Evolution of public transit networks in polycentric urban regions

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Evolution of public transit networks in polycentric urban regions

Thesis to obtain the degree of Master of Science

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Preface

This thesis concludes my time as a student at TU Delft and forms the last step to conclude the master's program Transport & Planning. My interest in this topic was mainly sparked by my interest in public transportation. While searching for a suitable topic, Oded Cats introduced me to the Master Thesis of Alex Vermeulen and sparked my interest into combining public transportation with network science. To combine this theoretical topic with practical applicability, Royal HaskoningDHV provided me with the opportunity to conduct my research at their company.

Therefore, I would first like to thank Royal HaskoningDHV for providing me with this opportunity. I would also like to thank my colleagues, who have made it very pleasant for me to work at the office and who taught me a lot about trains during my time there. I have now also been offered and accepted the opportunity to continue at Royal HaskoningDHV as employee and am therefore very grateful to the company.

There are also some people I would personally like to thank. First and foremost, I would like to thank Oded Cats for helping me since day one to find a suitable, challenging topic that lies within my interests and helping me shape this thesis. You were always available for any questions I had, no matter if you were at the TU, in Athens, Washington or wherever. During our meetings your feedback was always constructive and has always helped me move forward during these past months. The second person I would like to thank is Barth Donners. I always enjoyed our meetings and the enthusiasm you showed for this research, despite it not being something you typically work on. I truly believe your ideas and feedback have helped me move forward and improve this thesis. Thirdly, I would also like to thank Martijn Warnier. Especially your advice on how to improve things in the model have helped me save a lot of time. Despite that we only had a few meetings together, the enthusiasm you showed for the progress I was making motivated me to keep moving forward. Lastly, I would of course like to thank the chair of my thesis committee: Serge Hoogendoorn. Your comments during our meetings have always been very helpful and help me see things differently. To my entire thesis committee: I am truly grateful for all your help.

Furthermore, I would like to thank Alex Vermeulen for helping me understand his model and providing me with insights into difficulties he ran into, as his model also forms the basis of the model I developed.

Lastly, I would like to thank the people that have been there for me outside of working hours. Firstly, I want to thank my parents for supporting me these past years during my time at TU Delft. I would also like to thank my girlfriend Robin and my friends for providing me with the necessary distractions when I needed them.

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Summary

Background and research objectives

In the coming 30 years, it is expected that there will be a growth in mobility and population in the Netherlands. This growth is expected to be especially pronounced in the Randstad area, which can be characterized as a polycentric urban region. There are however uncertainties as to where this growth will be most prominent within the Randstad, which may lead to changes in travel demand patterns. Besides this potential change in travel demand distribution, there are also increasing trends towards automated vehicles. In the future it is also expected that vehicle automation will also happen in public transportation. The use of automated vehicles in public transit networks is expected to bring along reductions in operational costs, mainly due to the reduction in staff.

To gain insight into how the changes in operational costs and travel demand distributions may affect the future evolution of the public transit network in the Randstad in 2030, it is desirable to understand how these variables generally affect the evolution of a public transit network in a polycentric urban region such as the Randstad. While research has been done on network evolution, there is very limited research available on network evolution in polycentric urban regions specific. This research aims to fill this knowledge gap.

Considering polycentric urban regions in general, it is found that these regions can vary in terms of their spatial structure. This makes it important to also consider various 'types' of polycentric spatial structures. Furthermore, it is important to also consider multiple public transit modalities within the network. For different public transit network levels, different types of public transit modalities operate most optimally based on the distances to be covered. As there are various types of polycentric spatial structures in which the distances to be covered vary, it is also important to consider multimodality within the public transit network.

The main objective of this research is therefore to gain insights into how the spatial structure, travel demand distribution and operational costs in a public transit network with multiple modalities have an impact on the topological evolution of this network in a polycentric urban region. To help reach this objective, the following main research question was posed:

> *When considering a polycentric urban region, what is the impact of the spatial distribution of nodes, the travel demand distribution and the operational costs on the topological evolution of a public transit network consisting of multiple transit modalities?*

The secondary objective of this research is to investigate how current predictions on the future travel demand in the Randstad area have an impact on the topological evolution of its PT network.

To find the required answers, a network evolution model was developed. This model was used to investigate how the various aspects have an impact on the topological evolution of such a network and was also applied to the Randstad PT network.

Network evolution model

The framework of the network evolution model is shown in Figure 1 on the next page. The main components of this framework are the input, initialisation phase, evolution phase and output. Based on the provided input, an initial network is generated and the trips between each node pair is determined in the initialisation phase. The input consists of spatial structure parameters which

determine the spatial structure of the urban area, the demand distribution function and the various mode attributes of the public transit modalities that operate in the generated network.

Hereafter, the evolution of the public transit network in the generated network starts. At each iteration the model looks for all possible investments that can be made into expanding the existing network or by increasing the frequency of existing links, referred to as bulking.

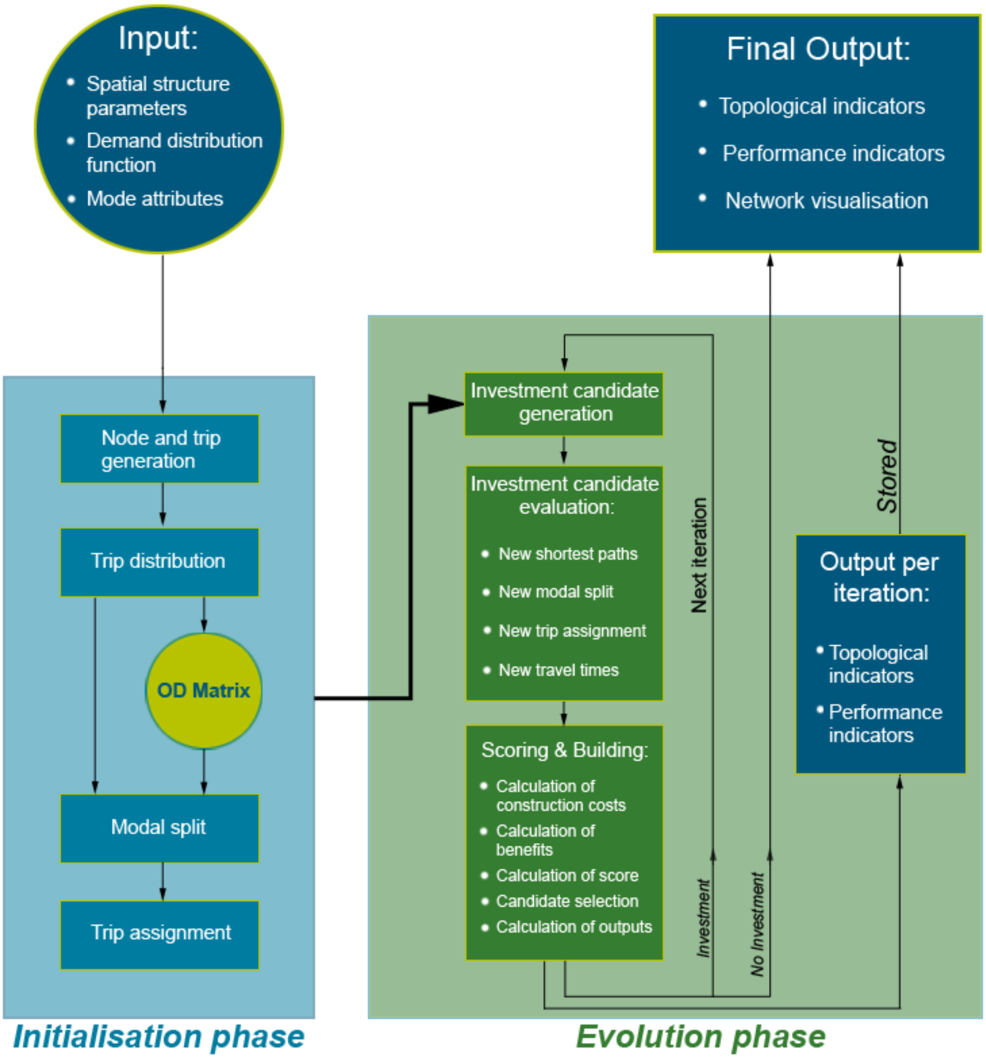


Figure 1: Flowchart of the model framework

For each of these investment candidates, the model calculates the costs associated with the investment and the benefits that the investment will provide. The costs of investments consist of infrastructure, rolling stock and operational costs. The benefits are based on travel time gains in the entire network and are also translated into a monetary value. Both costs and benefits are discounted over a period of 30 years. Based on the calculated costs and benefits, the investment score is determined by taking the ratio between benefits and costs. The scores of each investment candidate are then compared to each other and the highest scoring investment is then invested in, under the condition that this score is above 1.0.

After every iteration, if an investment is made, the network is updated and selected topological and performance indicators are calculated and stored. When the highest scoring investment candidate is below 1.0, no investment is made and the evolution phase is ended. The last step of the model is to calculate various indicators and present a visualization of the generated public transit network.

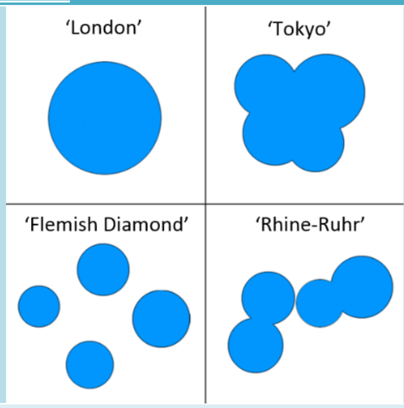
Numerical experiments

To investigate how the various aspects named in the main research question have an impact on the topological evolution of such a network, a number of numerical experiments were conducted.

14 scenarios were designed for these numerical experiments, each with variances in spatial structure, demand distribution, operational costs and multimodality. For each variable, the following specifications are made:

Table 1: Scenario variables and their specifications

Variable	Specification
Spatial structure	• 'London' prototype • 'Tokyo' prototype • 'Flemish Diamond' prototype • 'Rhine-Ruhr' prototype
Demand distribution	• Uniform • Linear • Exponential
Operational costs	• Non-automated vehicles • Automated vehicles
Multimodality	• Multimodal • Unimodal



The specifications of the spatial structure prototypes are based on distinct structures of polycentric urban regions. The names correspond to the city or region in which this structure is found.

For the demand distribution, three types of functions are identified: a uniform distribution, a linear decay from the CBD and an exponential decay from the CBD. In terms of operational costs, the distinction was made between non-automated vehicles and automated vehicles. For automated vehicles it is assumed that the operational costs decrease by 35%. Finally, a distinction is made between multimodal and unimodal. In the multimodal situation, the public transit network consists of three modes: agglomeration, regional and interregional. Each mode has a different service area, where agglomeration mainly serves local trips while the interregional serves long distance trips. For the unimodal situation, it is assumed that only the agglomeration mode operates within the public transit network. Each scenario has a four letter name based on the first letter of the spatial structure, demand distribution, operational costs and multimodality in that order.

The visualizations of all generated networks in the numerical experiments are shown in Figure 2.

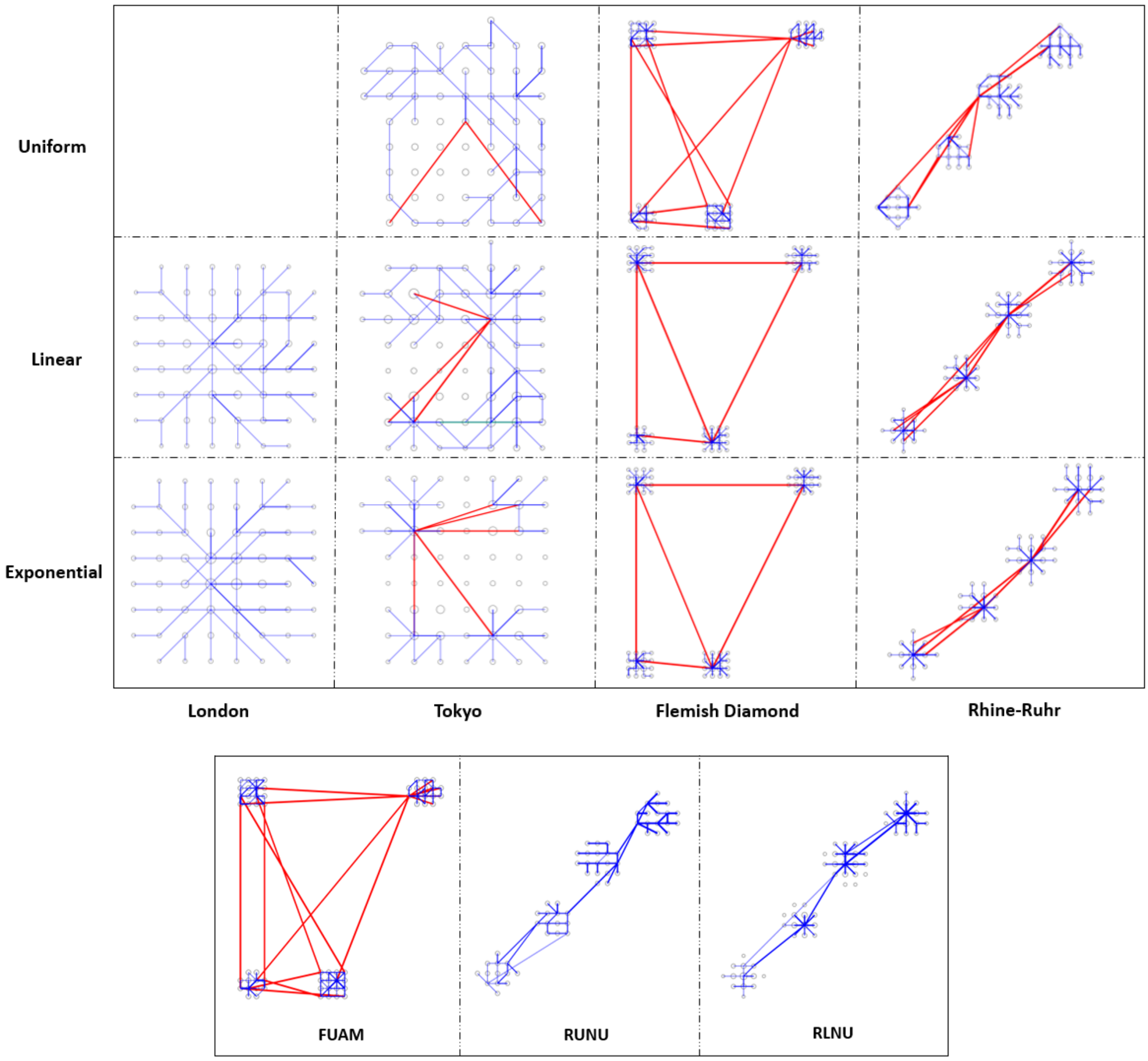


Figure 2: The networks generated for the 14 scenarios of the numerical experiments

The main impact(s) that the four variables have on the topological evolution of the networks are the following:

Impact of spatial structure:

- The evolution phases observed
- The type of mode that is invested in
- Emergence of hierarchy among nodes

Impact of demand distribution:

- Emergence of hierarchy among nodes

Impact of operational costs:

- Length of the evolution process

Impact of multimodality vs. unimodality:

- The evolution phases observed

Case study: Randstad area

After the numerical experiments were conducted, the network evolution model was also applied to the Randstad area. This was done to investigate how future predictions regarding the travel demand in the Randstad impact the topological evolution of the current Randstad public transit network. First the network which is considered was determined: the national Dutch railway network, the RET metro network and parts of the HTM tram network and GVB metro network. The modes assumed to operate were the High Speed Line (HSL), Intercity (IC), Sprinter (SP) and LRT/Metro (LM). The considered network with corresponding modalities is shown in Figure 3.

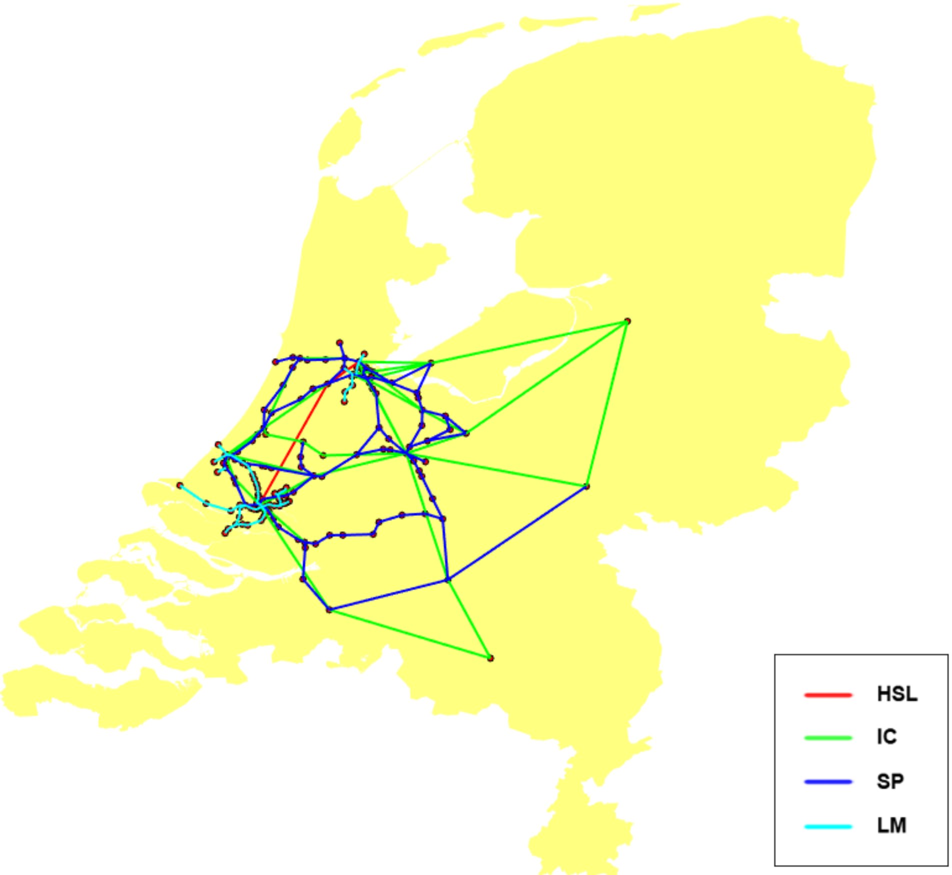


Figure 3: The considered Randstad public transit network with distinguished public transit modalities

The demands were based on the interzonal origin-destination (OD) data on public transit and car trips for the high-scenario of 2030, which was extracted from the 'Verkeersmodel Metropoolregio Rotterdam Den-Haag' (VMRDH). These interzonal OD's were aggregated to the stations in the public transit network.

After application of the network evolution model, there were 17 investments made in the Randstad PT network. The most notable investments are the following:

- Densification of the tram network in Den Haag by connecting Den Haag HS to Den Haag, Spui.
- Bulking of IC links between Zwolle and the central Randstad area.

In general, the limited number of investments made indicates that the PT network in the Randstad is already in a 'mature' state for serving the high-scenario demand anticipated in 2030. In terms of the topology and performance of the Randstad PT network, the investments that are made in the evolution process barely impact the existing network. The main impact is the reduction in total user costs.

Conclusions

Considering the main and secondary research objective, the following conclusions are made. Firstly, an answer is found to the main research question:

> *When considering a polycentric urban region, what is the impact of the spatial distribution of nodes, the travel demand distribution and the operational costs on the topological evolution of a public transit network consisting of multiple transit modalities?*

The spatial distribution of nodes, travel demand distribution and operational costs all have an impact on the topological evolution of a multimodal PT network. These impacts however differ in terms of their intensity and in terms of what they have an impact on. These differences can mainly be found in the various evolution phases that occur in each scenario. The most notable differences are observed for different types of spatial structures.

The spatial structure determines how the network physically evolves and has an impact on the emergence of hierarchy among nodes in the network. The demand distribution mainly has an impact as to which nodes become better connected to the network and the operational costs mainly impact the amount of investments that are made in the network. Unimodal systems also show a specific pattern in evolution phases, regardless of the spatial structure and demand distribution. For multimodal systems, the evolution pattern is however more dependent on the spatial structure.

Regarding the secondary research objective, insights have been gained into how current predictions on the future travel demand in the Randstad area have an impact on the topological evolution of its PT network. While there were a number of limitations to this method, it is believed that this first step into the application of the network evolution model in practice has provided insights as to how it can be improved further for it to be used in practice. It is furthermore believed that such network evolution models could be used in an early stage of the planning process of networks in general. In this early stage it is possible to apply such a model for a quick-scan to gain insights into where the network could potentially be improved in the future.

Scientific contributions

- *The impact of spatial structure on the topological evolution of a network*: This research and the developed model provide insights into the impact of spatial structure on the topological evolution of a network and may form the basis for future research.
- *The impact of multimodality on the topological evolution of a network*: This research and the developed model provide insights into the differences in the topological evolution of a multimodal versus a unimodal network and may form the basis for future research.
- *Sensitivity of network evolution*: This research provides initial insights into how sensitive the topological evolution of a network is based on the initial assumptions made. This research and the developed model may form the basis for future research into this relationship.

Practical contributions

- *Initial insight into future evolution of Randstad PT network:* Based on demand predictions for 2030 and the developed network evolution model, a number of potential future investments in the Randstad PT network have been identified.
- *Applicability of network evolution model in practice:* With the application of the model to the Randstad PT network, several limitations of applying the model to practice have been identified. This provides insights as to what could be changed for future application of the model to other networks in practice.

- *A tool for decisionmakers*: The model which is developed is expected to be of use for decisionmakers as it can function as a quick-scan tool that roughly determines the CBA for multiple potential investments. More steps will be necessary for it to realistically be applied in practice, but the first steps into this direction have been taken in this research.

Discussion and recommendations

The network evolution model in its current state consists of a number of constraints and simplifications made in certain calculations and assumptions. Removing these constraints and simplifications could improve the accuracy of calculations made in the model. The most notable constraints and simplifications are the following:

- *Shortest path calculations:* The current algorithm used, only considers the in-vehicle time for determining the shortest paths. Including the waiting times and transfer times in the algorithm is expected to lead to more accurate calculations in certain situations.
- *PT mode ranges:* Each PT mode could only connect node-pairs if the distance between these pairs was within a certain range of values. While this was done to save a significant amount of computational times, it does limit the freedom of the model to find investment candidates.
- *PT mode candidate nodes:* For higher-level PT modes another assumption was made to reduce computational times. By only considering the most populated node within a cluster of nodes as a candidate node, it is expected that hierarchy towards these nodes was slightly steered especially at the start of the evolution process.
- *Decision rule for evolution:* The decision rule for the evolution of the network is based on a simplified CBA function. It is possible that other types of decision rules may provide different results.

Besides removing these constraints and simplifications, there are also a few improvements to be made to make the model more applicable in practice. These improvements are mainly to ensure more realistic calculations rather than generalized calculations as is currently the case:

- *Line operations:* The addition of line operations means that within a certain mode, passengers will have to make additional transfers as well. This addition would make the model more realistic as in practice networks also consist of multiple lines. This is expected to lead to more realistic travel times, as transfers and waiting times would then be calculated more accurately.
- *Physical constraints:* By adding physical constraints, the costs and benefits of each potential link would be calculated more accurately.
- *Crowding effects:* Including crowding effects is expected to lead to more realistic benefits.
- *Access and egress costs:* As the coverage area of stations differ in practice, the addition of access and egress costs is expected to provide more realistic travel time calculations.

As it was found that the network evolution is sensitive to the input of the model in terms of parameters and the initial network. It is recommended to do further research on this aspect as this may significantly influence the findings of this research.

It is also recommended to further investigate the relation between multimodality, spatial structure and network evolution. There is limited research into the relation between these three aspects and the model developed during this research is expected to be a good tool to do further research into this topic.

Following the previous point, it may be desirable to develop this model with another program than Matlab. The simulation times per scenario were currently between 8 and 24 hours which was acceptable for the purpose of this research. However, if further research is done into the relations discussed on the previous page, it may be desirable to reduce computational times as it is expected many simulations would have to be run.

Furthermore, it is recommended to further test the applicability of the model by applying it to other types of networks as well. Examples of other types of networks are the European rail network, aviation network or the metro network in a city. These applications can provide further insights to help improve the model further for practical application.

Lastly, it is recommended to test other decision rules than the simplified CBA which is applied in the current model. Additional factors such as environmental effects could be implemented to represent a CBA which is more common in practice. While this is a recommendation to improve the model itself, it also makes the results of the model more realistic.

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1. Introduction

Every year the Netherlands is growing in multiple aspects. Based on a prognosis made by CBS (2016) up to the year 2030, the population in the Netherlands will keep growing. This growth in population is expected to be especially strong in the larger cities in the Randstad area, while in the more rural areas a decrease in population is expected. The Randstad area is typically characterized as a polycentric urban region (Kloosterman and Lambregts (2009); Van Der Heijde (2012)), where Amsterdam, Rotterdam, The Hague and Utrecht are the main cities in this region. Besides the growth in population, mobility will also keep growing. As stated in a document drafted by the Rijksoverheid (2016) on the Public Transport 2040 Vision (Toekomstbeeld OV 2040) in the Netherlands, there will also be a growth the coming years in the passenger flows on both the road- and public transport-networks. Furthermore, there are technological and social developments which are expected in the coming years and one of these is the increase in automation among modalities such as buses, trains and cars. While it is unclear how the increase in level of automation among these modalities will develop over the coming years, there are already multiple metro systems worldwide which are defined by grade of automation level 4 (GoA4) as shown in a report drafted by UITP (2016). GoA4 means that these systems are fully automated without any staff on board. Furthermore, it is reported that a strong growth in GoA4 metro systems is expected by 2025 where the growth is mainly expected in Europe, the Middle East and Asia. In line with these expectations, it is possible that in 2030 the rail-bound public transit (PT) systems in the Netherlands are also fully automated. At the same time ProRail has announced on their website ProRail (2017a) that tests will be conducted on automated trains with GoA2 for freight transportation in 2018. While it may be unrealistic to expect the entire train network to be functioning with GoA4 in 2030, it is clear that a trend towards this development has already started. The automation of vehicles in public transportation is expected to bring along a change in how the operational costs are built up Bösch *et al.* (2017).

