 2009; Gattuso & Miriello, 2005) with the results of this study can provide new insights into the value graph theory processes to understand certain aspects of networks.

The third sub question: “How can graph theory be used to explain spatial growth and decline in Dutch cities” remains to a great extent unanswered after this research. Although the growth of Zwolle has been compared to the establishment of a new link, there are a lot of other factors and reasons for spatial growth and decline. This sub question in particular is of relevance for planning practice since there appears to be links between a location within a network and potential growth but this cannot be directly linked. While cities on the edge of a network near a geographical border appear to show decline, cities in the centre of a network with high accessibility appear to be highly demanded locations. This possible linkage between location and potential growth can be seen as an important goal of research in transportation planning as well as planning in general.

The fourth and final sub question discusses the relation between recent trends in Dutch infrastructure planning and the concept of graph theory. While the holistic view of recent trends in infrastructure planning were hard to link the simplistic visualisation of graph maps, these two can be seen as complementary. While graph maps represent the network on a bigger scale or macro level, indicating the strong and weak points in a network, new trends in infrastructure planning such as sustainable mobility and transit-oriented development (Wey et al., 2016) can translate this to the meso and micro level (Alexander, 2005). In planning theory, the micro scale seems to become more and more important leading to infrastructure trends such as the line to area-oriented approach (Heeres et al., 2012) in which the surroundings of a line on a micro scale become more important. Linking this micro scale to a macro scale, such as the entire network provides a more complementary overview. Other trends like sustainable mobility (Banister, 2008; van Wee et al., 2013), integrated infrastructure planning (Arts et al., 2016) appear to becoming more customary as well.

The research question: “How can graph theory provide a framework for transportation planning in inter city networks while accounting for increasing complexity based on the case of the region of Zwolle?” can now be answered partially. While the framework is identified during the case study, it is far from holistic and requires further studying to be validated for more cases. Nevertheless, the increasing complexity can be dealt with using the dynamic adaptive approach. This is, however, only one of the approaches that can be used. For the region of Zwolle, the application of graph theory revealed great potential in terms of location in the network. Compared to 's-Hertogenbosch, the location of Zwolle in the network is more favourable in terms of betweenness centrality and can, therefore, be seen as an important city in the network. Consequently, the answer to the research question has been identified to a great extent, the specific values and implications of the framework to apply graph theory to inter city transportation planning remains remain yet to be explored further. This study has shown some interesting results while exploring the possibility to apply the graph theory to inter city networks. Therefore, future research is recommended to further explore this exciting topic. In the next section, the recommendations for future research are elaborated.

6.3 Future research

Following from the discussion and conclusion, there remain some questions left unanswered. Moreover, throughout this research, certain choices and assumptions are made which leave possibilities for alternative options and also different results. The first recommendation is a more in depth analysis of possibilities for transportation planning to deal with increasing complexity. While the DAP approach offers a good solution, there may be different methods that can be used. Furthermore, the DAP approach that is used for Zwolle is based on only limited research and can be complemented by more data through a more intensive case study. Another aspect that can be integrated in further research is the implications for institutional design and institutional requirements that are required for a DAP approach to be implemented in the region of Zwolle

The second recommendation has to do with the framework that has been introduced in this research. While it provides some first steps to apply graph theory to inter city networks, it is still in its infancy and more research is required to complement this. Furthermore, 's-Hertogenbosch is used in the research as a comparison and proved to be an interesting case for further research linked to the case of Zwolle. A possible method to compare the networks of the both cities is by increasing the travel limit to such an extent the cities are within the others time limit. This network would, however, include almost every train station in the Netherlands in this case.

The third recommendation concerns the link between spatial growth and decline and graph theory which has remained uncovered throughout this research. The previously 'dependent variable' linking spatial growth and graph theory is yet undiscovered. Therefore, a more detailed study on this subject in particular is required to understand this possible link.

7. Reflection

Throughout the process of this research, there have been several issues delaying the process. First and most important is the moment of starting writing this thesis. This moment brought me some problems since I started writing this thesis prior to some crucial courses of my study. Therefore, I had only limited knowledge about some of the important theories of planning. In retrospect, I could catch up on these parts after finishing the courses but it increased the workload towards the end of the process considerably. An exciting part in my point of view, while writing this thesis, was the data part. Since there was only limited research done on this topic, there was a lot of experimenting and puzzling to obtain valuable information. However, once the framework and the guidelines were identified, it became a lot easier for the subsequent cases because I did not have to reinvent the wheel again every time. In hindsight, it would have been easier to identify the guidelines before experimenting with networks. However, if I would have done that, some insights might have been left out or overlooked.

With regards to the conclusions, the research did not really go where I thought where it would have gone initially. Linking the networks to theories of transportation planning proved to be quite difficult. This resulted in a somewhat unbridgeable dichotomy of theory on the one side and data on the other side. After completing the first draft I discussed with my supervisor about the validity of my research question. Throughout the process, a different point of view was taken focusing more on getting a framework than explaining spatial growth and decline. Therefore, the research question was no longer representative for the research and had to be adjusted to match the content of the research in a proper way.

Nevertheless, I am satisfied with the results identifying a framework to apply graph theory to networks on a larger scale. Moreover, contriving a new method combining several derivatives of graph theory proved to be a challenge for me to be creative. Therefore, I am contented with the results in the end although the results deviate from my initial expectations.

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