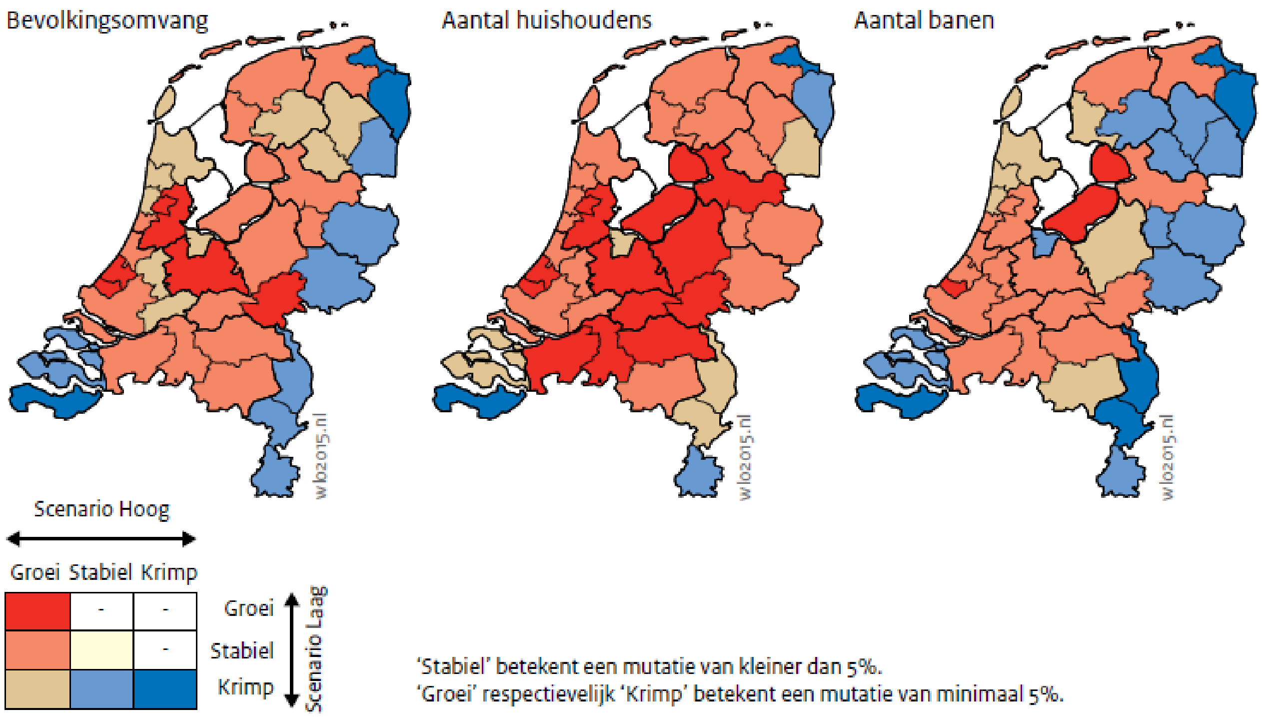

Figure 1.1: Expected growth in population, households and number of jobs in the Netherlands by 2050; respectively from left to right (PBL and CPB (2015))

Regarding the growth in population, households and jobs, Figure 1.1 shows where growth is expected within the Netherlands by 2050 based on research conducted by PBL and CPB (2015). There is however uncertainty in these predictions and it is therefore not entirely clear in what manner the cities in the Randstad may expand further in the future. It is for example possible that the outer areas of these cities may grow relatively more than the central areas, or vice versa. These growths can lead to different types of travel patterns, where more trips might be made to and from the central areas or perhaps the central areas become more relieved and there are more trips to and from the more outer areas. Certain cities may also grow more rapidly than others, possibly leading to a relatively larger increase in trips to and from these faster growing cities. This means that the current travel demand distribution within the Randstad area may potentially change.

The remainder of this introductory chapter first consists of the problem statement in which the research objective and research questions are posed in section 1.1. Hereafter, the research scope is described in section 1.2 and finally the research approach and report outline are discussed in section 1.3.

1.1 Problem statement

To gain insights into how the potential changes in operational costs and travel demand distributions may affect the future evolution of the PT network in the Randstad in 2030, it is desirable to understand how these variables generally affect the evolution of a PT network in a polycentric urban region such as the Randstad. While research has been done on network evolution, there is very limited research available on network evolution in polycentric urban regions specific. Besides the impacts that travel demand distribution and operational costs have on network evolution, it is found that also the spatial structure of the polycentric urban region and the consideration of multiple PT modalities are important aspects to incorporate in the research. The importance of these two additional aspects will be elaborated further in chapter 2.

1.1.1 Research objective

The main objective of this research is therefore to gain insights into how the spatial structure, travel demand distribution and operational costs in a PT network with multiple modalities have an impact on the topological evolution of this network in a polycentric urban region.

The secondary objective of this research is to investigate how current predictions on the future travel demand in the Randstad area have an impact on the topological evolution of its PT network.

To reach these objectives, the choice is made to develop a network evolution model which can provide the necessary insights.

1.1.2 Research questions

In order to reach the research objective, an attempt has been made to find an answer to the following main research question:

> *When considering a polycentric urban region, what is the impact of the spatial distribution of nodes, the travel demand distribution and the operational costs on the topological evolution of a public transit network consisting of multiple transit modalities?*

This main research question consists of multiple aspects. To fully answer this research question, the following sub-questions are posed; of which some again consist of their own sub-questions:

1. *What network indicators can be used to quantify the topological evolution of a public transit network in a polycentric urban region?*

2. *What is the impact of the spatial distribution of nodes in a polycentric urban region on the topological evolution of a public transit network?*
   - *What are the parameters that can be used to describe the spatial distribution of nodes in a polycentric urban area?*

3. *What is the impact of travel demand distribution in a polycentric urban region on the topological evolution of a public transit network?*

4. *What is the impact of operational costs on the topological evolution of a public transit network in a polycentric urban region?*
   a. *What are the operational cost variables that are mode-dependent?*
   b. *What is the effect of vehicle automation on the operational costs?*

5. *When considering a polycentric urban region, what is the impact of the consideration of multiple transit modalities on the topological evolution of a public transit network opposed to the consideration of a single modality?*

Regarding the secondary objective of this research, an additional research question is posed:

> *Considering the current future predictions on travel demand in the Randstad area in 2030, what is the impact of these predictions on the topological evolution of the current public transit network in the Randstad area?*

1.2 Research scope

To set certain boundaries and define certain terms, the following assumptions and definitions are made:

Assumptions

There is a strong relationship between transport and urban growth (Aljoufie *et al.* (2011)). In this research however, it is assumed the urban areas are already in a certain state and do not evolve further as the PT network evolves. Only the PT network evolves based on a certain travel demand in the region which also does not change over the course of the network evolution process.

Polycentric can be in terms of different aspects (Smith (2011)). In this research, the polycentric urban region is considered to be polycentric with regard to the spatial structure aspect. The definition of a polycentric urban region is given below.

Definitions

- *Polycentric urban region:* a region in which there are multiple centers of activity or multiple cities of similar in size, which are located in close proximity and strongly linked. This definition is based on what is found in literature and will be further discussed in the following chapter.
- *Node:* representation of a PT station.
- *Link:* representation of a PT connection between two nodes.
- *Evolution:* topological evolution (emergence of new links between nodes); not evolution of transport services.

1.3 Research approach

An outline of the research approach is shown in Figure 1.2, which is divided into 5 main parts. For each part, the corresponding chapter(s) in the report are indicated. Firstly, the literature review is presented in chapter 2. This literature review provides the basis for the development of the network evolution model and scenarios for the numerical experiments, which are discussed in chapters 3 and 4. Hereafter, the results of the numerical experiments are synthesized in chapter 5. Besides applying the model to the numerical experiments, it is also applied to the Randstad PT network for a case study. This is done to gain insights into potential future evolution of the network, as well as to investigate the applicability of the model in practice. This case study is covered in chapter 6. Finally, based on the results of the numerical experiments and the case study, the conclusions of this research and recommendations for future research are discussed in chapter 7.

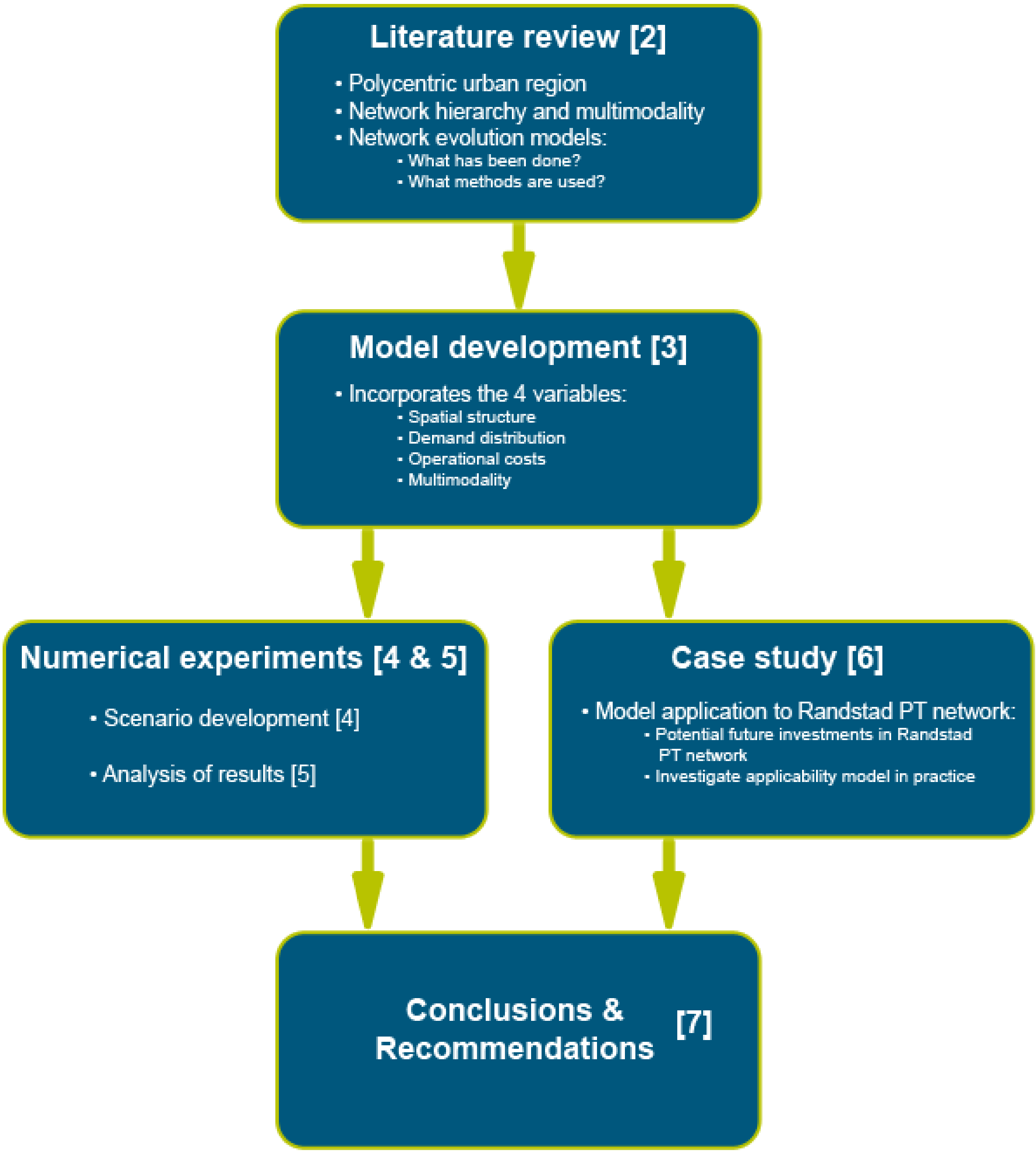

Figure 1.2: Outline research approach where numbers correspond to the respective chapter in this report

2. Literature review and contributions

As stated in section 1.1, it is important to first understand what a polycentric urban region is and how it relates to a PT network within such an area. Furthermore, it is important to know if similar research has been conducted in the past. This chapter will cover these aspects in order to identify the research required.

2.1 Polycentric urban regions

Polycentric urban regions have become one of the defining characteristics of the urban landscape in advanced economies (Kloosterman and Musterd (2001)). Similarly Meijers, Hollander and Hoogerbrugge (2012) estimate that almost half the urban population in Europe lives in polycentric metropolitan areas when conservative standards are used. They state that polycentric metropolitan areas are becoming the dominant urban form in Europe. The question however arises as to what the definition of a polycentric urban or metropolitan area is.

Kloosterman and Musterd (2001) define metropolitan areas as polycentric when they have the following characteristics:

- They consist of a number of historically distinct cities
- They lack a clear leading city which dominates in political, economic, cultural and other aspects
- They tend to consist of a small number of larger cities that do not differ much in size or overall economic importance
- These cities are located in more or less close proximity and are thus concentrated in one specific part of a country
- They are not only spatially distinct, but also constitute independent political entities

Lambregts (2009) found several definitions for a polycentric metropolitan area. While some definitions focus on morphological aspects, others focus more on relational, administrative and socio-cultural factors. As this thesis is focused on the topological evolution of PT networks, a definition that focuses on morphological aspects is most relevant to highlight. In this sense, a metropolitan area can be considered polycentric when there are multiple centers of activity in a given area.

Regarding the wording of a polycentric area Meijers, Hollander and Hoogerbrugge (2012) found that in past literature, there are various names that are used to reflect the concept of polycentricity. The names 'networked cities', 'the Regional City', 'Global City Regions', 'polycentric urban regions', 'megalopolitan areas', 'polycentric mega-city-regions' and 'polycentric metropolis' are the most well-known. One thing that they found however was that all these concepts consider two important aspects, namely polycentricity and strong linkages between centers.

Based on these findings, a polycentric urban region can be characterized in a morphological sense with the following characteristics:

- It consists of multiple centers of activities or multiple cities that do not differ much in size
- The centers or cities are located in more or less close proximity
- The centers or cities are strongly linked

When considering the spatial structure of polycentric urban regions, one of the complexities regarding a 'polycentric urban region' is that polycentricity has a broad definition in terms of spatial structure. Meijers, Hollander and Hoogerbrugge (2012) show that a polycentric region has differently identifiable structures. They state that polycentric regions have two ways of evolving: the first is the incorporation mode where dominant cities extend their influence outwards and 'incorporate' the smaller cities around the dominant cities. The second is the fusion mode where multiple independent cities merge into one area. As these regions continue to evolve, they eventually become a polycentric metropolitan area. Figure 2.1 shows the visualization of the different phases for both modes.

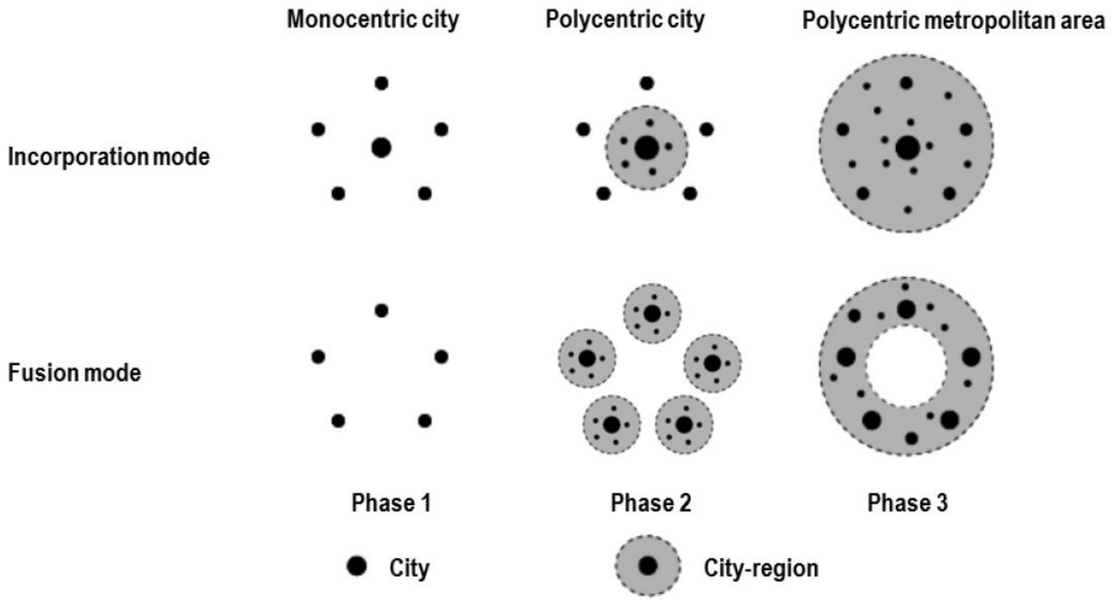

Figure 2.1: Evolution of polycentric metropolitan areas (Meijers, Hollander and Hoogerbrugge (2012))

To compare these visualizations with real examples, a city such as Tokyo could be defined as a polycentric metropolitan area in the incorporation mode (top right image in Figure 2.1), while the Rhine- Ruhr area in Germany is comparable to something between the bottom middle and top right image and the Randstad area is more comparable to a shape somewhere between the bottom middle and bottom right image. These comparisons can be made on a large scale within the entire urban areas, while it is also possible to compare these visualisations on a lower level. For the Randstad example, on the larger scale of an urban area, one of the city-regions could be for example The Hague. The smaller dots within this city-region could for example represent Scheveningen or Rijswijk. When these visualisations are compared to real examples on a lower scale, the evolution of the city-regions such as The Hague can be characterized as incorporation mode. As there are different types of polycentricity, which vary due to the manner of clustering of different areas/cities, and there is not one clear definition for a polycentric urban region, it is important that multiple types of polycentricity are considered when speaking of a polycentric urban region.

2.2 Network hierarchy and multimodality

Besides the complexity of the exact definition of what a polycentric urban region is, when a PT network in such an area is considered there are additional complexities regarding multimodality and network hierarchy.

In a multimodal PT network, depending on the area to be covered there are different types of modalities which are most suited to serve these areas. Van den Heuvel (1997) shows that for different types of linking systems (e.g. conurban, regional, national) there are different modalities of PT which are most optimal based on the features: class of travel distances, average speed, average distance between stops and frequency of the modalities. This suggests that for a polycentric urban region it is important to consider multiple modalities within the PT network as the above-named features will vary in different types of polycentricity and thus the most suitable PT mode can differ for connecting certain areas. Other research also showed that some of the above named features can determine what PT mode is most optimal to serve certain areas based on costs. Tirachini, Hensher and Jara-Díaz (2010) developed a model to compare the operational costs of LRT, heavy rail and BRT. For this study, they assumed an operation that aims to minimize the total costs, which consist of both the operator- and user costs. They found that BRT is generally the most cost-effective mode, mainly due to the lower operational costs, access time costs and waiting time costs. However, when a higher operational speed is considered for LRT and heavy rail these modes become more cost-effective compared to the BRT. Based on this study it can be concluded that the most cost-effective mode depends on the assumptions made for the decision variables.

Van Nes (2002) also states that different types of modes are most suitable for different distances, but lays more focus on network hierarchy in his research. He found that hierarchy in transport networks can be seen as a natural phenomenon. For the case of line-bound PT networks he found that the hierarchy among modalities in such networks is determined by the hierarchy in spatial structures. The network consists of multiple network levels in which a higher-level network is suited for covering longer distances and a lower-level network is suited for covering shorter distances and provides access to the higher-level network. This in turn affects which modality would be most optimal to connect certain areas. In other literature where the focus was more on network hierarchy, Yerra and Levinson (2005) and Levinson and Yerra (2006) make use of a model to show that for road networks, a hierarchical structure can form within the network due to self-organization. While hierarchies seem to be designed by planners and engineers, their results show that hierarchies are intrinsic properties of networks. This is in line with the earlier statement that hierarchy in transport networks can be seen as a natural phenomenon. Furthermore, Louf, Jensen and Barthelemy (2013) looked at growths of spatial networks, based on cost-benefit analysis. Based on their model results they found that spatial hierarchy emerges in structures in a certain intermediate regime. In this intermediate regime, they assume the costs and benefits to be of the same order of magnitude. After estimating important parameters for various world railway networks, they found that these networks all fall in the intermediate regime. This suggests that spatial hierarchy is a crucial feature in all these networks and possibly possesses an important evolutionary advantage.

From these past studies, it can be concluded that the spatial structure of a polycentric urban region has an impact on the network hierarchy in the PT network. While hierarchy in the network is a natural phenomenon, it is also linked to hierarchy in modalities. Different modalities are most suitable based on the distances to be covered and therefore operate on different network levels. The spatial structure of a polycentric urban region determines the hierarchy in these network levels, and thus the hierarchy in modalities. This underlines the importance of considering multimodality in the PT network in a polycentric urban region, where the spatial structures can vary as was shown in section 2.1.

2.3 Network evolution models

It is important to review past research on network evolution models. Not only to gain knowledge on what has been done in the past, but also to gain insights into different modelling methods that have been applied to simulate network evolution.

Firstly, two literature reviews are considered, after which a number of relevant network evolution models are highlighted. It is important to note that not much research has been done into network evolution models. Barthélemy (2011) provided an extensive review on research done into spatial networks and found that evolution of transportation (and spatial) networks was still a problem that was not very well understood. It was concluded that theoretical ideas and models to describe the evolution of spatial networks should be developed. Another relevant literature review was conducted by Xie and Levinson (2009a). They provided a review on the progress that has been made up to 2009 in modeling and analyzing the growth of transportation networks. In this review, they give an overview of network growth studies that follow five main streams: transport geography, optimization and network design, empirical models of network growth, economics of network growth and network science. Starting with limited modeling efforts using heuristic and intuitive connection rules, research methods have evolved into adapting concepts of preferential attachment and self-organization from natural science. As was also found by Barthélemy (2011), there are not many models to describe the evolution of spatial networks.

One model on network evolution that is notable from the literature review however, is the study conducted by Xie and Levinson (2009b). They studied the topological evolution of surface networks, and what is most interesting about this study, is the manner in which the network evolution is modelled. The model they use assumes a fully connected network in which a degeneration process is then started. The links which are more valuable are reinforced while the less used ones shrink and are eventually removed. As the network evolves over time in this simulation model, they also evaluated the temporal change of various topological attributes during the evolution process. Similarly, Verma *et al.* (2016) have studied the emergence of core-peripheries in networks and developed a model to study this. In their model, they also apply some sort of degeneration process of the network which they call network pruning. The links in an initial fully connected network are iteratively pruned based on removal of underutilized links and the load over a pruned link is then redistributed through the next shortest path. A third study on network evolution which uses a model that includes a degeneration process is that of Schultz, Heitzig and Kurths (2014). They propose a growth model to create spatially embedded random networks, especially suitable for modelling power grids. This model first engages in an initialisation phase in which an initial network is formed based on minimizing costs, leading to a tree shaped network. Hereafter, the growth phase is engaged in which a trade-off is made between cost-optimization and redundancy. Besides the relevance of their method used to model network growth, they suggest that while their model is especially suited for modelling power grids, the concept of having at least two phases (initialisation and growth) is also suitable for modelling the growth of other types of infrastructure networks.

Besides models that use link removal methods, there are several notable studies that model the evolution of networks with link addition. Louf, Jensen and Barthelemy (2013) studied the emergence of hierarchy in spatial networks based on cost-driven growth. Within a grid consisting of uniformly distributed nodes they use cost-benefit-analysis (CBA) to iteratively add links between the nodes in order to simulate the growth of a rail network until all the nodes are connected. The network growth is however in a simplistic tree shape, as their focus is mainly on the emergence of large-scale structures. Lems (2017) studied the impact of PT infrastructure investment decision rules on the topological evolution of a PT infrastructure network. He has used a simulation model to investigate how different policies (objective functions) have an impact on the evolution of the network. The model starts without an initial network and new links are then built within the network, based on the decision rules. All possible links are evaluated and are assigned a score for each decision rule; the link with the most beneficial score is then determined and added to the network until there are no beneficial links left to be constructed. While the focus of this research is on the impact that different policies have on the evolution of the network, the method of modelling the growth provides interesting insights. The latest research into modeling network evolution was conducted by Vermeulen (2018). He has done similar research into how operational costs and travel demand distribution affect the topological evolution of monocentric ring-radial metropolitan public transport networks. Starting with a network of pre-defined nodes, the links within the network that connect the nodes to each other are iteratively added until there are no more benefits in adding new links.

Based on a cost-benefit analysis (CBA) function, after each iteration the most beneficial link is added to the network and various topological indicators are evaluated. While this research has similarities to this thesis, there are however a few aspects which this research does not consider that are important. In the model developed by Vermeulen (2018) multiple alternative modalities were considered, but these modalities were not simultaneously modeled meaning each simulation only considers one modality. As stated above, multimodality is however an important aspect in this thesis. Furthermore, while his findings apply to a monocentric network with a ring-radial structure, with a polycentric network there is not necessarily the specific case of a ring-radial structure. Due to the fact that when multiple agglomeration centers are considered in a polycentric network, there will also be the interaction between the different agglomerations as opposed to only within each agglomeration center. Due to these differences in spatial structure it is therefore expected that the findings of his research may not apply for a polycentric network.

2.4 Contributions

As stated in section 2.1, it is important to note that there are various types of polycentric networks in terms of spatial structures. Besides the importance of variance in spatial structure, multimodality is another important aspect that needs to be considered as was discussed in section 2.2. From the past models, there are however none that investigate the impact of different polycentric spatial structures, travel demand distribution and operational costs on the evolution of a network, while also considering multimodality within the network. The modelling methods from these past models do however provide insights for the proposed model. The two model-phases proposed by Schultz, Heitzig and Kurths (2014), the modelling methods for link removal and link addition and the model evaluation methods are notable points taken from these past studies.

The research conducted has several scientific and practical contributions. These are discussed in the following sub-sections.

2.4.1 Scientific contributions

The research conducted in this thesis, including the model which is developed, has several scientific contributions. Table 2.1 gives an indication of how the model developed during this thesis relates to research done in the past. As can be seen, not much research has been done with regard to modeling a PT network in a polycentric urban region. Similar to several past studies, the research focus of this thesis is on network growth.

In terms of network evolution methods, there are two types identified: link removal and link addition. While some models use link removal on a fully connected network, some models use link addition. Both methods could be used for the proposed model, however link addition is arguably a more realistic manner of network evolution as a PT network in the real world does not start from a fully connected state either.

The models from previous research are focused on node structures which are radio-centric or uniformly distributed. What is new in the proposed model is that it will be focused on polycentric node structures, while it can also consider other generic node structures such as a monocentric structure. In relation to the fact that the model will be focused on polycentric node structures, spatial distribution of the nodes will be important. That means that unlike the other models, this model will also take into account different spatial structures in which a network evolves. This is an addition that has not been proposed in previous found models. While Schultz, Heitzig and Kurths (2014) state that it is possible to have exogenous input with regard to the node structure, they do not focus on the relation between different structures and network growth. In their model it was more of an addition.

Table 2.1: Thesis in scientific context

Paper	Research focus	Network evolution method	Node structure	Varying node structure	Multimodal network	Method of evaluation
Xie and Levinson (2009b)	Relation between spatial hierarchy and network growth for varying pre-defined networks	Link removal	Uniform distribution with varying pre-defined networks	No	No	Topological indicators
Louf, Jensen and Barthelemy (2013)	Relation between spatial hierarchy and network growth	Link addition	Uniform distribution in square grid	No	No	Threshold values (to quantify hierarchy)
Schultz, Heitzig and Kurths (2014)	Network growth (for power grids)	Link removal	Uniform distribution in square grid	No, but possible	No	Topological indicators
Verma *et al.* (2016)	Relation between network pruning and emergence of core-peripheries in the network	Link removal	Uniform distribution around a sphere	No	No	Threshold values (for balancing connectivity and profit)
Lems (2017)	Network growth, investment decisions	Link addition	Equal node spacing in square grid	No	No	Topological indicators
Vermeulen (2018)	Network growth	Link addition	Radio-centric	No	No	Topological & performance indicators
This thesis	**Network growth**	**Link addition**	**Generic, monocentric or polycentric**	**Yes**	**Yes**	**Topological & performance indicators**

As it was found that multimodality has an important relationship with the spatial structure in a polycentric network due to the hierarchy in spatial structure, this model will also consider multimodality. This is an addition that has not been proposed in previous found models.

With regard to the evaluation method of the network growth in the model, similarly to most studies, certain topological and performance indicators are used. This is a useful method to quantify the network growth based on these indicators.

In comparison to similar research done by Vermeulen (2018), the main additions of this research are the consideration of different types of (polycentric) spatial structures and multimodality. While the focus in this past research was mainly on the impact of operational costs and demand distribution on network evolution, this thesis also focuses on the impact of the spatial structure and multimodality on network evolution.

2.4.2 Practical contributions

In a practical sense, this model should be able to give insights into how the PT network in the Randstad area could evolve in the future based on different predicted future scenarios for the Randstad.

Furthermore, the model should be able to function as a CBA tool to help decision makers. While traditionally each potential investment in a PT network is currently supported by individual CBA's, the model is capable of analyzing multiple investments simultaneously and roughly determining the costs and benefits of each investment. The model is expected to be of use as a tool for such a quick-scan to determine where a network can potentially be improved.

3. Network evolution model

To find answers for the posed research questions, a network evolution model has been developed during this thesis. Section 3.1 firstly describes the framework of the model and consist of a brief explanation of how it functions. Following the framework, the model assumptions are defined in section 3.2 after which the model inputs are discussed in section 3.3. Hereafter, the mathematical formulations of the model elements are given in section 3.4, and lastly the outputs of the model are described in section 3.5. In that section, the various topological and performance indicators used to evaluate the simulation results of the model are explained.

3.1 Modelling framework

The network evolution model developed during this thesis is built on the basis of the model which was developed by Vermeulen (2018), leading to a similar framework of the model. Furthermore, it is noted that a distinction is made in the two phases (initialisation and evolution) as also proposed by Schultz, Heitzig and Kurths (2014). The framework of the model is shown in the figure below.

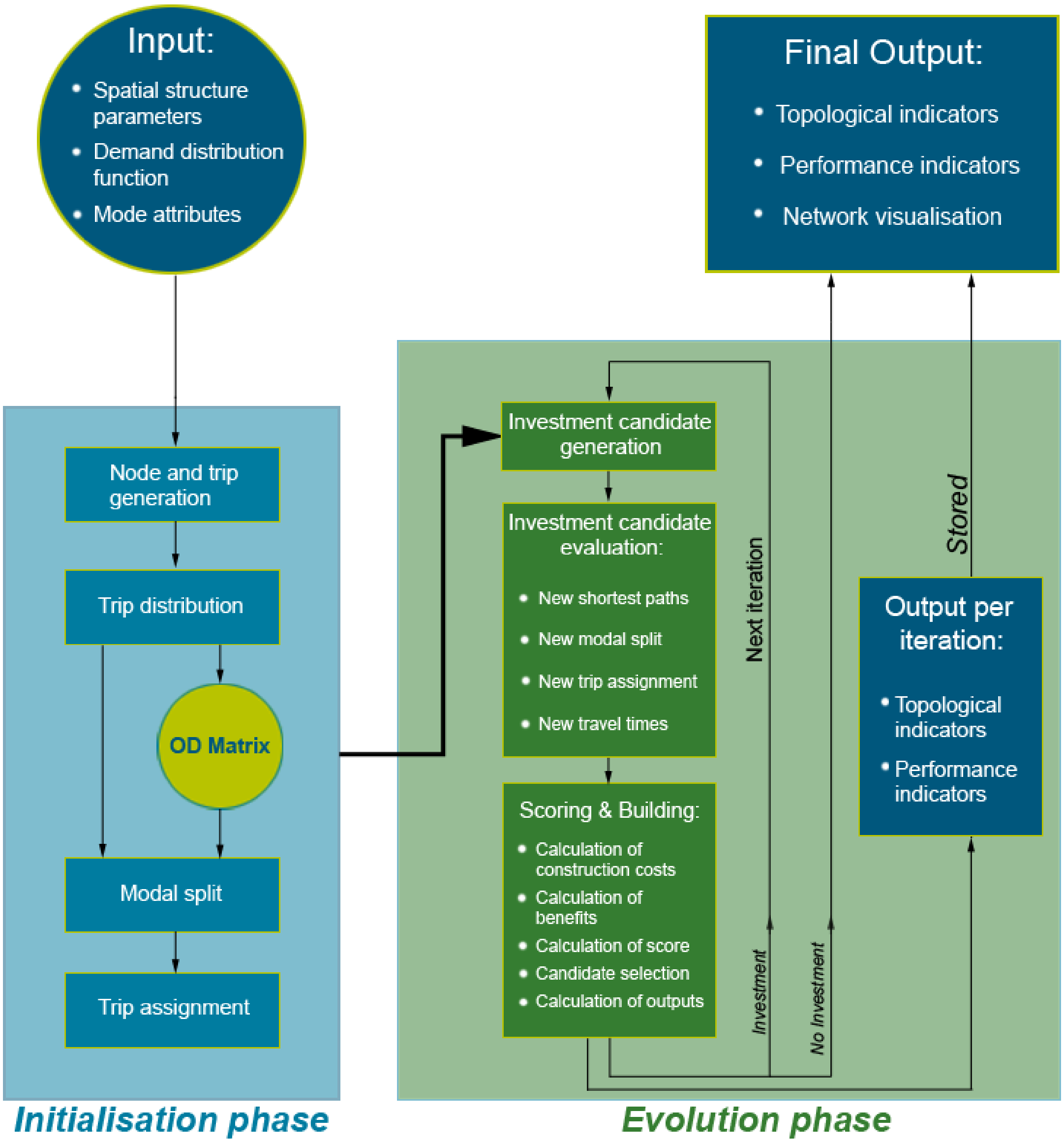

Figure 3.1: Flowchart of the model framework

As shown in Figure 3.1, the model is divided into four main parts which are discussed further in this chapter:

- Input (section 3.3)
- Initialisation phase (section 3.4.1)
- Evolution phase (section 3.4.2)
- Output (section 3.5)

The separate parts and the steps within each part that the model follows are briefly described as follows:

1. **Input**: The first step is to define the input for the model. The spatial structure parameters, demand distribution function and mode attributes are all exogenous inputs that the user must define. What these parameters and functions consist of exactly is described more in detail in section 3.3.
2. **Initialisation phase:** Based on the provided input, an initial network is generated and the trips between each node pair is determined in the initialisation phase. The initialisation phase consists of the following steps:
    a. **Node and trip generation**: Based on the spatial structure parameters and the demand distribution function, a set of nodes is generated which consist of certain populations. This is the initial polycentric urban region existing of one or multiple agglomerations in which the evolution of the PT network will occur. Simultaneously, the number of trips made to and from each node is determined.
    b. **Trip distribution:** Following the node and trip generation, based on the locations of the nodes, the trips generated and the mode attributes, the number of trips made between each origin-destination (OD) pair is determined by using a gravity model. This leads to the **OD-matrix** which is used for the following steps. This OD-matrix does not change over time.
    c. **Modal split:** Based on the initial network state, the modal split is determined. Here it is determined for each OD-pair what the portion of trips made by PT is, and what the portion of trips made by an alternative mode is. This alternative mode is seen as a type of personal modality that passengers have access to, such as car or bicycle.
    d. **Trip assignment:** After the modal split is determined, the next step is to determine the trip assignment. Based on the OD-matrix and the modal split, the trips made by PT are assigned over the existing PT network where travelers take the shortest path to their destination. This is done in one iteration, an All-or-Nothing assignment. This means that travelers do not take into account any capacity constraints that may exist and simply choose for the shortest path.
3. **Evolution phase:** After the initialisation phase, the initial network and the OD-matrix are used as a starting point for the network evolution. The evolution phase consists of the following steps per iteration:
    a. **Investment candidate generation:** Starting with the initial network, the most beneficial link to be constructed should be determined. The first step in this is to generate all possible candidates of links that can be constructed or 'bulked'. Bulking of a link means that the frequency on an existing link is increased. The candidate generation only considers nodes that are already part of the network (i.e. node degree ≥ 1) for the construction of a new link starting at these nodes. This is also in line with the theory of preferential attachment (Barabási and Albert (1999)). The concept of preferential attachment follows the assumption that the more connected

a node is, the more likely it is to generate a new link to another node. For bulking, naturally only the existing links can be considered as investment candidates.

b. **Investment candidate evaluation:** for each of the candidates generated in the previous step, it is evaluated how these investments would impact the network if they were to be invested in. Therefore, the shortest paths, modal split, trip assignment and travel times for each OD pair are recalculated.
c. **Scoring and building:** Based on the investment candidate evaluation, the most beneficial candidate is then invested in. The changes which are calculated in the evaluation part can potentially lead to benefits in terms of travel time gains. Besides the benefits, the investment also has certain construction costs. The ratio between benefits and costs is the investment score. All scores above 1.0 are beneficial and the highest scoring investment is then invested in. After this candidate is invested in, the network is updated. Certain topological and performance indicators are then also re-calculated for the updated network. If there are no investment candidates with a score above 1.0, the evolution process is stopped.

4. **Output:** After each iteration, the information on the chosen investment is stored. This includes the resulting topological and performance indicators. This is done to give insights into how the network has evolved over time. Hereafter, a new iteration is started and the model returns to the investment candidate generation step. If there is no investment made, the model stops and shows a visualization of the final network. The final output consists of the cumulative output stored after each iteration.

To verify that the network evolution model functions as intended, a number of tests and verifications were conducted. For this verification of the model, the reader is referred to Appendix A. As the model consists of separate modules, these are all verified separately with small datasets to ensure they work as intended. The validation of the model is difficult as there is no reference to compare the outcomes of the model with. The model has therefore been validated by expert judgement by looking at the plausibility of the model outcomes.

3.2 Model assumptions

While the research scope has been discussed in section 1.2, the developed model also follows certain assumptions and has certain boundaries. These are discussed in this section. The following assumptions have been made with regard to the model in general:

- The network representation is in L-space Berche *et al.* (2010). This is a representation in which each node represents a station and a link between the nodes is seen as a connection between the two stations in both directions, thus an undirected graph.
- This graph consists of a set of nodes N and links E.
- The demand in a node is assumed to be equal to the population in this node.
- Regarding the general assumptions made for travel time aspects, the following assumptions are made:
  - Similar to most traditional PT assignment models, the assumption is made that passengers arrive randomly and thus have an average waiting time of half the headway (Ingvardson *et al.* (2018)). The waiting time therefore relates to the frequencies of the modalities that are assumed.
  - Access and egress time are not considered in the model. It is assumed that passengers start and end their journey at a node.

- Passengers can only travel an entire route by PT or alternative mode. It is not possible to take PT for half and then use alternative mode. This simplification is made to reduce the number of route-choices to be calculated and thus the computational time.

- As stated in section 3.1 as well, the OD-matrix is not updated after each iteration. While it is quite realistic that the OD-matrix changes over time as the network grows, again to save computational time, the OD-matrix is determined beforehand and is not updated during the process of network evolution.
- While in reality, urban policies are related to PT network evolution (Smith (2011)), this model does not take different policies into account. The only form of policy that the model considers is incorporated in the CBA function, where return on investment calculations are considered. These follow from the guide to CBA of investment projects in the EU (Sartori *et al.* (2014)).

3.3 Model input

The different model inputs shown in the model framework in Figure 3.1 are discussed in this section. Each input is discussed separately in the following sub-sections.

3.3.1 Spatial structure parameters

The spatial structure parameters determine the spatial structure of the polycentric urban region in which the PT network evolves. The polycentric urban region consists of a number of agglomerations of certain sizes which are located at a certain distance from each other, and the agglomerations consist of a number of nodes with a certain distance between them. Therefore, there are four main spatial structure parameters identified that define the spatial structure of the polycentric urban region (Table 3.1). For networks with a pre-defined spatial structure these parameters are not used as the node coordinates can then be used as input.

Table 3.1: Description of the spatial structure parameters

Spatial structure parameter	Description
Agglomeration centers	The number of agglomeration centers that the polycentric urban region consists of
Separation between centers [km]	The separation between agglomerations
Distance between neighbouring nodes [km]	The distance between nodes in each agglomeration
Radius [km]	The radius of the agglomeration

3.3.2 Demand distribution functions

To identify what types of demand distribution functions are relevant, past research is considered. Saidi (2016) has considered past research and identified three common assumptions made in these studies regarding demand distribution:

1. Uniform demand distribution
2. Specific zones of inner core and periphery, with a uniform population and job pattern in each zone
3. A population that is decreasing with increasing distance from the CBD with a linear or a known non-linear function such as exponential

These assumptions lead to the following three demand distribution functions which are considered in this thesis:

- Uniform
- A linear decay starting at a central business district (CBD)
- An exponential decay starting at a CBD

An indicative visualization of these distribution functions in 3D is shown in Figure 3.2. The exact formulations of these functions are given in section 3.4. For networks with a pre-defined spatial structure and pre-defined demands in the nodes, these demand distributions are not used.

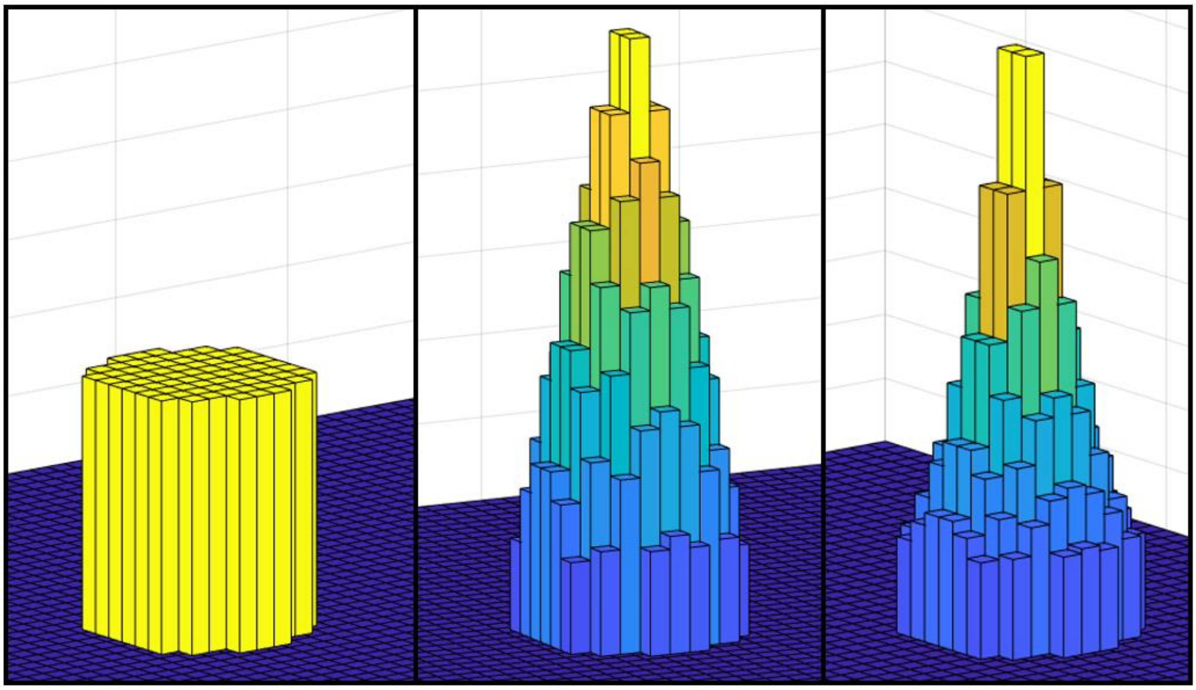

Figure 3.2: Indicative visualization of the distribution functions in 3D

3.3.3 Mode attributes

The different modalities that operate in the network are defined by the mode attributes. These attributes are used to calculate the travel times that are experienced when a certain mode is used, but also describe the service area that a certain mode serves. A description of all attributes is given in Table 3.2.

Table 3.2: Description of mode attributes

Mode attribute	Description
Operational speed [km/h]	The average speed at which the mode operates
Frequency [veh/h]	The frequency that a mode operates at
Construction costs [€/km]	The investment and operational costs associated to a mode
Minimum stop spacing [km]	The minimum distance between stops that a mode can serve
Maximum stop spacing [km]	The maximum distance between stops that a mode can serve

The minimum- and maximum stop spacing attributes determine the service area of a mode. An example of these service areas is visualized in Figure 3.3. In this visualization, the different colored rings give an indication of the minimum- and maximum stop spacing values per mode. In this example, when node A is considered as origin, a link between node A and B can only be realized with the mode that serves the outer-ring area. Considering node A as the origin, these areas can be categorized as first-degree, second-degree and third-degree rings, where the first-degree ring is the closest to A.

The construction costs are defined as the investment and operational costs associated to a mode. The operational costs associated with each PT mode will differ for each modality. The operational cost variables considered by Tirachini, Hensher and Jara-Díaz (2010) in their research to compare different modalities can be used as reference. They consider fixed operator costs which include the cost of infrastructure capital costs, land costs and rolling stock capital costs. Besides these fixed operator costs, they also consider the operating costs which include crew costs, operating costs (fuel, power & maintenance), infrastructure operations and maintenance costs and overhead operating costs (other costs such as scheduling, rostering etc.). For the construction costs assumed in the model, these are divided into infrastructure costs, rolling stock costs and operational costs.

How these mode attributes are implemented in the model, is described more in detail in section 3.4.

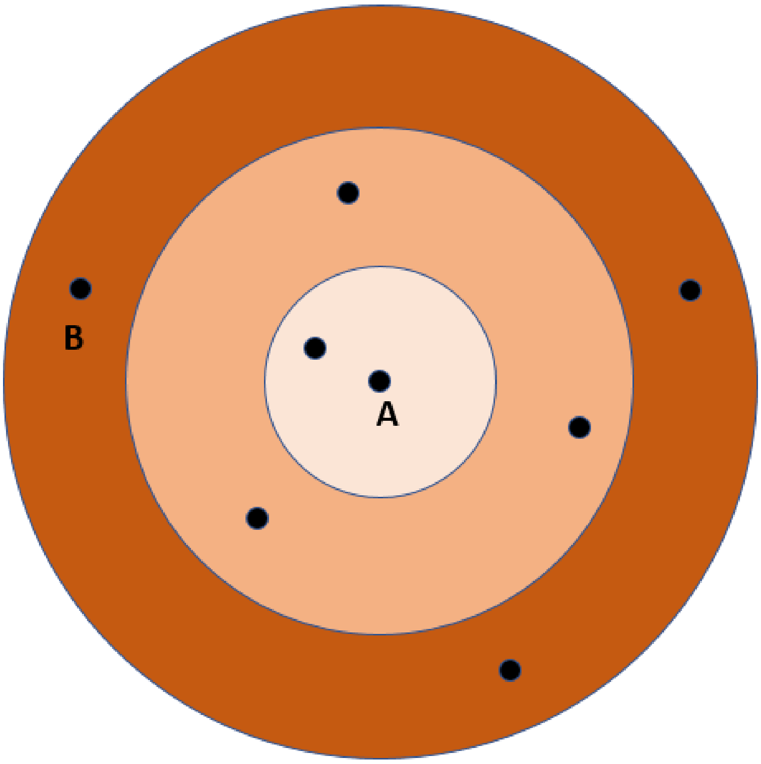

Figure 3.3: Visualization of coverage area different modalities

3.4 Model formulation

This section discusses the manner in which the model works more in detail and also shows the mathematical formulations used in the model. The first section discusses the initialisation phase of the model and the second section discusses the evolution phase of the model.

3.4.1 Initialisation phase

The initialisation phase consists of the node and trip generation, trip distribution, modal split and trip assignment steps described in section 2.1.

Node and trip generation

The first module of the model consists of the generation of a set of nodes. The node generation is dependent on the spatial structure parameters and demand distribution function but is also randomized. It is assumed that the number of trips generated in each node is equal to the population in the node. Therefore, the distribution of the trips generated is directly linked to the distribution of the population in the network. Table 3.3 gives a list of all the input parameters used to generate the set of nodes with a description of each parameter.

Table 3.3: List of input parameters for node generation

Parameter	Description
λ	Value of the width and length of square area in which the nodes are generated [km]
ω	Number of agglomerations
δ	Separation between agglomerations [km] This is a range of values between which the distances between centers can vary
σ	Min. stop spacing [km]
ξ^{tot}	Total population in the network [pax/day]
ξ^{min}	Minimum population per node [pax/day]
ξ^{max}	Maximum population per node; Demands of the center nodes [pax/day]
ρ	Radius of the agglomeration centers [km] This is a range of values between which the radii of the centers can vary
γ	Demand distribution function; 1 = Uniform, 2 = Linear decay, 3 = Exponential decay

The first step of the module is to generate center nodes, which represent the centers of the agglomerations and are assumed to be the CBD's in the cases of linear decay and exponential decay demand distributions. To do this, first the total area is defined in which the network is generated. The network is displayed in the area $(\lambda^{tot})^2$; $\lambda^{tot} \in [0, (2 * \lambda)]$ and to display the center nodes in the middle of this area, 100,000 nodes are randomly generated within the area λ^{nodes} ; $\lambda^{nodes} \in [(0.5 * \lambda), (1.5 * \lambda)]$. The number of center nodes is equal to the number of agglomerations and these are chosen from the 100,000 randomly generated nodes. With the condition that the distance between a node and the previous node is equal to the separation value (δ), the center nodes are chosen from the large set of randomly generated nodes. The separation value varies between a range of values, so the centers are not equally separated from each other. After this process, the x and y coordinates of the center nodes are found and defined as follows:

$$N_n^{center}(x_n, y_n) \qquad \forall n \in \{1, \dots, \omega\}$$

With the coordinates of the center nodes of each agglomeration defined, the next step is the distribution of population (ξ) over the nodes. For this, the maximum population value (ξ^{max}) is then assigned to the center nodes and based on the demand distribution (γ) given, the decay of the population is started with the center nodes as starting points. The 3 formulas used to generate the travel demands are as follow:

1. Uniform

Over the entire circular area of the agglomerations with a certain radius value (ρ) the population is assumed to be equal. The radius of each agglomeration varies between a range of values that is defined. The mathematical notation for the population over space with a uniform distribution is as follows:

$$\xi_n(x, y) = \xi^{max} * \left(\sqrt{(x - x_n)^2 + (y - y_n)^2} \leq \rho\right) \tag{3.4.1}$$

2. Linear decay

Starting from the center node of each agglomeration, a decay in population towards the other area of the agglomeration is applied in a linear manner. The population in the center is equal to ξ^{max} , and the population on the periphery of the agglomeration is equal to the minimum population (ξ^{min}). The mathematical notation for the population over space with a linear decay is as follows:

$$\xi_n(x,y) = \xi^{max} - \frac{\sqrt{(x-x_n)^2+(y-y_n)^2}}{\rho} * (\xi^{max} - \xi^{min}) \tag{3.4.2}$$

3. Exponential decay

Starting from the center node of each agglomeration, a decay in population towards the other area of the agglomeration is applied in an exponential manner. The population in the center is equal to ξ^{max}, and the population on the periphery of the agglomeration is equal to ξ^{min}. The mathematical notation for the population over space with an exponential decay is as follows:

$$\xi_n(x,y) = \xi^{max} * \mathrm{e}^{-\left(\frac{1}{\theta}\right)*\sqrt{(x-x_n)^2+(y-y_n)^2}} \tag{3.4.3}$$

The value of θ here varies based on the radius and this value is adjusted manually. This value is also a value chosen from a range of numbers to ensure the radii of the agglomerations are not equal.

Based on the given stop spacing value, the x-y plane is then divided into cells where the area of each cell is equal to σ^2. In the middle of each cell, a node is generated when the condition $\xi(x,y) \geq \xi^{min}$ holds. This leads to the complete set of nodes which is considered in the network evolution module. To keep the total demand equal in all scenarios, for each scenario the total demand in all the nodes is calculated and compared with the set total demand (ξ^{tot}). The demand in all nodes is then multiplied by a factor to ensure the calculated total demand becomes equal to ξ^{tot}.

Trip distribution

Once a set of nodes is generated with populations assigned to them, the trip distribution within the network is determined. The trip distribution is dependent on the generated set of nodes and input variables given. These input variables are shown in Table 3.4.

Table 3.4: List of input variables for trip distribution

Variable	Description
v_k	Operational speed of PT mode k [km/h]
v_{alt}	Operational speed of alternative mode [km/h]
s_k^{min}	Minimum stop spacing of PT mode k [km]
s_k^{max}	Maximum stop spacing of PT mode k [km]
t_{pen}	Transfer penalty a user experiences when changing modes [h]
β_{wait}	Factor to account for how users experience waiting time compared to the actual time spent waiting
β_{IVT}	Factor to account for how users experience in-vehicle time compared to the actual in-vehicle time
f_k	Frequency of PT mode k [veh/h]
$C_{infra,k}$	Infrastructure costs of PT mode k [€/km]
$C_{RS,k}$	Rolling stock costs of PT mode k [€/veh]
$C_{OCt,k}$	Time-dependent variable operational costs of PT mode k [€/h]
$C_{OCd,k}$	Distance-dependent variable operational costs of PT mode k [€/h]
α	The alpha value used in the gravity model
β	The beta value used in the gravity model
τ	Value of time (VoT) [€/h]

After the node positions and the population in each node are known, the demand between each node pair is determined based on a gravity model. As the assumption is made that the trip attraction is equal to the trip production, the gravity model is considered to be doubly constrained. The general form of the doubly constrained gravity model is as follows:

$$T_{ij} = a_i * P_i * b_j * A_j * f(c_{ij}) \tag{3.4.4}$$

Where it holds:

$$\sum_j T_{ij} = P_i \quad , \quad \sum_i T_{ij} = A_j \tag{3.4.5}$$

a_i and b_j are iteratively determined balancing factors:

$$a_i = \frac{1}{\sum_j A_j * b_j * f(c_{ij})} \tag{3.4.6}$$

$$b_j = \frac{1}{\sum_i P_i * a_i * f(c_{ij})} \tag{3.4.7}$$

Where:
T_{ij} = Trips between origin i and destination j
P_i = Trips produced at origin i
A_j = Trips attracted to destination j
a_i, b_j = Balancing factors
$f(c_{ij})$ = Deterrence function related to travel impedance c_{ij} between origin i and destination j

Kim (2010) highlights that the standard gravity model with a deterrence function only based on distance has limitations when considering a polycentric region. Since there are multiple modes to choose from, the user costs are chosen as impedance. The user costs taken for this are the calculated potential minimum travel times, in the case of a fully connected network, multiplied by a certain value of time (τ). Since the operational speeds of modes differ, it does not seem logical to only consider the distance in the deterrence function but to also consider the travel times. Therefore, it has been chosen to consider the user costs as impedance, which incorporates both distances and travel times.

Besides the impedance, it is also necessary to determine the deterrence function which is used. While there are multiple possibilities to consider when choosing a deterrence function, one of the functions proposed by Ortúzar and Willumsen (2011) is chosen in this case. This is called the combined deterrence function and is defined as follows:

$$f(c_{ij}) = c_{ij}^{\alpha} * e^{-\beta * c_{ij}} \tag{3.4.8}$$

The value chosen for α is set to 0.5, but the β value is estimated as recommended by Ortúzar and Willumsen (2011). They also state that a useful way to estimate this value is to take one over the average travel cost, or in this case the average user costs. In an iterative process an initial β value of the deterrence is chosen and based on this value, the calculated OD matrix is multiplied by the minimum user costs which have been calculated with the initially chosen β value. This leads to a value of total travel time within the entire network: $\sum_{i,j}(q_{ij} * t_{ij}^*) = t_{tot}^*$ This is the sum of the demand between each OD pair multiplied by the corresponding travel time. The next step is to calculate the average travel time: $t_{avg}^* = t_{tot}^* / q_{tot}$ The last step is to calculate the new β value: $\beta_{new} = \frac{1}{t_{avg}^*}$ After a number of iterations, a value for β is then found.

The calculation of the minimum user costs is as follows:

$$c_{ij}^{*} = t_{ij}^{*} * \tau \tag{3.4.9}$$

Where:
c_{ij}^{*} = Minimum total user costs between origin i and destination j in a fully connected network [€]
t_{ij}^{*} = Minimum total travel time between origin i and destination j in a fully connected network [h]

Here it is important to note that the * indicates that these values are calculated considering a fully connected network, where all nodes are thus directly connected to each other.

By making use of the determined gravity model it is then possible to calculate the demands between each origin i and destination j (q_{ij}). These values are stored in the OD-matrix (Q) which is used for the evolution phase. This OD-matrix is not updated after each network evolution iteration in order to save computational time and is in principal the OD-matrix based on a fully connected network. The reason for this assumption is that as the process of network evolution starts, this network will grow towards the fully evolved and connected network. The assumption is then that the OD-matrix would also evolve towards an OD-matrix based on the fully evolved and connected network. Therefore, this OD-matrix is calculated once based on the fully evolved and connected network and it is used for all iterations. The limitation of this method however, is that when the network does not evolve into a fully connected state, the demand between some OD pairs may be overestimated if the OD pair is not connected directly.

The first step to calculate the demand between each OD pair is to calculate the direct distances between all node pairs (d_{ij}), thus the geodesic distances in the non-planar graph. These distances are stored in the distance matrix D. Hereafter, the adjacency matrices for all modes in a fully connected network (A_k^*) are determined, where k denotes the PT mode. For each PT mode, the directly neighbouring nodes are determined by the minimum and maximum stop spacing values (s_k^{min} and s_k^{max}). If the distance between two nodes is between these values for a certain PT mode, then these nodes are considered neighbours for the corresponding PT mode.

With the distances between all node pairs and the adjacency matrices as input, for each PT mode the minimum travel distances ($d_{ij,k} = d_{ij} * A_k^*$) are calculated. As the PT modes k have specific ring areas they can serve, these calculated distances are mode dependent. Next, while considering the operational speeds of each mode, the frequencies (and thus waiting times) and the minimum travel distances that are possible, the travel times for each possible node pair is calculated per mode:

$$t_{ij,k} = \beta_{IVT} * t_{ij,k}^{IVT} + \beta_{wait} * t_{ij,k}^{w} + t_{pen} * Y = \frac{\beta_{IVT} * d_{ij,k}}{v_k} + \frac{\beta_{wait} * 0.5}{f_k} + t_{pen} * Y \tag{3.4.10}$$

Where:
$t_{ij,k}$ = Travel time between origin i and destination j with mode k. [h]
$t_{ij,k}^{IVT}$ = In-vehicle travel time between origin i and destination j with mode k [h]
$t_{ij,k}^{w}$ = Waiting time between origin i and destination j with mode k [h]
$d_{ij,k}$ = Distance between origin i and destination j with mode k [km]
$Y = \begin{cases} 1, & k_x \neq k_{x-1} \\ 0, & k_x = k_{x-1} \end{cases}$; Where: k_x = mode taken after transfer; k_{x-1} = mode taken before transfer

The next step is to determine the shortest paths between each OD-pair, which are computed with Dijkstra algorithm. For each origin node, this algorithm searches for the shortest path to all other nodes based on the travel times on each link. These travel times however only include the in-vehicle time. To consider waiting times and transfer times as well for the shortest path calculations, the algorithm would have to be adjusted to incorporate k network levels where k is the number of PT modes. For this thesis it was opted to make use of an existing algorithm, instead of developing an algorithm that incorporates waiting times and transfer times. This choice was made to save both computational time and time spent on modelling this during the timespan of this thesis. The author acknowledges this limitation, but for the purpose of this research it is expected that this limitation does not impact the results significantly.

Based on the shortest paths, a matrix is generated with the minimum travel times between each node pair, while considering all possible modes:

$$t_{ij}^* = \sum_k \min(t_{ij,k}) \tag{3.4.11}$$

Here it is again important to note that the * indicates that these values are calculated considering a fully connected network, where all nodes are thus directly connected to each other.

When the values of t_{ij}^* have been calculated, it is possible to estimate the necessary values of the gravity model. It is then possible to compute the demand between each node pair based on travel times and the estimated gravity model.

Modal split

The next step in the model is to determine the modal split. It is chosen to use the Logit model (Ortúzar and Willumsen (2011)). The general formulation of the Logit model, based on Random Utility Maximization (RUM), is given as follows when considering two alternatives:

$$P_1 = \frac{e^{U_1}}{e^{U_1}+e^{U_2}} \tag{3.4.12}$$

$$P_2 = \frac{e^{U_2}}{e^{U_1}+e^{U_2}} \tag{3.4.13}$$

Where:
P_1 = The probability that alternative 1 is chosen
P_2 = The probability that alternative 2 is chosen
U_1 = The utility that alternative 1 provides
U_2 = The utility that alternative 2 provides

When in this case alternative 1 provides more utility to the user, the probability that alternative 1 will be chosen over alternative 2 is higher. The sum of the probabilities always equal 1. In the network evolution model it is possible for users to choose between PT, consisting of multiple PT modalities, and the alternative mode, thus giving the users two possibilities. The probability (P) of a user to choose a certain mode is dependent on the utilities (U) that both choices offer to the user. It is acknowledged that the chosen Logit model is simplistic as it does not consider the correlation between the two alternatives. For example, if a majority of users chooses alternative 1 it is expected that this will lead to congestion. Due to this congestion, alternative 2 would then become more attractive and the probabilities for using the alternatives would change. While this model is arguably not entirely realistic, it is expected that the impact on the resulting modal split is limited as the focus of this research is on a strategic level.

In the network evolution model, the utility is seen as the negative value of travel time that users experience. A higher travel time should mean more disutility so therefore the negative value of the travel time is taken in this case. The modal split for both PT and alternative mode are then given by the following formulas:

$$P_{PT} = \frac{e^{U_{PT}}}{(e^{U_{PT}} + e^{U_{Alt}})} \tag{3.4.14}$$

$$P_{Alt} = \frac{e^{U_{Alt}}}{(e^{U_{PT}} + e^{U_{Alt}})} \tag{3.4.15}$$

As the PT network evolves with each iteration, the modal split calculation is performed after each iteration in the model. As new links are built in the network, the probability of a user to travel by PT increases and therefore the modal split should be re-calculated. The existing links are denoted by $(e_{i,j,k})$ and are stored in the list of existing links (E).

Trip assignment

After the modal split has been calculated, the number of trips for each OD is determined for both PT and the alternative mode. These are calculated as follows:

$$T_{PT} = P_{PT} * Q \tag{3.4.16}$$

$$T_{Alt} = P_{Alt} * Q \tag{3.4.17}$$

The calculation of trip assignment in this manner is done with an All-or-Nothing assignment as opposed to iteratively finding a user equilibrium. This means that travelers do not consider possible capacity problems that may arise as more travelers use a certain route and simply choose the shortest path. While this simple form of trip assignment requires limited computational power, the resulting passenger flows may not always be realistic. As the modal split is recalculated after each iteration, the same holds for the trip assignment as this is dependent on the modal split.

3.4.2 Evolution phase

The network evolution process in the model consists of three parts: investment candidate generation, investment candidate evaluation and scoring & building. This is an iterative process in which the network evolves from an initial to final state. These three parts involved in this process are explained further in the following part.

Investment candidate generation

The first step in the evolution process is the generation of investment candidates. These investment candidates can either be an investment in the construction of a new link, or an investment in bulking an existing link. Based on the existing network, a new link can be constructed if it connects to this existing network and a link can be expanded if it already exists.

When finding candidates for new link constructions, they are required to connect to the existing network. This information is stored in adjacency matrix in the 'current' state (H), The values of this matrix can either be 1 or 0:

$$H_{i,j} = \begin{cases} 1, & i \text{ and } j \text{ are connected} \\ 0, & i \text{ and } j \text{ are not connected} \end{cases} \tag{3.4.18}$$

For an origin i if it holds that $H_{i,j} = 1$, links starting from i are investment candidates. As the network graph is undirected, adjacency matrix H is symmetrical and thus this condition is sufficient to determine the candidate nodes. When considering the construction of a new candidate link starting from a candidate node, it can only be linked to another node with a certain modality based on the distance between the two nodes. Information on the neighbouring nodes is stored in the adjacency matrices A_k. For each candidate node, a list of candidate links (L) that can be constructed is identified for each modality k:

$$L_k = A_k - H_k \tag{3.4.19}$$

For bulking investments, all existing links $e_{i,j,k}$ may be considered.

Investment candidate evaluation

For each candidate that is generated, new calculations are made for the potential situation in which this candidate is realized. The following calculations are done for each candidate:

- Determination of the shortest paths
- Calculations of the modal split
- Calculations of the trip assignment
- Calculations of the travel times

These calculations are done in the same manner as described in section 2.4.1. The resulting calculations made for all candidates are stored and used for the step that follows after the candidate evaluation, the scoring and building.

Scoring & building

Based on the calculations performed in the candidate evaluation step, the next step is to calculate the construction costs and benefits associated with each candidate.

The associated construction costs for links with a length d consist of fixed costs and variable costs. For each mode k the fixed costs are calculated as follows:

$$C_{fixed,k} = C_{infra,k} * d + C_{RS,k} * f_k \tag{3.4.20}$$

Where:
$C_{fixed,k}$ = Fixed costs; costs necessary for the initial investment in infrastructure and rolling stock [€]
f_k = Frequency of PT mode k [veh]*

*It should be noted that the assumption is made that the frequency corresponds to the number of vehicles necessary to operate in both directions on a link. Therefore, the frequency here is given in [veh] instead of [veh/h].

The variable costs per year associated with the construction of links with a length d for each mode k are calculated as follows:

$$C_{var,k} = f_k * (C_{OCt,k} * \kappa + C_{OCd,k} * (\frac{v_k}{\kappa})) * \delta \tag{3.4.21}$$

Where:
$C_{var,k}$ = Variable costs per year [€/yr]
κ = Operating hours per day [h]
δ = Days of operation per year [days]

These costs are then discounted with a rate of 5% over a time horizon of 30 years (Sartori *et al.* (2014)). This then leads to the total costs associated with the investment:

$$C_{tot,k} = C_{fixed,k} + \sum_{t=0}^{30}(\frac{C_{var,k}}{(1+0.05)^t}) \tag{3.4.22}$$

For the costs associated with bulking investments, these are assumed to be the same as the construction costs for new link with the exclusion of the infrastructure costs.

The benefits associated with each candidate are based on travel time savings when the candidate is realized. As the potential new travel times are calculated for each candidate, the new total travel time is compared to the total travel time in the network in its 'current' state. The calculations of the benefits per year are as follows:

$$b = (tt_{new} - tt_{cur}) * \tau * 365 \tag{3.4.23}$$

Where:
b = The potential user benefits if investment were to be realized [€/yr]
tt_{new} = The total travel time in the new situation if investment were to be realized [h]
tt_{cur} = The total travel time in the 'current' situation, before an investment is made [h]

These benefits are also discounted with a rate of 5% over a time horizon of 30 years in the same manner as $C_{var,k}$ in (3.4.22). Once the costs and benefits have been calculated for each candidate, each candidate is assigned a score. This score is calculated as follows:

$$Score = \frac{b}{C_{tot}} \tag{3.4.24}$$

In the case that the score has a value below 1, the candidate assumed to not be beneficial. All the candidates with a score above 1 are then compared to each other, and the highest scoring candidate will be realized. If there are no candidates with a score above 1, the network evolution is stopped.

3.5 Model output

This section discusses the different types of model outputs:

- Network visualization: 2D graph of the nodes and links constructed with a visual distinction between the different link types/modalities. This is done at the end of the evolution process. A step-wise visualization of each investment is also made in the form of an mp4 file.
- Topological indicators: Various indicators that are used to quantify the network topology Some of these are calculated at every iteration, others are only calculated at the end of the evolution process.
- Performance indicators: Various indicators that are used to quantify the performance of the network. Some of these are calculated at every iteration, others are only calculated at the end of the evolution process.

Regarding the latter two outputs, sections 2.4.1 and 2.4.2 describe which topological and performance indicators respectively are part of the model output and how they are calculated. These indicators have been chosen based on what has been used in past research (Derrible and Kennedy (2009), (2010); Cats (2017); Lems (2017); Ul Abedin *et al.* (2018); Vermeulen (2018)).

3.5.1 Topological indicators

Considering the complexities of a PT network in a polycentric urban region, as described in section 1.1, the topological indicators have been chosen while taking these complexities into consideration. As the spatial structure and modal hierarchy are important aspects, indicators which can quantify these aspects have been considered:

1. <u>Connectivity:</u> This indicator quantifies the degree by which a network is connected. It is a ratio between the number of links in the existing network and the number of links in the fully

connected network. This indicator is calculated at the end of the evolution process. The connectivity (γ) is formulated as follows:

$$\gamma = \frac{E}{E^{max}} \tag{3.5.1}$$

2. Directness: The directness is related to the number of transfers that need to be taken to travel between each OD pair. It is the ratio between the average distance between each OD pair in the fully connected graph, which is equal to the geodesic distances (d^*), and the average distance between each OD pair in the existing network (d). As this value increases towards 1, the network consists of more direct links. This indicator is calculated at the end of the evolution process. The directness (τ) is formulated as follows:

$$\tau = \frac{\bar{d}^*}{\bar{d}} = \frac{(\frac{\sum_i \sum_{j \in N} d^*_{ij}}{N})}{(\frac{\sum_i \sum_{j \in N} d_{ij}}{N})} \qquad \forall\, i \in N \tag{3.5.2}$$

3. Average node degree: The node degree describes how many links are attached to a node. The number of links attached to each node can be determined with the adjacency matrix (A). If the value of the average node degree increases over time, it means that the network is densifying. This indicator is calculated per iteration. The average node degree is formulated as follows:

$$\bar{k} = \frac{\sum_i k_i}{N} = \frac{\sum_i \sum_{j \in N} A_{ij}}{N} \qquad \forall\, i \in N \tag{3.5.3}$$

4. Network length: The network length is a simple indicator that describes how the network grows in terms of realized links. The network length (l) is given in kilometers and is formulated as follows:

$$l = \sum_{e \in E} l_e \tag{3.5.4}$$

5. Average link length: The average link length helps to determine if the network is more regionally or locally focused. Where a higher average link length indicates a more regionally focused network, a lower value indicates a more locally focused network. This value is dependent on the spatial distribution of nodes, but with different demand distributions per prototype it is expected to lead to different results. This indicator is calculated per iteration. The average link length ($\bar{l}$) is given in kilometers and is formulated as follows:

$$\bar{l} = \sum_{e \in E} \frac{l_e}{n(E)} \tag{3.5.5}$$

6. PT infrastructure shares: This indicator quantifies which PT mode is most dominant in the network. Per PT mode, the percentage of network length is compared to the entire PT network length. This indicator is calculated at the end of the evolution process. For each mode k, the percentage of network length (ψ_k) is formulated as follows:

$$\psi_k = \frac{l_k}{l} \tag{3.5.6}$$

7. Betweenness centrality: The betweenness centrality of nodes is an indicator which quantifies hierarchy among nodes in the PT network. The betweenness centrality of a node is determined based on the number of shortest paths that passes through it. To compare the values of different scenarios with each other, the betweenness centrality of a node is

calculated as the share of shortest paths that pass through it. This indicator is calculated at the end of the evolution process. The betweenness centrality (μ) is formulated as follows:

$$\mu(n) = \sum_{i \neq n \neq j} \frac{\sigma_{ij}(n)}{\sigma_{ij}} \tag{3.5.7}$$

Where:
n = The node which is considered
$\mu(n)$ = The betweenness centrality of node n
σ_{ij} = The total number of shortest paths from i to j
$\sigma_{ij}(n)$ = The total number of shortest paths from i to j that go through node n

3.5.2 Performance indicators

The following performance indicators are analyzed during and after the network evolution process in this model:

1. Total travel time: The total travel time is a sum of all travel times experienced both by PT and by alternative mode on an average weekday. This indicator is calculated per iteration. The total travel time (tt) is formulated as follows:

$$tt = \sum_{i,j,k} t_{ij,k} + t_{ij,Alt} \tag{3.5.8}$$

2. User costs: The user costs are a breakdown of the total travel time and translated into monetary values with the VoT. The user costs consist of the travel time by alternative mode (t_{alt}), in-vehicle time (t_{IVT}), waiting time (t_w) and transfer time (t_t). All user cost components are expressed in [€] and these are calculated at the end of the evolution process.

3. Modal share: The modal share quantifies the percentage of users in the entire network that use PT. This indicator is calculated per iteration. The modal share (ϕ_{PT}) is formulated as follows:

$$\phi_{PT} = \frac{T_{PT}}{T_{PT}+T_{Alt}} \tag{3.5.9}$$

4. Investment score: The investment score ($Score$) is chosen as output to analyze the importance of each investment made. The investment scores are calculated per iteration and are calculated as shown in (3.4.23).

3.6 Conclusions network evolution model

This chapter has provided descriptions of the four main components of the model framework (input, initialisation phase, evolution phase and output) and discusses the assumptions made in the model. Furthermore, the detailed descriptions of these four main components have been provided including the corresponding mathematical formulations.

4. Numerical experiments: Scenario development

To find answers to the research questions posed, the model described in the previous chapter is used to investigate how the spatial distribution of nodes, the demand distribution, the operational costs and the consideration of multimodality as opposed to unimodality impact the topological evolution. Prior to the application of this model to a real-world scenario, a number of numerical experiments are conducted where the model is applied to a number of fictional scenarios. Here it is important to identify the most important scenarios as there are many possibilities to think of. There are four aspects which are varied to find answers to the research questions. These aspects are the following:

- Spatial distribution of nodes
- Demand distribution
- Operational costs
- Multimodality

Section 4.1 discusses how each of these aspects is varied for different scenarios and provides specifications of these variables. Hereafter, section 4.2 quantifies the scenarios in terms of these specifications and summarizes the scenarios which are considered. Lastly, the general assumptions made for the numerical experiments are discussed in section 4.3.

4.1 Specification of variables

As there are many possibilities to consider when varying all of the four aspects named above, it is important to specify a number of scenarios in which there are clear distinctions. The following subsections will go more in depth into how the aspects named above vary and specify these distinctions. For the application of the specifications to the numerical experiments, further assumptions are made to apply the findings to the numerical experiments, which are discussed in the respective subsections. Lastly, the four variables and the specifications of these variables are summarized in section 4.1.5.

4.1.1 Generating prototypes for the spatial distribution of nodes

As the spatial distribution of nodes can be varied in many manners, it is important to make clear distinctions between these variations to be able to comment on the impact that it has on the topological evolution of the network. Therefore, in this thesis a distinction is made between different 'prototypes'. These prototypes are characterized by certain distinctive spatial structures and are based on real life polycentric regions, where multiple nodes represent an agglomeration. The aspects that characterize each prototype are the number of agglomerations, the radii of the agglomerations and the distance between the agglomerations (separation value). The distance between directly neighbouring nodes is kept equal in all scenarios. The prototypes are named after real cities and urban regions. It should be noted that when city names or urban regions are noted with single quotation marks, it is a reference to the prototype. The four prototypes that have been selected and generated are the following:

1. <u>'London' prototype</u>

When we consider Figure 2.1 from section 2.1 again, the 'London' prototype can be seen as a polycentric metropolitan area in the incorporation mode. This type is arguably something close to a monocentric city where there is a clear CBD. However Meijers, Hollander and Hoogerbrugge (2012) characterize London as polycentric metropolitan area, where the urban core of London incorporates the smaller, distinct cities such as Reading or Cambridge. The characteristics of this prototype in terms of spatial aspects are the following:

- There is one agglomeration

- The radius of this agglomeration center is larger than in the case of multiple agglomerations

While London can be considered polycentric, this prototype consists of only one agglomeration. The reason for this is to ensure that there is a clear CBD area within the region.

2. ‘Tokyo’ prototype

Tokyo is similar to London in the sense that it can be seen as a polycentric metropolitan area as well. However, the difference is that in Tokyo the metropolitan area consists of multiple agglomeration centers (Sorensen (2001)). In this case there is no clear CBD, but multiple CBD areas. The characteristics of this prototype in terms of spatial aspects are the following:

- There are four agglomerations
- The diameters (2 times the radii) of the agglomerations are larger than the separation values of these agglomerations, which leads to overlap of the agglomerations

3. ‘Flemish Diamond’ prototype

The Flemish Diamond is similar to the Randstad where the configuration can be seen as something between a polycentric city and a polycentric metropolitan area in fusion mode. Meijers (2007) explains the pattern by referring to the historical development of the Flemish Diamond and Randstad regions. As there was fragmentation in political and administrative structures in the past, this prevented the rise of one dominant city within the region. The characteristics of this prototype in terms of spatial aspects are the following:

- There are four agglomerations
- There is a clear separation between the agglomerations
- The agglomeration centers are generated in a sort of diamond/square shape

4. ‘Rhine-Ruhr’ prototype

The Rhine-Ruhr area is a mix of polycentric cities in fusion mode, polycentric metropolitan area in fusion mode and polycentric metropolitan area in incorporation mode (Figure 2.1). What makes this prototype special is that the centers are somewhat developed along a pivotal axis, making a sort of ‘banana’ shape. Similarly to the Flemish Diamond and Randstad area, Meijers (2007) explains that the Rhine-Ruhr area developed without there being a dominant city in the region due to historical developments. However, the Rhine-Ruhr area experienced a rapid process of urbanization and industrialization along two axes. This led to the different agglomeration centers in the region to expand into one another, creating the ‘banana’ shape. The characteristics of this prototype in terms of spatial aspects are the following:

- There are four agglomerations
- The agglomerations can have a slight overlap
- The agglomerations are developed along an axis with a small deviation

The visualizations of these prototypes are depicted in Figure 4.1.

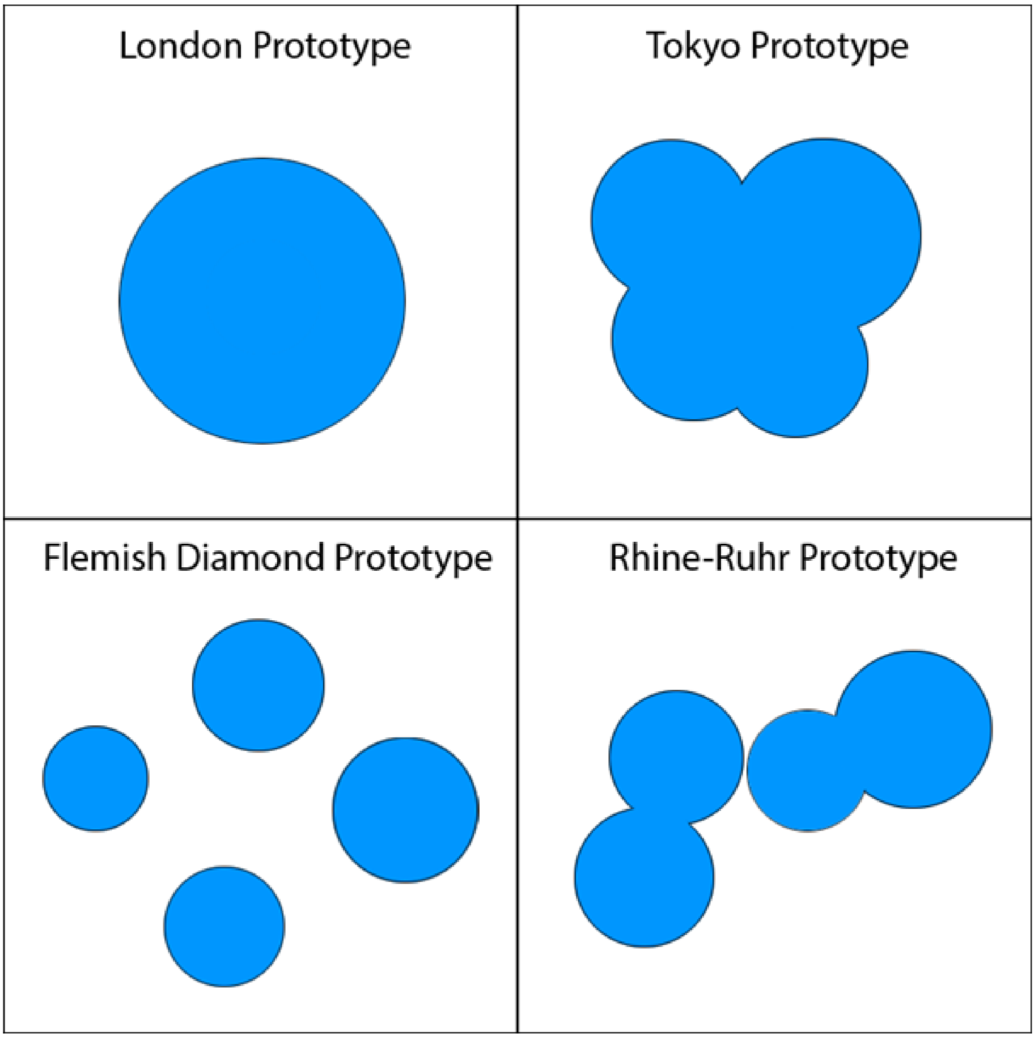

Figure 4.1: Visualization of spatial structure prototypes

In terms of the quantification of the radii and the separation values between the agglomerations, estimates of these variables are determined based on the examples from the real world. To help with this, Google Earth (Google (2018)) has been used to get an idea of what a realistic value for the radius of agglomerations could be. Here the area of land of each city is considered and it is then assumed that this area has a circular shape, after which it is possible to calculate a value for the radius. While the author recognizes that these calculations are arbitrary, it should be noted that there is however consistency in this arbitrariness and the calculations are only used to get indications and do not have to be perfectly accurate. Radii of the large cities in the Randstad vary from 5.5 to 8.5 km, for the Rhine-Ruhr area the radii vary from 5.5 to 11.3 km and for the Flemish Diamond between 4.1 and 8.1 km. The radii for Tokyo and London are more sensitive to the definition taken for the area to be considered. While the 'Tokyo' prototype is assumed to consist of multiple agglomeration centers, similarly to London it can be seen as a polycentric metropolitan area in which it is difficult to determine the different agglomerations exactly. When the urban areas in Tokyo and London are considered, the radii are 26.4 and 23.5 km respectively.

Based on these radii found in Google Earth, ranges of radii in the different prototypes are determined. These ranges are also chosen to ensure the total number of nodes in the network stays limited, while keeping the same distances between neighbouring nodes. While the 'London' prototype consists of one agglomeration, the 'Tokyo', 'Flemish Diamond' and 'Rhine-Ruhr' prototypes consist of four agglomerations. For 'London', a radius ranging between 9 and 9.5 km is considered. For the other three prototypes smaller radius values have been chosen as well, where agglomeration radii ranging between 4 and 5 km are considered.

As with the radii, the separation values for 'London' and 'Tokyo', which are polycentric metropolitan areas, are difficult to determine. For the Randstad, Flemish Diamond and Rhine-Ruhr, however, it is easier to estimate the separation values as there are clear distinct agglomerations. For the Randstad the separation values vary between 20 and 58 km, for the Flemish Diamond these values vary between 25 and 68 km, and for the Rhine-Ruhr area the distances vary between 10 and 20 km.

Based on these values, the separation value ranges are determined for the prototypes. For the 'London' prototype, there is no separation value assumed as there is only one agglomeration. For the 'Tokyo' prototype, it is important to ensure overlap between the agglomerations. To do this, the separation values should be less than diameters of the agglomerations. As the radii vary between 4 and 5 km, the separation values will vary between 6 and 8 km to ensure overlap. For the 'Flemish Diamond' prototype, the separation values vary between 20 and 60 km. For the Rhine-Ruhr prototype, the agglomerations can have slight overlap. The separation value assumed therefore varies between 8 and 12 km.

To summarize the specifications of these prototypes, the parameters that determine the spatial distribution of the nodes for the 'London', 'Tokyo', 'Flemish Diamond' and 'Rhine-Ruhr' prototype are shown in Table 4.1.

Table 4.1: Spatial structure parameters of the four prototypes in numerical experiments

Parameter	**'London' prototype**	**'Tokyo' prototype**	**'Flemish Diamond' prototype**	**'Rhine-Ruhr' prototype**
Number of agglomerations	1	4	4	4
Radius [km]	9 - 9.5	4 - 5	4 - 5	4 - 5
Distance between neighbouring nodes [km]	2	2	2	2
Separation between centers [km]	-	6 - 8	20 - 60	8 - 12

While these parameters lead to a generation of a set of nodes which generally correspond to the four defined prototypes, in some random instances it is possible that this is not the case. Therefore, the initial set of nodes generated can be accepted or re-generated. This choice is made based on the authors expert judgement and based on the number of nodes that is considered desirable to generate, due to computational times. The focus of this research is not on the exact reproduction of selected areas but rather the principal investigation of the respective prototypes.

4.1.2 Demand distribution

The three demand distribution functions considered in the numerical experiments are the same three described in section 3.3.2: uniform, linear decay and exponential decay. The total population (ξ^{tot}) is kept constant as this thesis does not focus on the relation between network evolution and the population in absolute terms. Therefore, the total population assumed in each scenario should be constant. To get a rough idea about the total population, the populations of the prototype polycentric regions are considered. The populations of the Rhine-Ruhr, Flemish Diamond and Randstad area are nearly 12 million, 5 million and nearly 7 million inhabitants respectively (Meijers (2007)). For London it is found that there are around 8.8 million inhabitants (ONS (2018)) and for Tokyo around 9.2 million inhabitants (Tokyo Metropolitan Government (2015)). These numbers give a rough estimate for the range between which populations vary in the polycentric region. If a simple average is taken from these cases, a population of 8.4 million is found. The agglomeration sizes in the scenarios are however assumed to be smaller than their respective references in the real world. The total population is therefore determined based on population densities. Based on the values found for the reference cities and regions used for the prototypes, a value of 10,000 inhabitants/km^2 is assumed. This value is based on the world population density visualizations presented by Smith (2017). Each scenario consists of roughly 60 nodes, based on the spatial structure parameters which are assumed. 60 nodes correspond to roughly 240 km^2 and with the population density assumption this leads to a value for ξ^{tot} of 2.4 million inhabitants for each scenario.

The value for ξ^{min} is chosen to be 8000 inhabitants, which corresponds to 2000 inhabitants/km^2. This is roughly the population density found in the outer areas of the reference cities/regions. The value for ξ^{max} is chosen to be 60,000 inhabitants, which corresponds to 15,000 inhabitants/km^2. This is on average also roughly the population density found in the densest areas in the reference cities/regions. Table 4.2 summarizes the demand distribution parameters that are used as input for the model.

Table 4.2: Demand distribution parameters numerical experiments

Parameter	Value
Demand distribution function ***(number used as input corresponds to the respective type)***	1. Uniform 2. Linear decay 3. Exponential decay
ξ^{tot}	2.4 million [inhabitants]
ξ^{min}	8000 [inhabitants]
ξ^{max}	60,000 [inhabitants]

4.1.3 Multimodality

To investigate the impact of considering multiple modalities on the network evolution, as opposed to considering only one modality, there should be multimodal scenarios and unimodal scenarios. To this end, first the different modalities that operate in the multimodal PT network are determined. To determine these modalities and their specific attributes, it is important to consider that there are multiple network levels within the polycentric urban region. A reference to these different network levels can be found in the research by Van Nes (2002) and Van den Heuvel (1997). Within the different network levels, it is notable that there are different modalities that are most suited to operate in these network levels. One of the things to be researched in the numerical experiments is the impact that multimodality has on the topological evolution, as opposed to unimodality. Therefore, it is useful to have clear distinctions between different modalities and thus network levels. In these experiments, it has therefore been opted to split the network into three distinct network levels within the polycentric urban region: ‘agglomeration’, ‘regional’, and ‘interregional’. Based on these network levels, there are also three different types of mode classes that serve these network levels and are named respectively to the network levels. For these different types of mode classes, the mode attributes discussed in section 3.3.3 are defined for each mode class.

In terms of the mode attributes for the different PT modes, Vuchic (2002) shows how the system performance of different modes relate to the investment costs per line length (Figure 4.2).

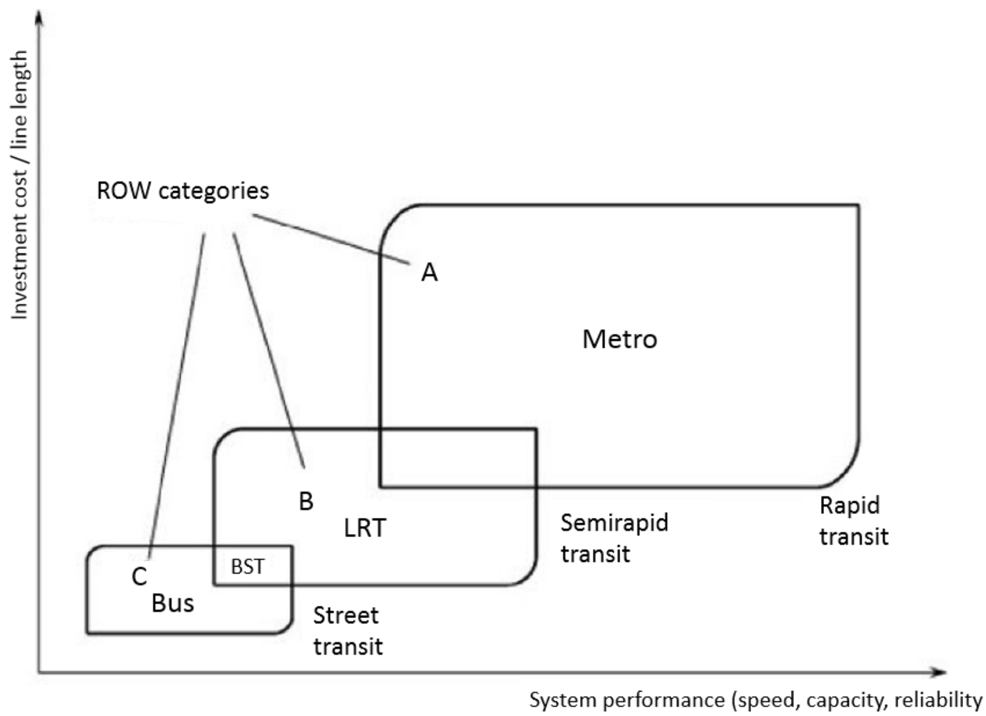

*Figure 4.2: Relation of PT system performance and investment cost / line length (*Vuchic (2002)*)*

He divides the classes based on right-of-way (ROW) categories and shows that generally when a mode has a better system performance, its costs are also generally higher. Following this line of thinking, the attributes for the three PT modes in the numerical experiments are determined.

Firstly, modalities in the real world that generally serve at the network levels (agglomeration, regional, interregional) are considered. The associated real-world modalities for each network level are shown in Table 4.3.

Table 4.3: Network levels with associated modalities in the real world

Network level	Associated modality
Agglomeration	BRT, LRT
Regional	LRT, Metro
Interregional	Metro, Train

As can be seen, certain modalities serve multiple network levels. When considering the values of the listed attributes for these modalities, it can also be seen that there are quite some differences among certain modalities, but also similarities between different modalities. For example, the operating speeds assumed for BRT can vary from 13 to 80 km/h, and the operating speeds of BRT and LRT can be very similar. Again, as there is not always a clear-cut distinction between the traditional modalities in the real world, it is more useful to make use of mode classifications with distinct differences in attributes based on the network levels they serve. The associated modalities can however give an indication for the assumptions as to what the attributes of the different mode classifications can be. Based on the aforementioned line of thinking and the various attribute values found for the listed traditional modalities (Deng and Nelson (2011); Hidalgo, Lleras and Hernández (2013); UITP (2015); ProRail (2017b); EMBARQ and BRT (2018); NS (2018b)) and indications made by Van den Heuvel (1997) and Van Nes (2002), the attribute values shown in Table 4.4 are assumed for the numerical experiments.

Table 4.4: Attribute values for the three mode classifications

Attribute	Agglomeration	Regional	Interregional
s_k^{min} [km]	0.5	3	6
s_k^{max} [km]	3	6	200
$C_{infra,k}$ [€/km]	8 mln.	14 mln.	21 mln.
$C_{RS,k}$ [€/veh]	1 mln.	2 mln.	8 mln.
$C_{OCt,k}$ [€/h]	40	60	100
$C_{OCd,k}$ [€/h]	4	6	10
f_k [veh/h]	8	8	8
v_k [km/h]	30	50	80

While these values do generally follow from the data found on actual modalities, and the classifications named by Van den Heuvel (1997) and Van Nes (2002), the values of stop spacing are slightly adjusted to ensure that there is a clear distinction between the three classes based on expert judgement. The stop spacing values for 'agglomeration' have been assumed to be larger than what is insinuated in past research for this classification. As the focus of this thesis is more on the backbone of the network, the assumed stop spacing between nodes has also been chosen to be larger. The frequency is kept equal for all modes as well, which is not in line with is observed in reality. This choice is made to avoid large waiting times and the choice of operating frequency is in principle arbitrary when a network is developed from scratch. Therefore, a relatively high frequency is assumed for all three modes.

For the cost components of the different modalities, Flyvbjerg, Bruzelius and Wee (2008); Tirachini, Hensher and Jara-Díaz (2010); Deng and Nelson (2011); Van Beurden (2017) are used as references. Based on timetables of the GVB and NS (GVB (2018); NS (2018a)), operating hours are roughly between 6 am and 12 am (18 hours). As there are peak moments and off-peak moments where they operate at a lower capacity than during peak hours, for the model the assumption has been made that PT operates 15 hours per day fully on average.

Besides these values, the value for the operational speed of the alternative mode (V_{Alt}) is set to 15 km/h. While the actual speed of an alternative mode such as car or bicycle is arguably higher than 15 km/h, this lower value has been chosen to incorporate disutility such as parking costs for cars or bad weather for bicycles.

It is acknowledged that the choices made with regard to the mode attributes as well as the operational speed of the alternative mode may impact the results of the numerical experiments. In terms of the mode attributes, a PT mode will generally be more attractive when the cost components are lower or the operational speed is higher. In terms of the speed of the alternative mode, the lower this speed is, the more attractive all PT modes will be.

4.1.4 Vehicle automation and operational costs

While there is uncertainty at this point on how the infrastructure and rolling stock costs could change with vehicle automation, more is known on the changes in operational costs. Generally, it is to be expected that the operational costs of buses, trams and metro's can be reduced by roughly 30-40% (Bösch *et al.* (2017); Wavestone (2017); SYSTRA (2018); Zhang, Jenelius and Badia (2018)).

It is acknowledged that for different modalities, there are differences in potential operational cost reductions and also infrastructure and rolling stock costs may potentially change. As there is ambiguity in these potential changes, for the sake of this research certain assumptions are made. For the numerical experiments, the assumption is made that the infrastructure and rolling stock costs in the case of automated vehicles are the same as in the case of non-automated vehicles. The operational costs are however reduced by 35%; both $C_{OCd,k}$ and $C_{OCt,k}$. These assumptions hold for all three PT modalities.

4.1.5 Summary of scenario specifications

There are four variables within the different scenarios in the numerical experiments. The specifications of these four variables have been discussed in the previous subsections and are summarized in Table 4.5. Based on these specifications, the relevant scenarios for the numerical experiments are determined in the following section.

Table 4.5: The four variables in the numerical experiments and their specifications

Variable	Specification
Spatial structure	• 'London' prototype • 'Tokyo' prototype • 'Flemish Diamond' prototype • 'Rhine-Ruhr' prototype
Demand distribution	• Uniform • Linear • Exponential
Operational costs	• Non-automated vehicles • Automated vehicles
Multimodality	• Multimodal • Unimodal

4.2 Scenario quantification

Based on the aspects described in section 4.1.1 to 4.1.4, relevant scenarios are defined in which these aspects are varied to find answers to the posed research questions. In total there are 48 possible scenarios when all possibilities are considered: 4 prototypes in terms of spatial structure, 3 types of demand distribution, 2 options in terms of operational costs (automated versus non-automated vehicles) and 2 options in terms of modalities (multimodal versus unimodal). As the expectancy is that not all scenarios will provide relevant results, the most relevant scenarios are determined and described in this section. Section 4.2.1 discusses how the scenarios for the numerical experiments are determined. Hereafter, a summary of these scenarios is given in section 4.2.2.

4.2.1 Scenario determination

In terms of the spatial structure and demand distribution, scenarios are defined in which for each prototype, each demand distribution type is considered (with an exception of 'London' with uniform demand distribution), leading to the first 11 scenarios. The uniform demand distribution is not considered for the 'London' prototype, as the uniform distribution insinuates that there is no CBD present. It is important to note that in these scenarios, the situation with non-automated vehicles and multimodality is considered and these are not varied yet. These scenarios are referred to as the 'standard' scenarios in the remainder of this thesis.

To analyze how the changes in operational costs impact the topological evolution of a PT network, it is again important to define scenarios in which these differences are expected to be most present. As the operational costs are expressed in costs per distance, distance is an important aspect that influences the topological evolution of the network. It is therefore expected that the 'Flemish Diamond' prototype is a good reference scenario in which the impact of a change in operational costs will become most visible as there are long distances, as well as short distances to be travelled in this prototype. This leads to one scenario in which the operational costs are varied.

To analyze the impact of considering unimodality as opposed to multimodality on the topological evolution of a PT network, it is important to define the scenarios in which the differences in impact will be most present. In the case of multimodality, all three mode classifications are considered. For unimodality however, only the agglomeration mode is considered. An example of such a system is the RandstadRail LRT system in the southern Randstad region. While this system serves the agglomerations Den Haag and Rotterdam, it also connects these two agglomerations. As this is a realistic example of a system that generally serves local areas, but is also used over longer distances, such a mode classification is also chosen to be used for the scenarios with unimodality. For the choice of spatial structure in which the differences in impact of considering unimodality as opposed to multimodality on the topological evolution of a PT network are expected to be most present, there are two aspects which are expected to be important. Firstly, it is expected that these differences will be most present in scenarios where there is a distinction in distances travelled. The reasoning behind this is that in the case of multimodality, there is a mode that is most suitable for serving longer distances while there is also a mode that is most suitable for serving the shorter distances. Whereas the agglomeration mode in the unimodal case is mostly suitable for the shorter distances, rather than longer distances. In the 'Flemish Diamond' prototype there are long distances to be travelled as well as short distances and it is expected that there will be some sort of hierarchy in modalities, as explained in section 2.2. It is however expected that the distances in this spatial structure will be too long. The 'Rhine-Ruhr' prototype then seems better suited for the unimodal scenarios. While the multimodal scenario may present hierarchy in modalities, in the unimodal scenario this is not the case as there is only one modality. It is therefore expected that in this prototype the differences in topological evolution between the multimodal and unimodal situation will be most present. Secondly, it is expected that the differences are more present in scenarios where there is a distinction in travel demand. For scenarios with for example a linear demand distribution in the same spatial structure prototype, the scenario which considers unimodality may show differences in the topological evolution compared to the scenario with multimodality since there may be node hierarchy but no modal hierarchy. This leads to two unimodal scenarios with the 'Rhine-Ruhr' prototype: one with a uniform demand distribution and one with a linear demand distribution. These two scenarios and the scenario with automated vehicles are referred to as 'non-standard' scenarios in the remainder of this thesis.

4.2.2 Summary of numerical experiment scenarios

In total, this leads to 14 fictional scenarios. A complete overview of all scenarios is shown in Table 4.6. The 'standard' scenarios are the first 11 scenarios listed and can be distinguished from the 'non-standard' scenarios by the darker shade of gray in the first column of the table.

Table 4.6: Summary of numerical experiment scenario specifications

Scenario	Spatial structure				Demand distribution			Operational costs		Multimodality	
	'London'	'Tokyo'	'Flemish Diamond'	'Rhine-Ruhr'	Uniform	Linear	Exponential	Automated	Non Automated	Multimodal	Unimodal
LLNM	X					X			X	X	
LENM	X						X		X	X	
TUNM		X			X				X	X	
TLNM		X				X			X	X	
TENM		X					X		X	X	
FUNM			X		X				X	X	
FLNM			X			X			X	X	
FENM			X				X		X	X	
RUNM				X	X				X	X	
RLNM				X		X			X	X	
RENM				X			X		X	X	
FUAM			X		X			X		X	
RUNU				X	X				X		X
RLNU				X		X			X		X

The different colours in Table 4.6 indicate the different aspects: blue for spatial structure, green for demand distribution, orange for operational costs and yellow for multimodality. To analyze how each of these different aspects affect the topological evolution of the network, the comparisons between scenarios as shown in Table 4.7 are made. The colours in this table correspond to the aspect which is analyzed.

Table 4.7: Scenarios which are compared to each other

Scenario comparisons	
TUNM, FUNM, RUNM	Uniform
LLNM, TLNM, FLNM, RLNM	Linear
LENM, TENM, FENM, RENM	Exponential
LLNM, LENM	'London'
TUNM, TLNM, TENM	'Tokyo'
FUNM, FLNM, FENM	'Flemish Diamond'
RUNM, RLNM, RENM	'Rhine-Ruhr'
FUNM, FUAM	(Non) Automated
RUNM, RUNU	Uniform, Unimodal
RLNM, RLNU	Linear, Unimodal

Finally, it is important to note that in all scenarios, the initial network starts with one existing link. This link connects the node with the highest population to one of its direct neighbours, therefore the first link in the network is always an 'agglomeration' link.

4.3 General assumptions for numerical experiments

As can be recalled from the model formulation of the trip distribution in section 3.4.1, the input values for the VoT and the β value of the gravity model must be determined for these scenarios specifically. First of all, a value for the VoT is necessary to determine the β value of the gravity model. While this value varies in literature and is also dependent on for example the gross domestic product (GDP) of a country, a value of € -8.75 is chosen for the VoT. This is the value proposed by Kouwenhoven *et al.* (2014) for all surface modes for all trip purposes. It is however important to note that the results of further calculations may differ when choosing a different value for the VoT. With the VoT it is then possible to calculate the total user costs based on a fully connected network. With the manually iterative process described in section 3.4.1, a β value can be found. After some iterations, a β value of 0.47 was found for the deterrence function (3.4.8). This β value and the chosen value for the VoT are used in all numerical experiments.

Furthermore, a number of assumptions are made with regard to the numerical experiments:

- The number of trips produced and attracted from and to a node is assumed to be equal.
- People make 3 trips per day on average (Ahern *et al.* (2013)).
- Agglomerations are assumed to have a circular shape with a certain radius.
- There is no pre-defined hierarchy among the agglomeration centers (Kloosterman and Lambregts (2009)). Therefore, the population values (and thus also the distribution function) are roughly the same. The sizes of the agglomerations may however differ.
- Thoroughly modeling the exact transfer penalties in the model is expected to be too complex and it is also not the focus of this research. Garcia-Martinez *et al.* (2018) underlines that making a transfer is perceived as disutility by the user and thus it seems valuable to not disregard transfer penalties entirely in the model. Similarly to what was used by Van Nes (2002) as a value

for transfer penalty, in this research a generic transfer penalty value is assumed to be 5 minutes. Besides this transfer penalty, additional waiting times are assumed for each transfer as well. These are again equal to half the headway. The transfer penalties and waiting times are only assumed when there is a change in mode on a certain path.

- The value of β_{IVT} is assumed to be 1.0. While this parameter increases with crowding effects (Cats, West and Eliasson (2016)), crowding effects are not assumed in this model. Therefore, it is chosen to assume a value of 1.0. The value of β_{wait} is assumed to be 1.5, which is based on values found in past research by Willer (2019). As the values for this parameter vary per situation, an 'average' value of 1.5 is assumed for this research.
- To reduce computational times, expansion candidates for the interregional mode are determined by choosing the highest populated node within a cluster of nodes in a radius of 6 km. This node is then considered as the candidate node for an interregional expansion. For the regional mode the same is done but with a radius of 4 km. The effect of this assumption is that hierarchy within nodes may be steered stronger.

5. Numerical experiments: Results and interpretations

The results of the numerical experiment are discussed in two parts. Firstly, the final network states of the different scenarios are discussed in section 5.1. Secondly, the evolution processes of the networks are discussed in section 5.2. Hereafter, a sensitivity analysis is done in section 5.3 to investigate the impact of the input assumptions on the resulting network evolution. Finally, the conclusions of the numerical experiments are discussed in section 5.4

5.1 Final network states

Section 5.1.1 firstly gives an overview of the generated networks. The overview consists of the visualisations of the networks and the user costs of each scenario. Besides this overview, various topological and performance indicators of the final network states are shown in this section. Hereafter, the impacts of the various aspects mentioned in chapter one on the network evolution are discussed: spatial structure of the urban area, demand distribution, operational costs and multimodality. These are discussed in sections 5.1.2 – 5.1.5 respectively.

5.1.1 Overview of generated networks

Firstly, an overview of the networks in terms of the number of nodes (N), links (E) and number of iterations (I) is given in Table 5.1.

Table 5.1: Overview of nodes (N), links (E) and number of iterations (I) done per scenario

Scenario	N	E	I
LLNM	60	73	88
LENM	60	69	85
TUNM	59	66	74
TLNM	59	76	96
TENM	58	44	60
FUNM	60	96	166
FLNM	60	65	119
FENM	64	69	121
RUNM	62	78	136
RLNM	62	71	118
RENM	62	64	113
FUAM	60	113	208
RUNU	62	71	179
RLNU	62	55	147

The visualisations of the generated networks of the ‘standard’ scenarios and ‘non-standard’ scenarios are shown in Figure 5.1 and Figure 5.2 respectively. The line colours indicate the PT mode used:

- Blue for agglomeration links
- Green for regional links
- Red for interregional links

The line thickness indicates the frequency on the link; a thicker line means that the frequency is higher. The size of the nodes indicates the population size of each node; a larger node means a larger population.

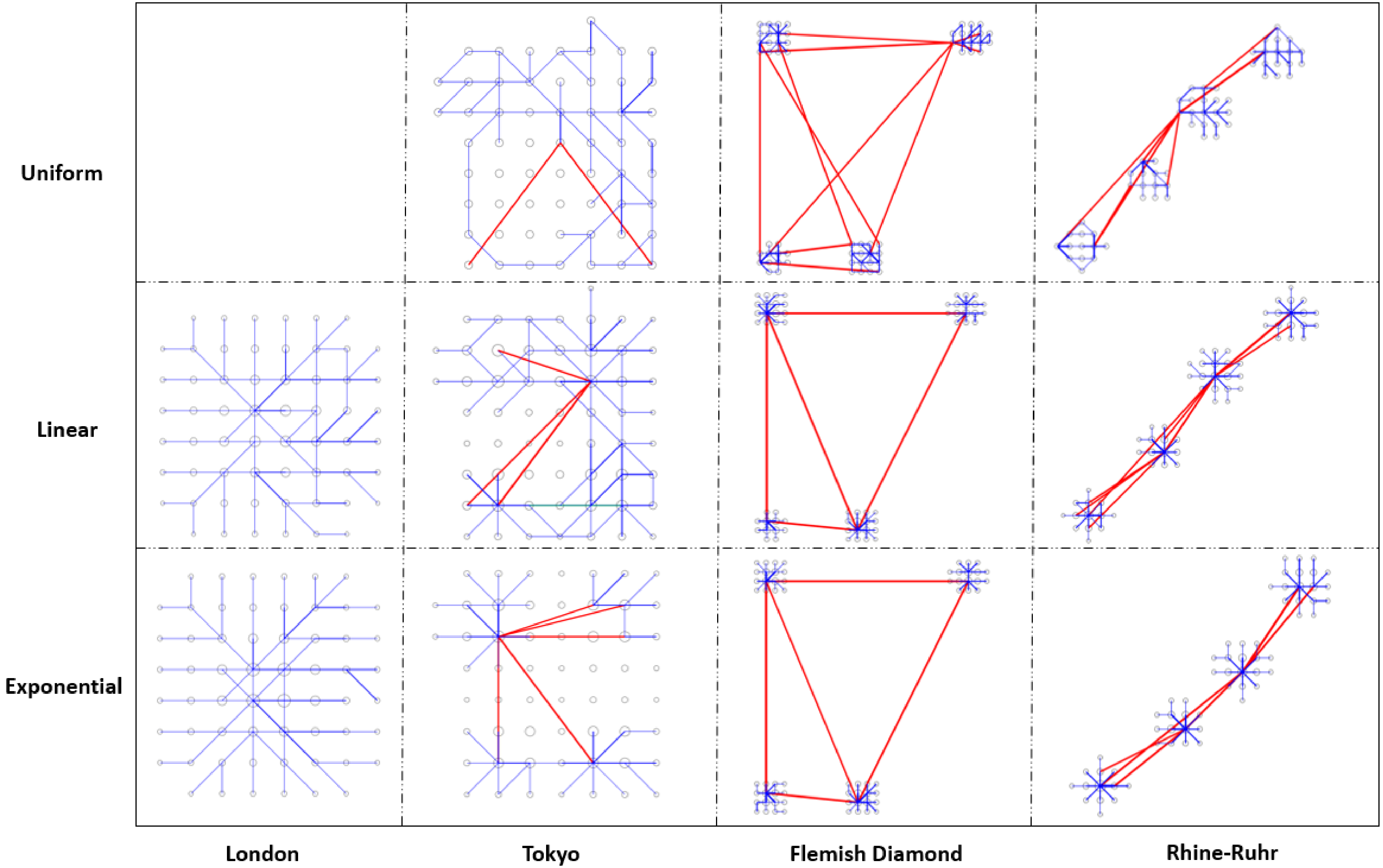

Figure 5.1: Visualisations of the generated networks in the 'standard' scenarios

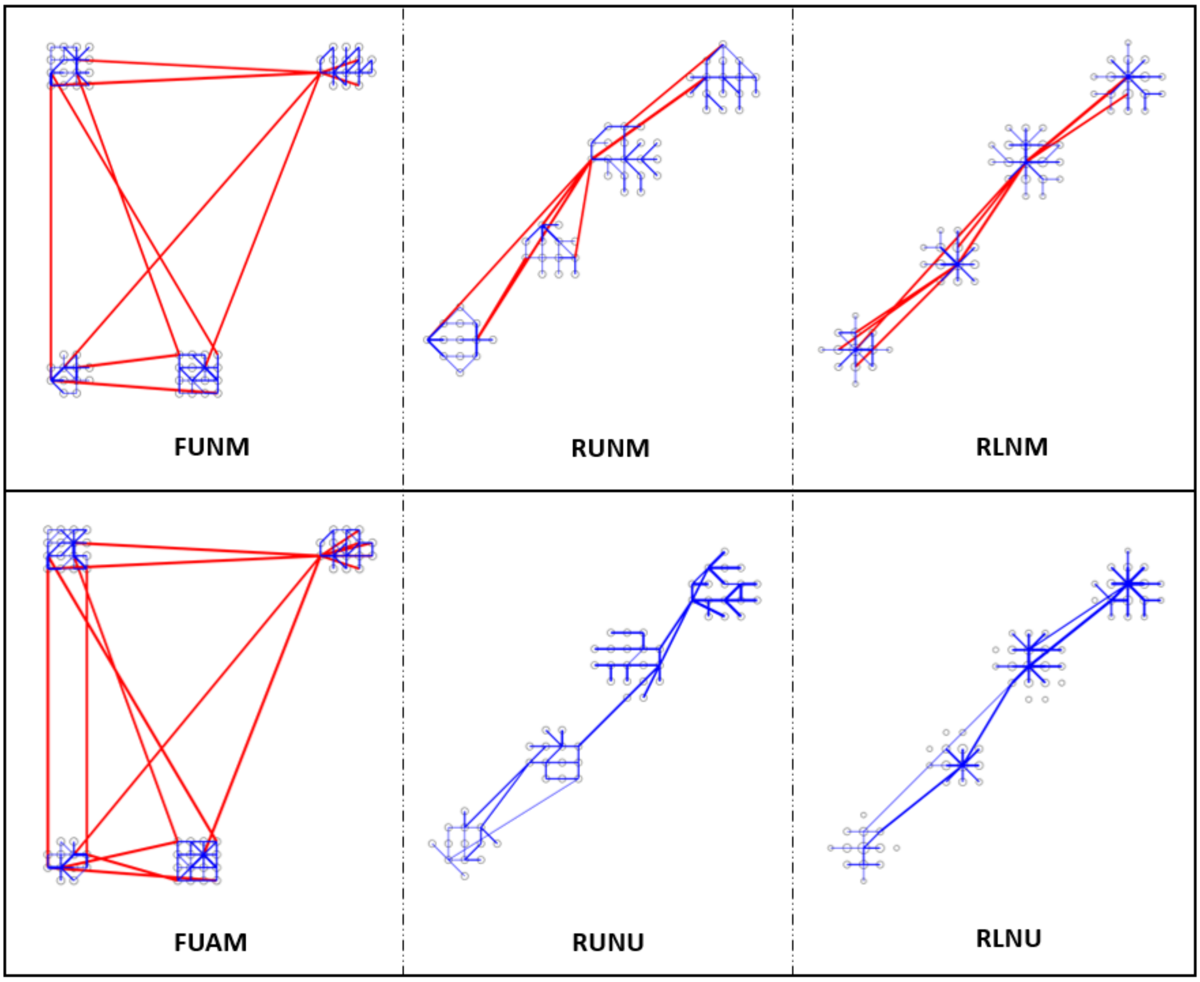

Figure 5.2: Visualisations of the generated networks in the 'non-standard' scenarios (bottom) and their respective 'standard' scenarios (top)

For all the 'standard' scenarios, with an exception of the 'Tokyo' scenarios, it is observed that all nodes get connected to the PT network. The reason for this exception could be found in the fact that the 'Tokyo' scenarios were 'unstable'. This means that with the initially set conditions for the network to evolve, the evolution process would stop very prematurely due to low scores (<1.0) early on. Therefore, additional tests were performed on the 'Tokyo' scenarios in which the networks evolved freely by choosing the highest scoring investment in each iteration without the condition that the score had to be above 1.0. Afterwards, the scores in each iteration were analysed and a cut-off point was determined manually. The general pattern in the scores was that these were almost all above 1.0, with sometimes a low scoring investment (<1.0) in between. These scores were accepted as long as the 4 subsequent scores were not also below 1.0. When a minimum of 5 low scores (<1.0) occurred, the last positive scoring investment would be set as the final iteration in the evolution process. The simulation would then be re-run up to this point, leading to the presented results. It is acknowledged by the author that this is an arbitrary method. However, for the sake of this research it is chosen to adapt this method in order to gain the necessary insights into the network evolution process. In sections 5.1.2 – 5.1.5 the results of the 'Tokyo' scenarios are therefore also interpreted more carefully, acknowledging that the results may be inaccurate.

For the 'non-standard' scenarios only in the RLNU scenario not all nodes were connected to the PT network. The unconnected nodes are all on the edge of the agglomerations. This could be due to the combination of low demands and low operational speed of the PT mode. This claim will be elaborated on further in section 5.1.3 and 5.1.5.

One notable point in these visualisations is that there is only one regional link constructed in all scenarios put together. The reason for this is possibly the limited distance ranges between nodes at which it is possible to consider a regional link (3 – 6 km). On top of this fact it is possible that the operational speed and the cost parameters assumed for the regional mode may not be in balance. This could mean that generally the costs are more likely to outweigh the benefits, while this is less the case with agglomeration and interregional links.

In every scenario the total of user costs and the break-down of these user costs vary, as can be seen in Figure 5.3. Further elaborations on these differences are given in sections 5.1.2 – 5.1.5.

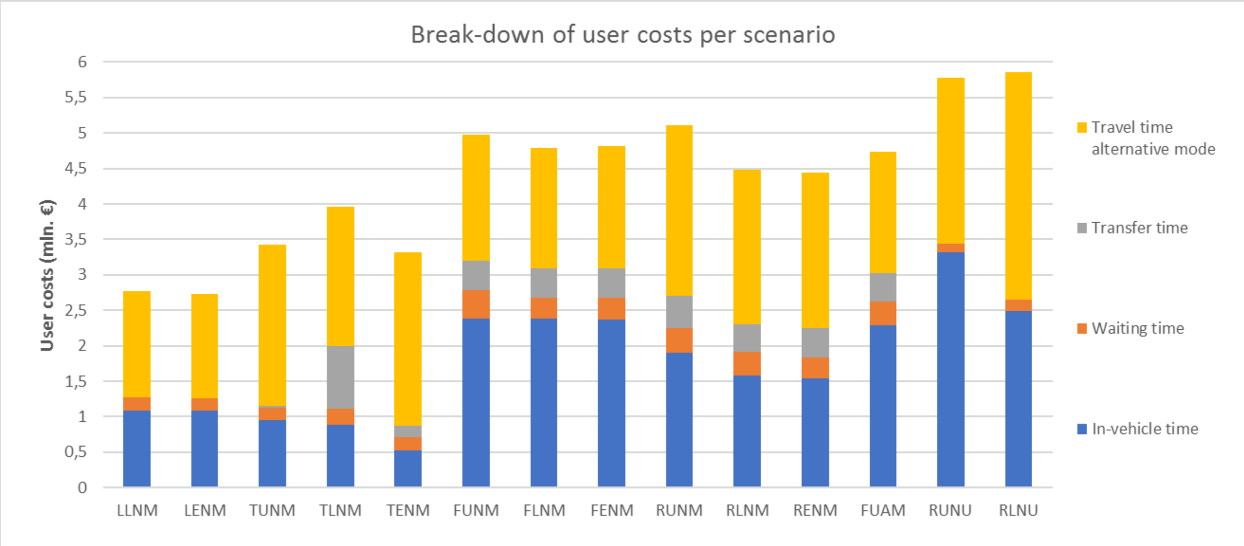

Figure 5.3: Break-down of user costs per scenario

In terms of topology and performance indicators, comparisons are made in the following sub-sections to discuss the notable differences in terms of connectivity, directness, the modal share of PT users, the modal split within the PT network and the betweenness centrality. Complete overviews of all these indicators are visualized and shown in Appendix B.

5.1.2 Impact spatial structure of urban area

To analyze the impact that the spatial structure of the urban area has on the topological evolution of the network, comparisons of the final network states are made between the 'standard' scenarios. Scenarios with different spatial structures but the same demand distribution are compared to each other; e.g. LLNM - TLNM - FLNM – RLNM.

Firstly, the spatial structure of the urban area has an impact on the modal share PT. An overview of these values is shown in Figure 5.4, where a division is made between different spatial structure prototypes and different demand distributions. The percentages below the circle diagrams indicate the modal share of PT, while the percentages within the circle diagrams are the shares of network length of each PT mode.

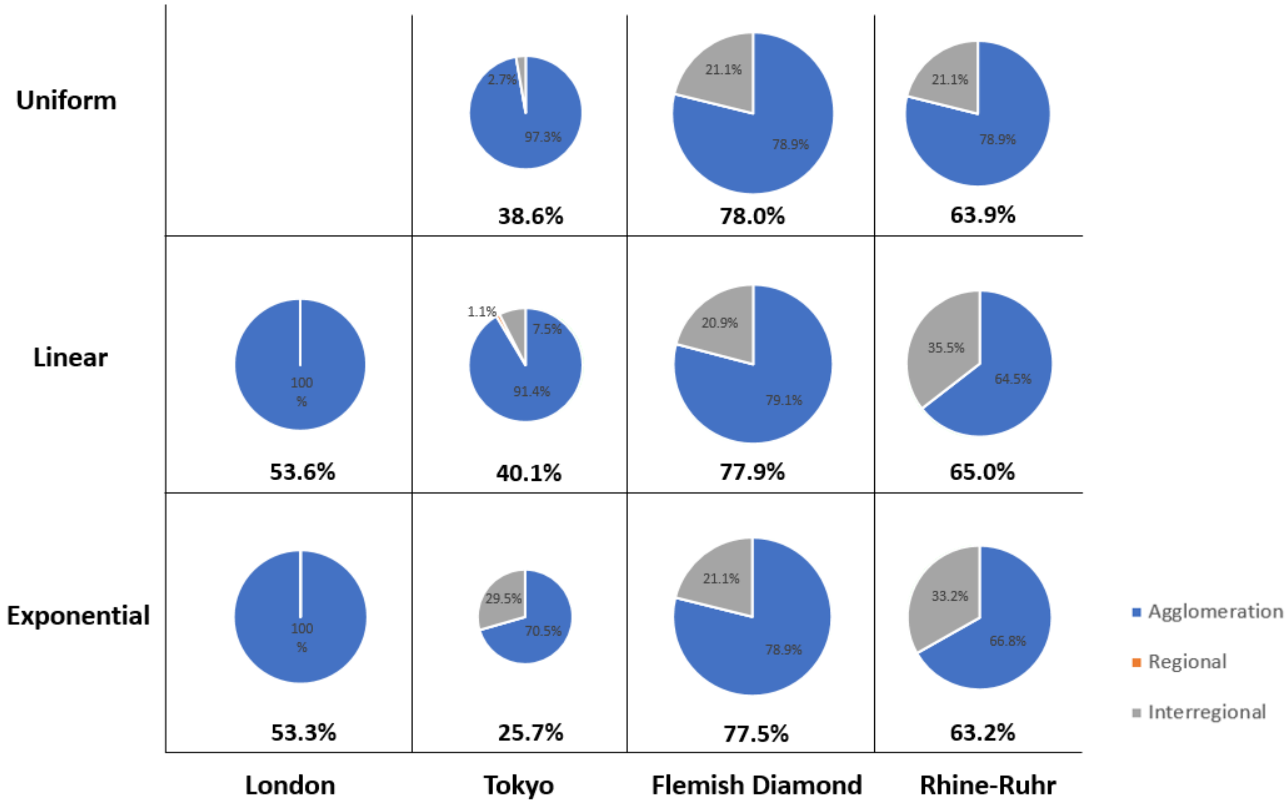

Figure 5.4: Overview of modal shares of PT for 'standard' scenarios per spatial structure prototype and per demand distribution

While these values are similar among spatial structures with different demand distributions ('Tokyo' as exception), there are differences to be observed between different spatial structures. The highest values are found in the 'Flemish Diamond' scenarios, followed by the 'Rhine-Ruhr' scenarios, the 'London' scenarios and finally the 'Tokyo' scenarios. The reason for this ranking can be found in the distances travelled; while the number of nodes within each scenario is equal, certain spatial structures cover a larger area in space. The distances between agglomerations in the 'Flemish Diamond' prototype for example are generally larger than in the 'Rhine-Ruhr' prototype, while the average distance between nodes in the 'London' prototype is even smaller. As the speed of the alternative mode is lower than those of the PT modes and does not change over distances travelled, the longer the distances to be travelled the more benefits PT has over the alternative mode. It therefore seems logical that the modal share of PT is higher in the 'Flemish Diamond' and 'Rhine-Ruhr' prototypes.

In hindsight however, using a varying value for the speed of the alternative mode may have led to more realistic results. For example, travelling between two agglomerations usually means driving over freeways where generally a higher speed can be reached.

Secondly, the spatial structure has an impact on the most optimal PT mode. The PT infrastructure shares visualized in Figure 5.4 show that mainly these shares vary over different spatial structures. As can be observed in the 'Flemish-Diamond' scenarios and 'Rhine-Ruhr' scenarios, it is generally observed that the interregional links are mainly used between agglomerations and rarely within an agglomeration (Figure 5.5). Within an agglomeration, generally the agglomeration links are used.

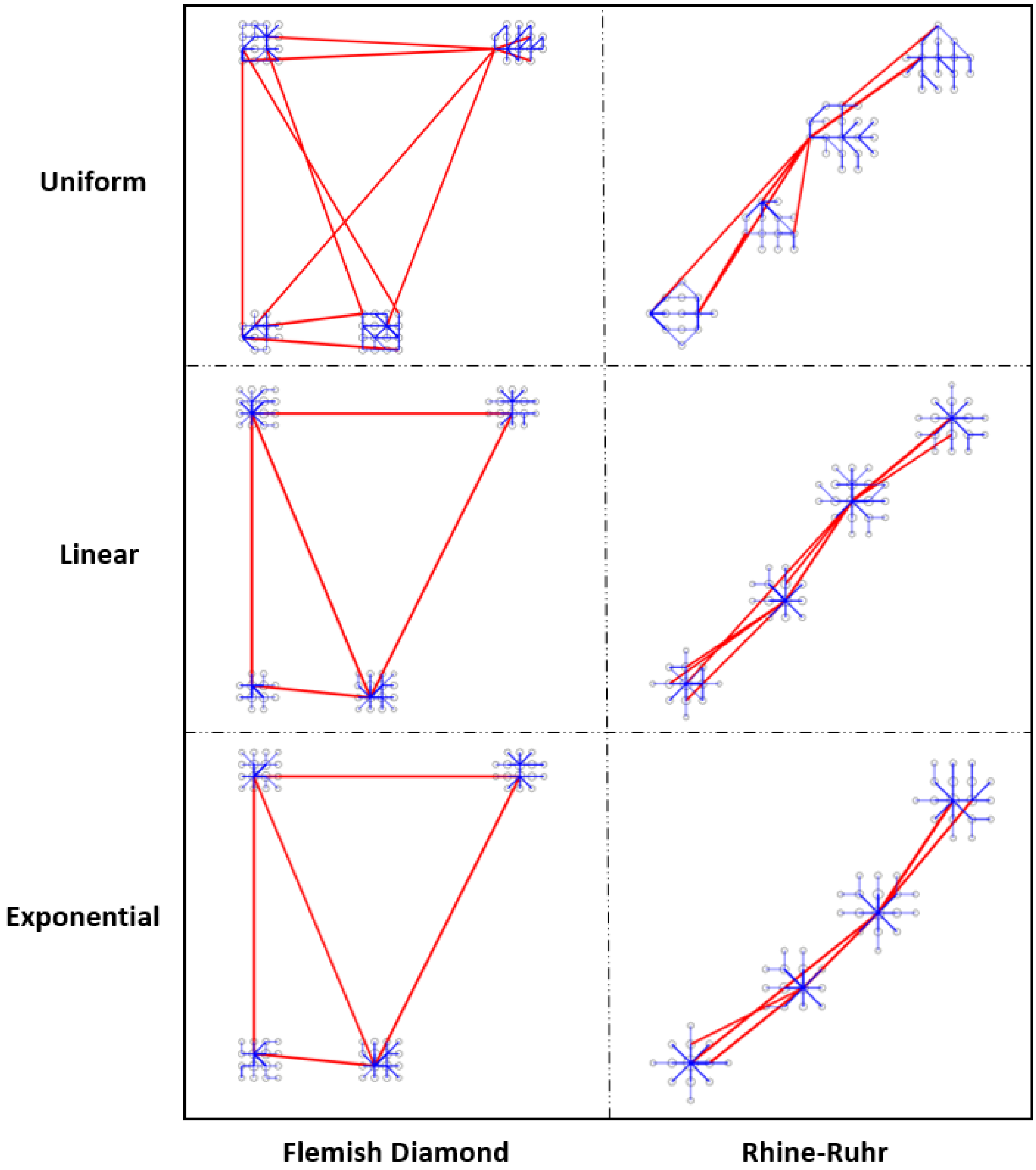

Figure 5.5: Visualisations of the generated networks in 'standard' scenarios of 'Flemish Diamond' and 'Rhine-Ruhr' prototypes

As the model does limit agglomeration links to be used for distances above 3 km to save computational time, two additional experiments were run in which only agglomeration links could be constructed without the distance conditions. For these experiments the 'Flemish Diamond' prototype was chosen. One experiment was with a uniform demand distribution and the other with a linear demand distribution. Figure 5.6 shows the networks generated for these scenarios.

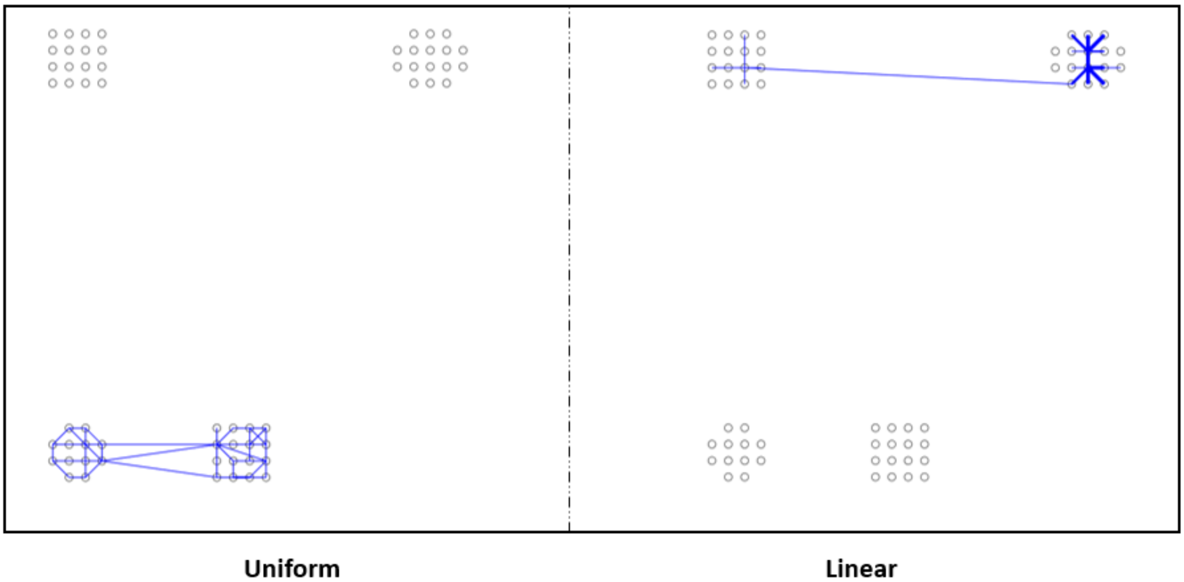

Figure 5.6: Visualization of generated networks of additional experiments

As can be seen, the Northern and Southern agglomerations don't get connected. The reason for this is arguably the large distance that has to be covered. As the operational speed on the agglomeration link is not much higher than that of the alternative mode, the costs of constructing long links outweigh the limited benefits that the link offers. This supports the claim that the spatial structure has an impact on the most optimal PT mode and is also in line with statements made by Van den Heuvel (1997); Van Nes (2002).

Thirdly, the spatial structure has an impact on the betweenness centrality. The comparisons of all unimodal, linear and exponential 'standard' scenarios are visualized in Figure 5.7, Figure 5.8 and Figure 5.9 respectively.

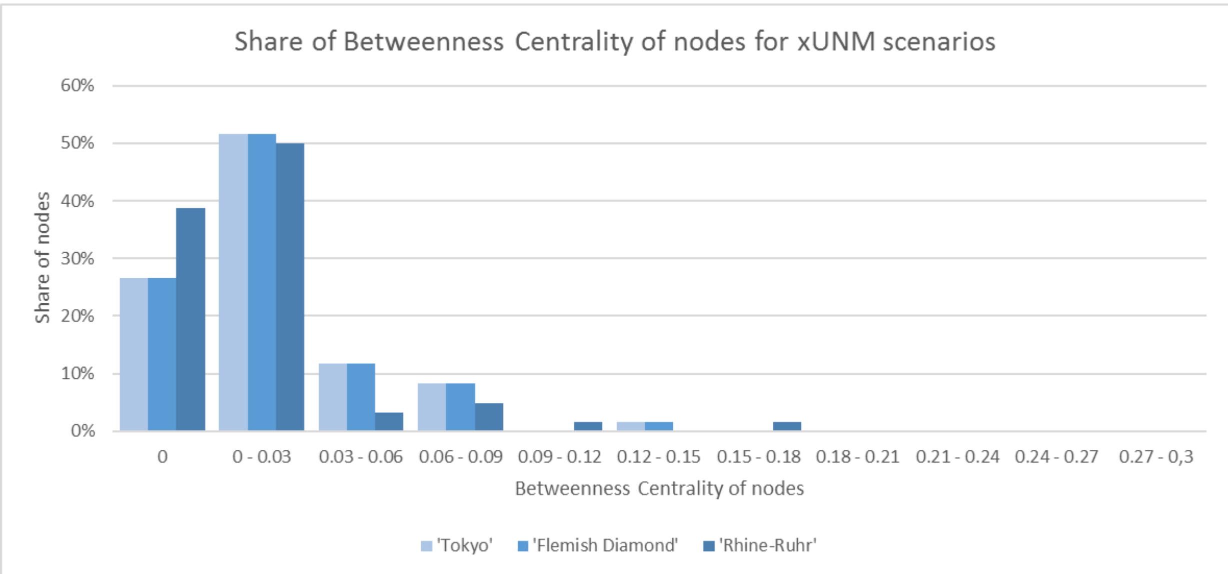

Figure 5.7: Share of betweenness centralities of nodes for the uniform 'standard' scenarios

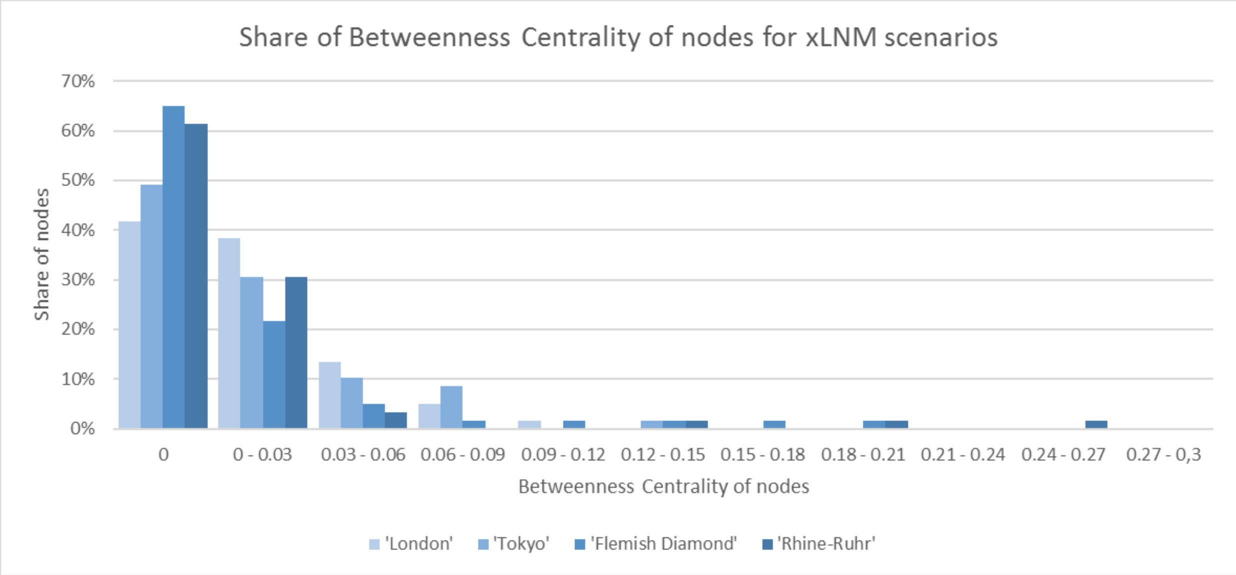

Figure 5.8: Share of betweenness centralities of nodes for the linear 'standard' scenarios

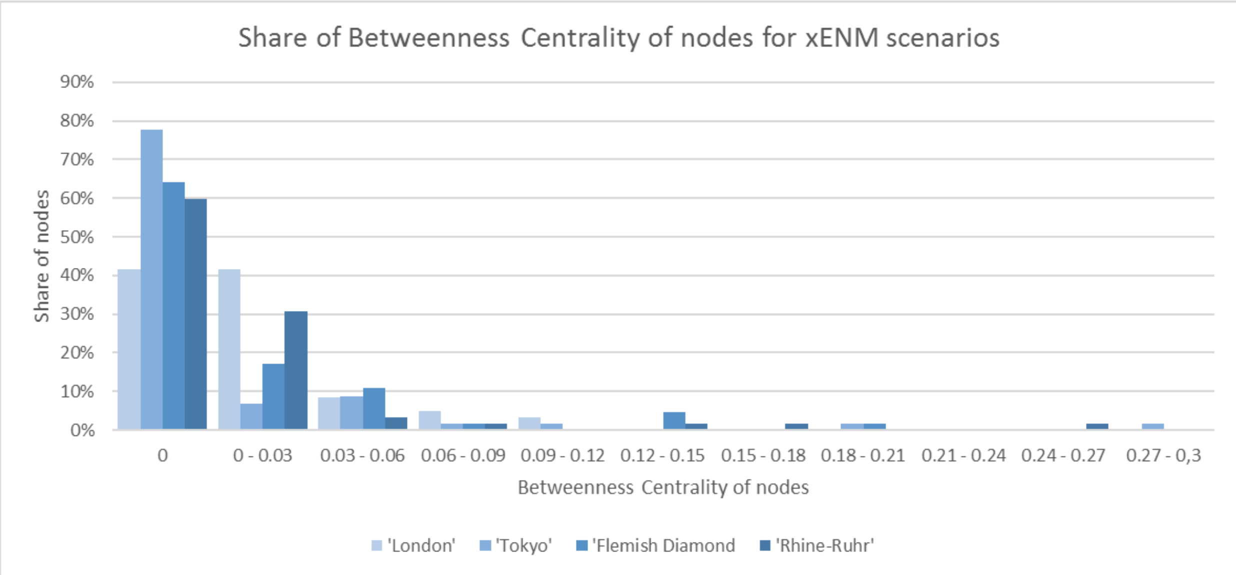

Figure 5.9: Share of betweenness centralities of nodes for the exponential 'standard' scenarios

In terms of the unimodal scenarios it is observed that the 'Rhine-Ruhr' scenario has a higher value at 0 and the maximum value is also larger, indicating that the hierarchy is more present in this spatial structure than in 'Tokyo' and 'Flemish Diamond'. This makes sense, as it is seen in Figure 5.10 that there is a clear 'central' point in the RUNM scenario at one of the agglomerations in the middle of the urban region. In this figure, the redder the dot, the higher the betweenness centrality value. In FUNM there is no clear central point, leading to more of a spread in terms of shortest paths. This spread is also more visible in the TUNM scenario, though these results may be inaccurate.

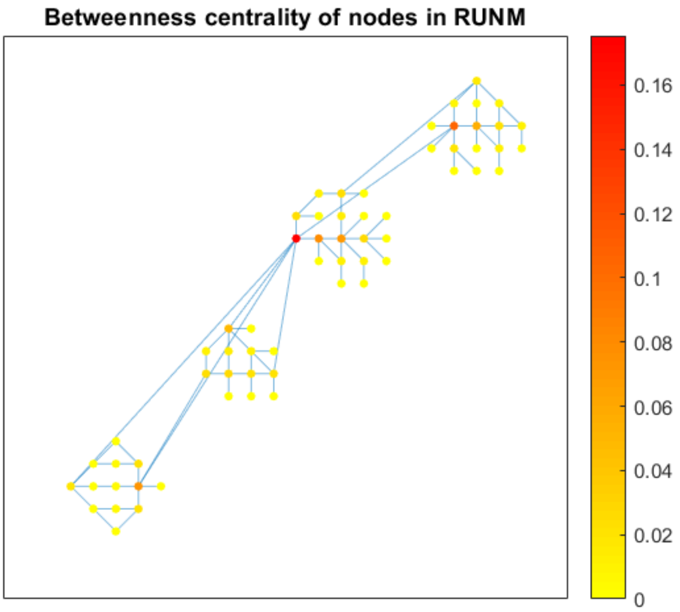

Figure 5.10: Visualization of betweenness centrality of nodes in RUNM

In terms of the linear and exponential scenarios, the main difference is that the 'London' scenarios have a smaller share of nodes with a betweenness centrality value of 0, while these are larger in the 'Flemish Diamond' and 'Rhine-Ruhr' scenarios (excluding TENM). As for the maximum betweenness centrality values, these are also lower for the 'London' scenarios. The 'Rhine-Ruhr' scenarios again have the highest maximum values of betweenness centrality, indicating that hierarchy in nodes is again strongest in this prototype, followed by 'Flemish Diamond' and then 'London'. The 'Tokyo' scenarios are left out of the comparisons as the results are not considered to be accurate.

Overall, it is concluded that the hierarchy in nodes is more evident in the 'Flemish Diamond' and 'Rhine-Ruhr' spatial structures, where there are multiple agglomerations, than in the 'London' spatial structure where there is a single agglomeration. The hierarchy is slightly more visible in the 'Rhine-Ruhr' spatial structure as the maximum value of the betweenness centrality is higher than the 'Flemish Diamond' spatial structure in all three demand distributions. This is arguably due to two of the four agglomerations in 'Rhine-Ruhr' having a more geographically central position.

Finally, the spatial structure of the urban area has an impact on the user costs (Figure 5.11).

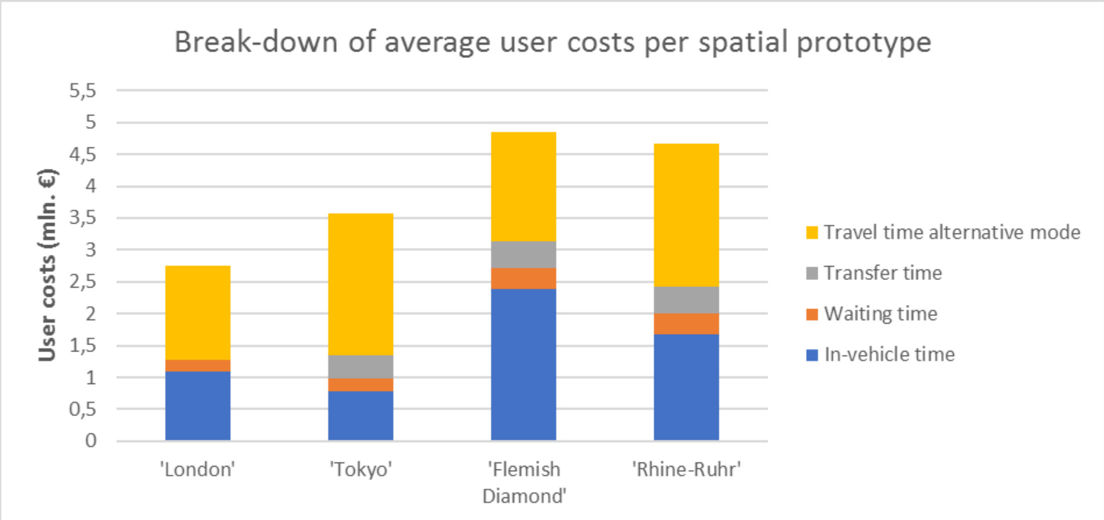

Figure 5.11: Break-down of average user costs for each spatial prototype ('standard' scenarios)

As can be expected, the networks in which longer distances have to be travelled, the total user costs are larger. This is mainly due to the costs linked to the higher in-vehicle times. As the 'London' scenarios both only consisted of agglomeration links, there is arguably only one network level. In the scenarios of the other prototypes there are multiple network levels; mainly interregional links between agglomerations and agglomeration links within agglomerations. In the cases of multiple network levels, there are additional waiting times and transfer times which also increase the total user costs. It should however be noted that in reality, there are transfer times even within the same network level due to the fact that each PT mode usually consists of different lines. This is however not incorporated in the model.

5.1.3 Impact demand distribution

To analyze the impact that the demand distribution has on the topological evolution of the network, comparisons of the final network states are made between the 'standard' scenarios. Scenarios with different demand distributions but the same spatial structure are compared to each other; e.g. FUNM – FLNM – FENM.

Firstly, the demand distribution has an impact on the connectivity of the network. For each spatial prototype, it holds that the connectivity is lowest in the case of an exponential demand distribution and highest in the case of a uniform demand distribution. The exception to this is the 'Tokyo' prototype with uniform demand distribution. This is possibly due to the unstable evolution process and the fact that in these scenarios not all nodes are connected to the PT network, while this is the case for the other scenarios. It is therefore opted to not include these scenarios in the comparison of connectivity. Comparisons of the connectivity values for the two/three demand distributions for the 'London', 'Flemish Diamond' and 'Rhine-Ruhr' scenarios are shown in Figure 5.12. The reason for a lower connectivity in the case of an exponential demand distribution can be explained by the differences in demand within agglomerations: the demand is much smaller in the outer areas than in the central areas. This means that it is less beneficial to connect the nodes in the outer areas in the network. Therefore, fewer links are constructed, leading to a lower connectivity. Following this reasoning, it then also seems logical that the connectivity is highest in the case of a uniform demand distribution as the demand is equal in all nodes. This means that the nodes in the outer areas will be generally better connected, also increasing the connectivity.

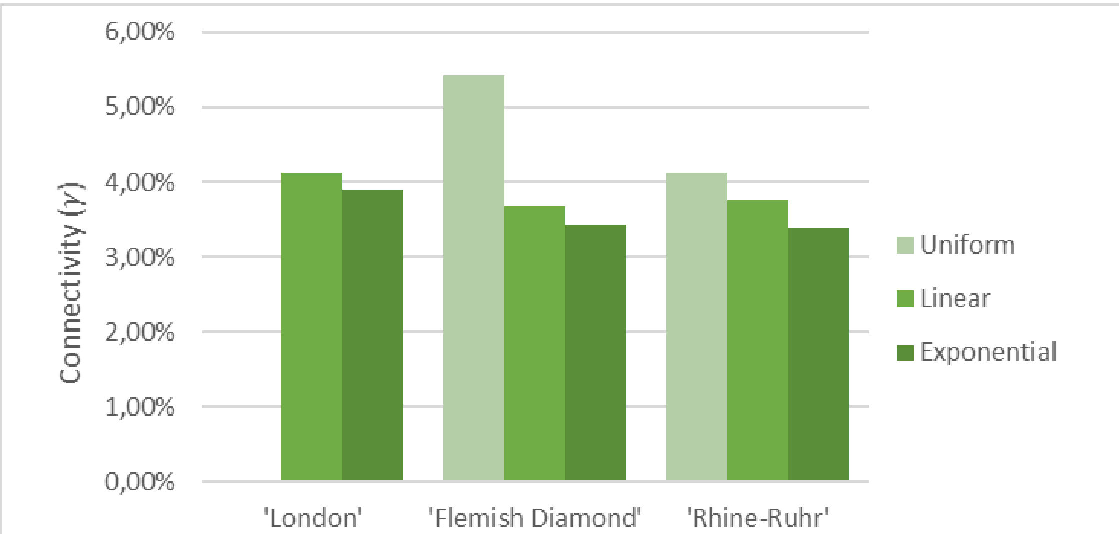

Figure 5.12: Connectivity values in generated networks for the 'London', 'Flemish Diamond' and 'Rhine-Ruhr' 'standard' scenarios

Secondly, the demand distribution has an impact on the most optimal PT mode. Considering the visualisations in Figure 5.1, the interregional links are mainly constructed between high demand nodes in the linear and exponential demand distribution scenarios. The exception of this rule is the 'London' prototype. However, in the 'London' prototype the high demand nodes are close to each other in the center of the agglomeration. It is therefore unlikely an interregional link is constructed between these nodes, as it has been explained in section 5.1.2 that these links are mainly beneficial for longer distances. It can also be seen, in the linear and exponential demand distribution scenarios, that the agglomeration links around the large demand nodes are upgraded more than links in the outer areas of the agglomeration. As these high demand nodes generally function as the gateway between different agglomerations, it is beneficial to have a high frequency on the links directly (and locally) connected to these high demand nodes. As for the uniform demand distribution, the interregional links are generally connected to nodes on the edges of the agglomerations. This is arguably the case as the benefits of connecting one node to any node in an unconnected agglomeration is almost the same due to the uniform demand distribution. The costs are however lower if the constructed link is shorter, therefore these links are mainly constructed from edge to edge.

Thirdly, the demand distribution has an impact on the network shapes within agglomerations. Referring to Figure 5.1, in the linear and exponential demand distribution scenarios there is one clear central area within the agglomeration with a high node degree. This central area is connected to the outer areas of the agglomeration in a radial manner, creating star-like shapes. In the uniform demand distribution scenarios however, it can be observed that rings on the outer edges of the agglomerations are created.

Lastly, the demand distribution has an impact on the betweenness centrality. This is visible in the share of betweenness centralities of nodes for the 'London', 'Flemish Diamond' and 'Rhine-Ruhr' 'standard' scenarios (Figure 5.13, Figure 5.14, Figure 5.15 respectively). The 'Tokyo' scenarios have again been left out of the comparison due to its instability.

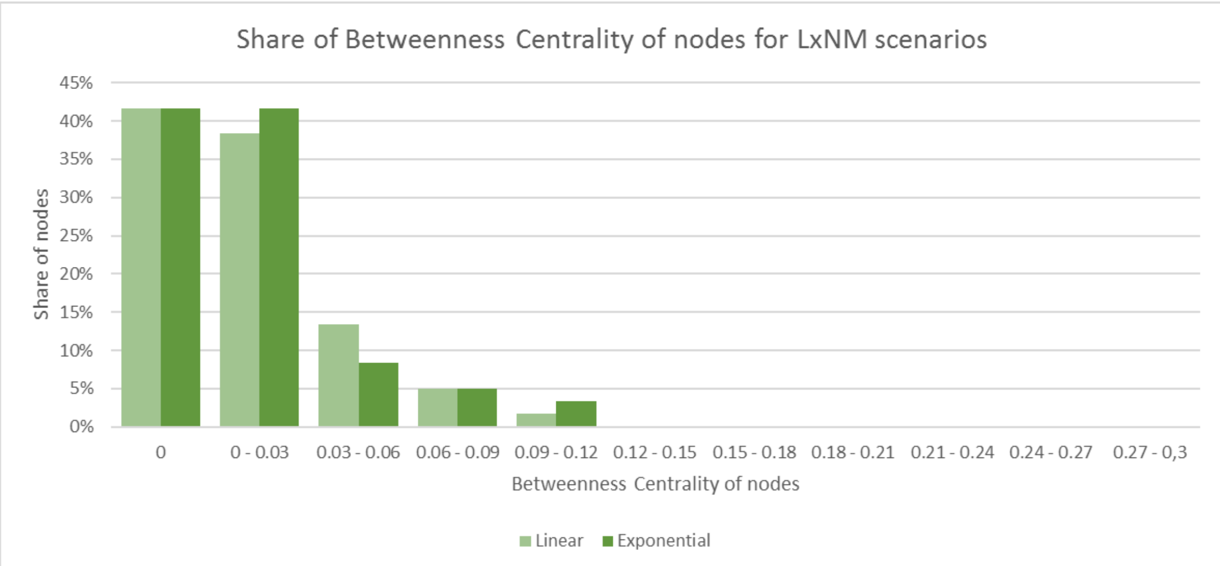

Figure 5.13: Share of betweenness centralities of nodes for the 'London' 'standard' scenarios

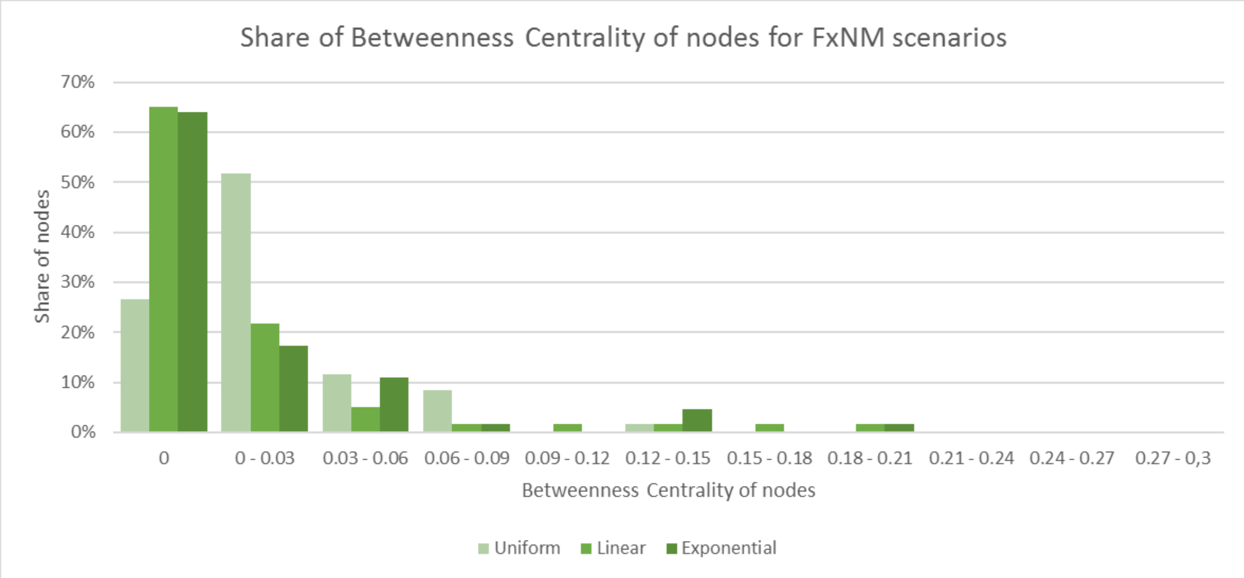

Figure 5.14: Share of betweenness centralities of nodes for the 'Flemish Diamond' 'standard' scenarios

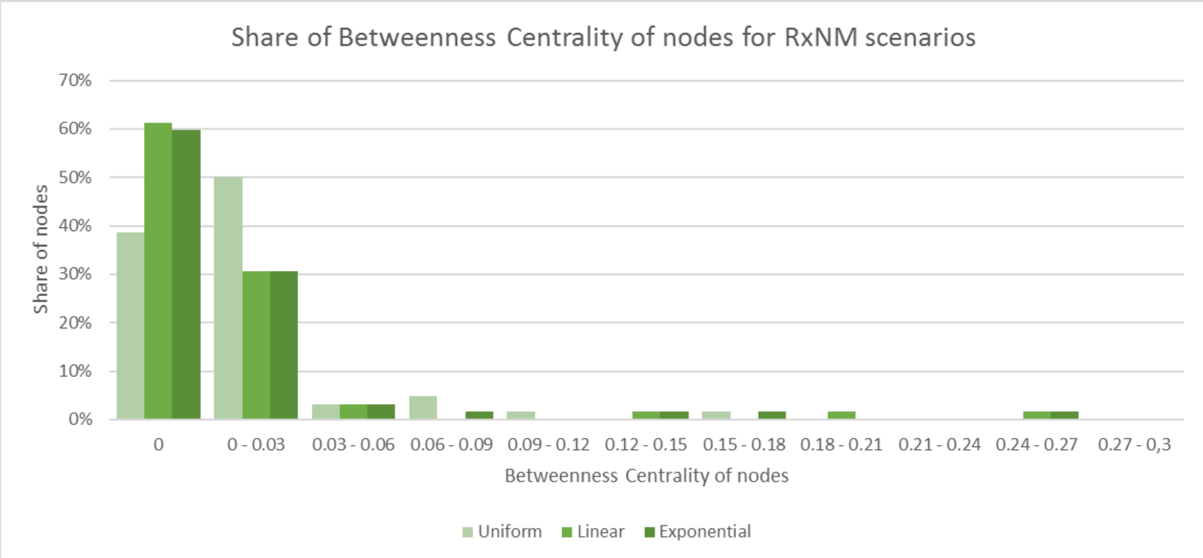

Figure 5.15: Share of betweenness centralities of nodes for the 'Rhine-Ruhr' 'standard' scenarios

For the linear and exponential scenarios, the share of nodes with a betweenness centrality of 0 is larger than for the unimodal scenarios. The peak of the distribution for the linear and exponential scenarios also lies at 0. For the unimodal scenarios it holds that the peak lies between 0 and 0.03, although this peak is lower than that of the linear and exponential scenarios. In terms of the tail of the distribution, the linear and exponential scenarios have a longer tail. This indicates that in these cases there are more nodes with a relatively high betweenness centrality. The combination of linear and exponential scenarios having a higher peak at 0 and a longer tail than the unimodal scenarios indicates that there is more of a hierarchy among nodes in these scenarios. Between the linear and exponential scenarios there are minimal differences.

Even though node hierarchy is less evident within the unimodal scenario, node hierarchy within the unimodal scenarios still occurs. Once one point gets connected to the network, it is more beneficial to connect another node to this already connected node rather than an unconnected node. As this node attracts more and more links because it offers more benefits as it is also connected to more other nodes, its position in the network becomes more and more important. The fact that hierarchy within the network develops in this manner, even though there is a uniform demand distribution, supports the theory of preferential attachment (Barabási and Albert (1999)) and that hierarchy in a network can be seen as a natural phenomenon (Van Nes (2002)).

5.1.4 Impact operational costs

To analyze the impact that the operational costs have on the topological evolution of the network, comparisons of the final network states are made between the FUNM and FUAM scenario (Figure 5.16).

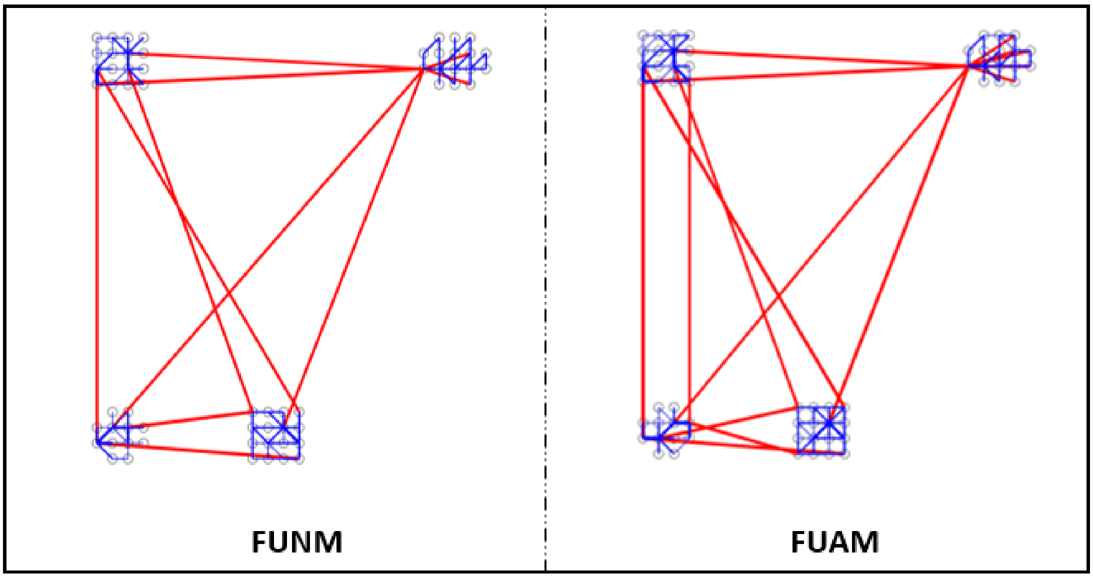

Figure 5.16: Visualisations of the generated networks FUNM and FUAM

Firstly, the operational costs have an impact on the connectivity and directness (Figure 5.17).

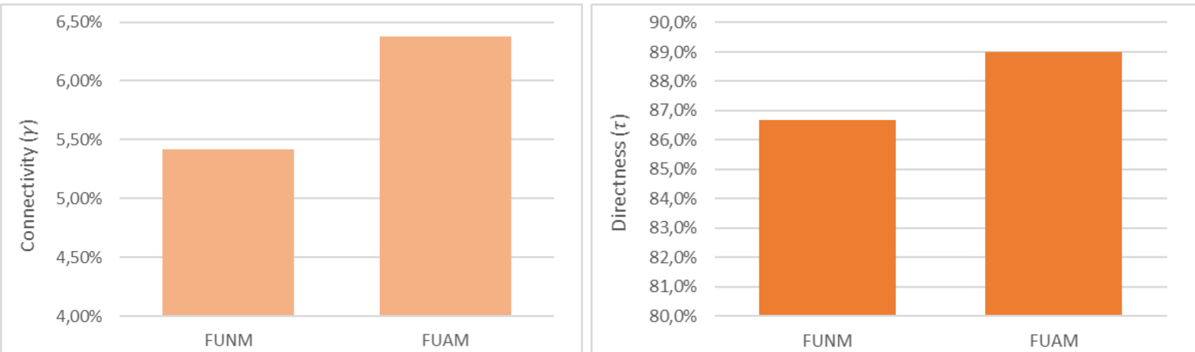

Figure 5.17: Connectivity values in generated networks FUNM and FUAM (left). Directness in generated networks FUNM and FUAM (right)

The lower operational costs assumed for vehicle automation means that generally the investment scores will be higher in FUAM as the benefits would be the same in both scenarios. As the generated network in FUAM is essentially the same as in FUNM, but with extra investments, it seems logical that more links are constructed in this case. These extra links lead to both a higher connectivity and directness value, 0.9% and 2.2% respectively.

Secondly, the operational costs have an impact on the total user costs and the break-down of these costs. The break-down of the user costs for FUNM and FUAM are shown in Figure 5.18. Due to the extra links constructed in the FUAM scenario the PT is slightly more attractive (78% vs 78.6%). This leads to a reduction in travel time with the alternative mode. Certain links have a higher frequency in FUAM and the extra links also lead to lower in-vehicle times in the FUAM scenario.

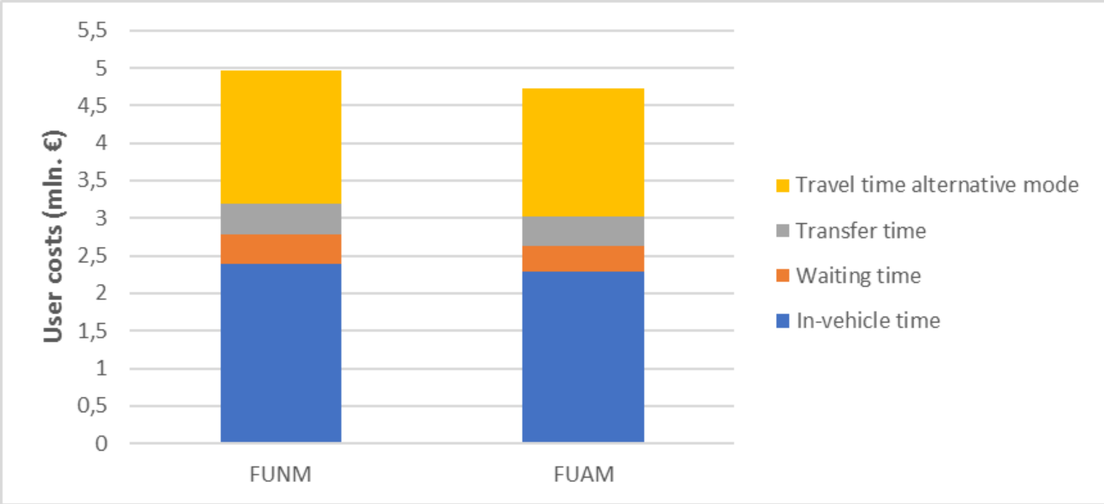

Figure 5.18: Break-down of user costs for FUNM and FUAM

Finally, the operational costs have an impact on the betweenness centrality. As the network develops further, due to the lower investment costs, the hierarchy in the network also shifts (Figure 5.19). As development continues, the share of nodes with a betweenness centrality of 0 decreases, while the share of nodes with a value between 0 and 0.03 increases. At the same time, the maximum value increases.

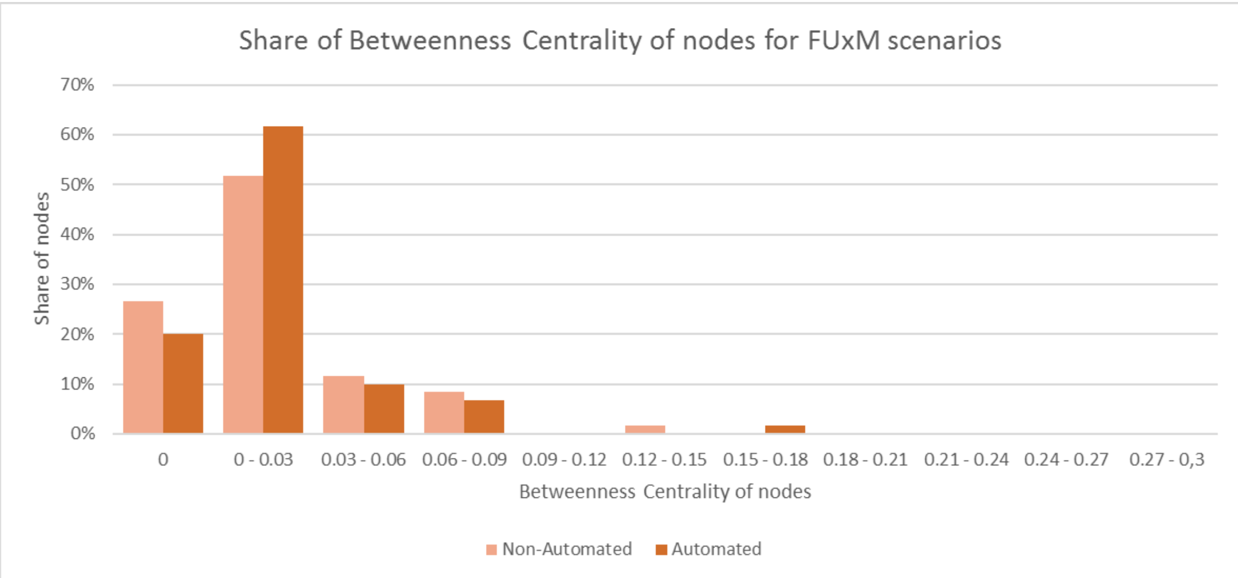

Figure 5.19: Share of betweenness centralities of nodes in generated networks FUNM and FUAM

This indicates that the 'important' node (the red node in the top-right in Figure 5.20) becomes more important, while the less 'important' nodes (with a betweenness centrality of 0) also become more important. Thus, the importance of the most 'hierarchical' node increases, while on the 'lower layers' of hierarchy, the nodes become relatively more equal in importance.

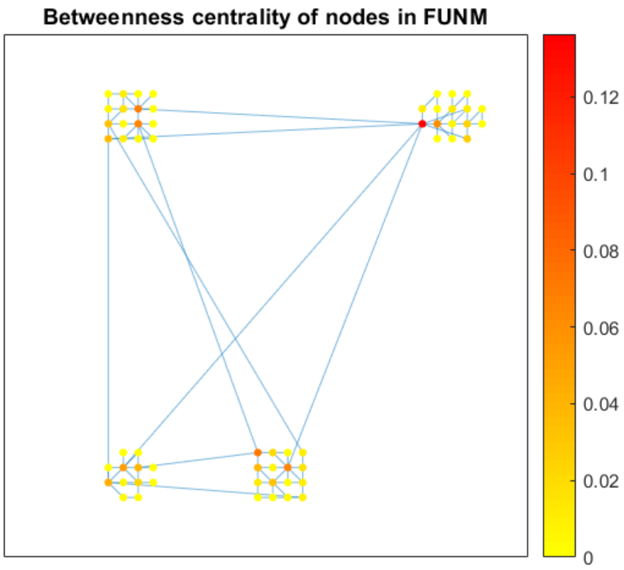

Figure 5.20: Visualization of betweenness centrality of nodes in FUNM

5.1.5 Impact multimodality

To analyze the impact that multimodality (in comparison to unimodality) has on the topological evolution of the network, comparisons of the final network states are made between the pairs RUNM-RUNU and RLNM-RLNU.

Firstly, multimodality in the network has an impact on the connectivity and directness values (Figure 5.21 and Figure 5.22 respectively).

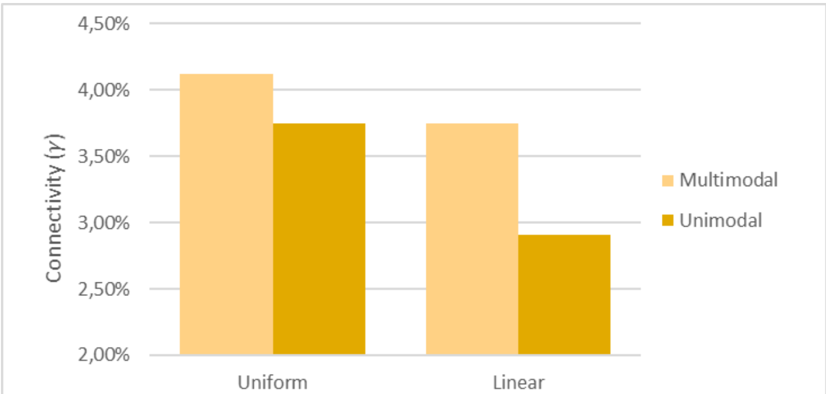

Figure 5.21: Connectivity values in generated networks RUNM, RLNM, RUNU and RLNU

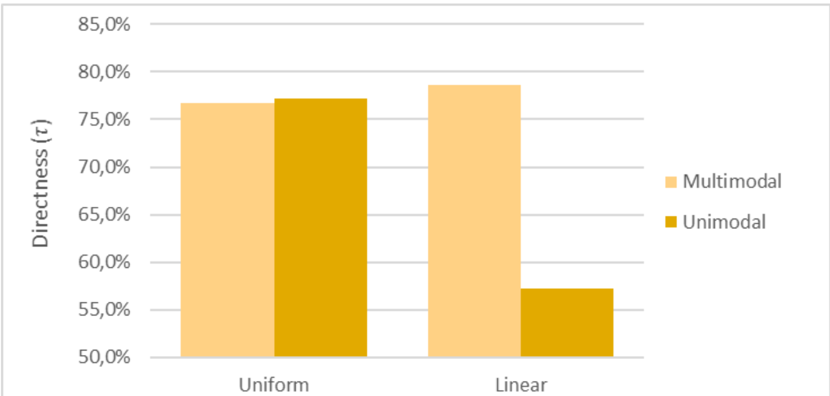

Figure 5.22: Directness values in generated networks RUNM, RLNM, RUNU and RLNU

In terms of connectivity, less links are constructed in the unimodal scenarios. In the RLNU scenario, certain nodes are even disconnected from the network. The disconnected nodes are in the outer areas of the agglomerations and therefore have a low demand. These low demands in combination with the low speed of the agglomeration mode in the unimodal case, lead to low benefits of connecting these nodes to the network. These disconnected nodes lead to the significantly lower connectivity and directness value in the RLNU scenario.

Secondly, multimodality in the network has an impact on the user costs and the break-down of these costs (Figure 5.23).

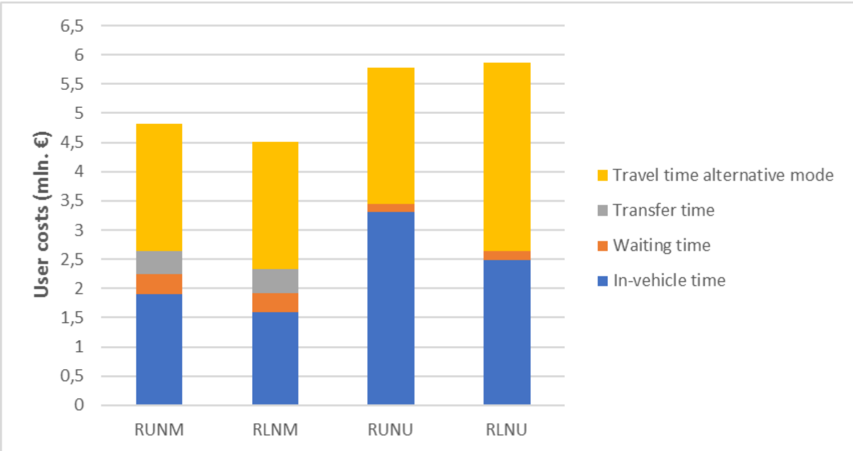

Figure 5.23: Break-down of user costs for RUNM, RLNM, RUNU and RLNU

The main differences between the multimodal and unimodal scenarios is that the in-vehicle time costs are higher in the unimodal scenarios. This is due to the fact that all links are agglomeration links in the unimodal scenarios, which have low speeds in comparison to the interregional links which are used in the multimodal scenarios. Furthermore, the waiting time costs are lower and there are no transfer time costs as there are no transfers to be made between different modes. Lastly, it can be observed that the travel time costs in the alternative mode are significantly higher in the RLNU scenario. This is due to the fact that some nodes are disconnected from the PT network in this scenario.

Lastly, multimodality in the network has an impact on the betweenness centrality (Figure 5.24 and Figure 5.25).

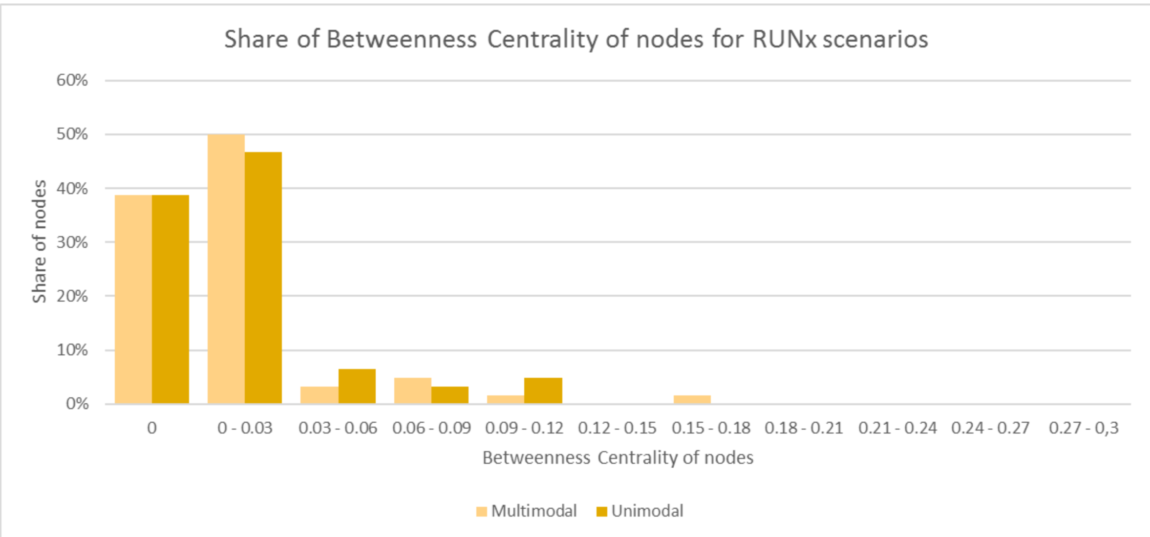

Figure 5.24: Share of betweenness centralities of nodes in generated networks RUNM and RUNU

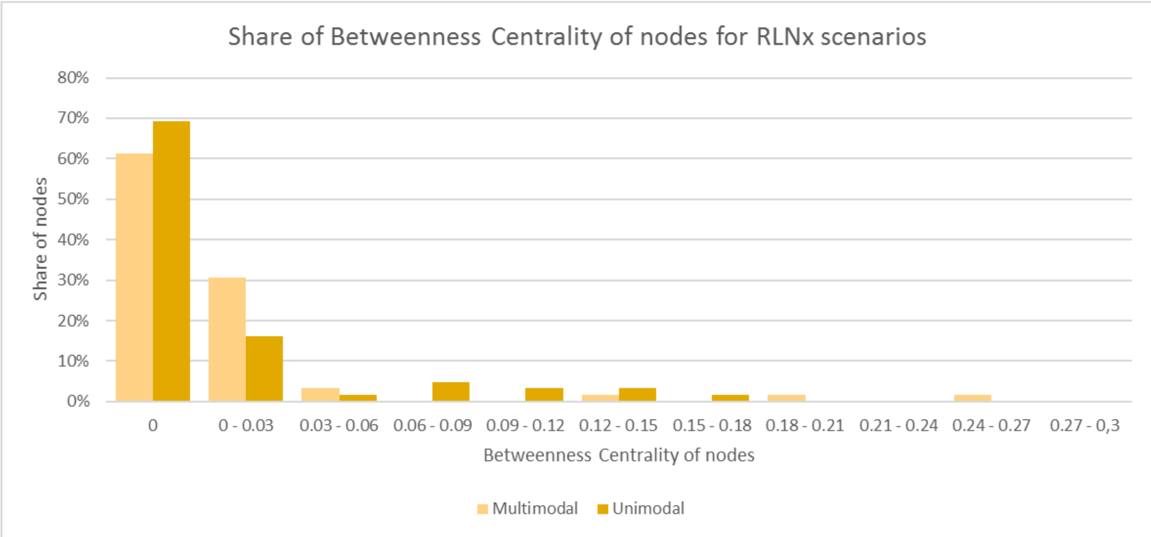

Figure 5.25: Share of betweenness centralities of nodes in generated networks RLNM and RLNU

In both comparisons it is observed that the maximum value is higher for the multimodal scenarios, while there are relatively more nodes with 'intermediate' values between 0.06 and 0.15 in the unimodal scenarios. This indicates that multimodality steers the network more towards a hierarchical structure, while this is less the case for a unimodal network.

5.2 Evolution process

In this section, the general patterns in terms of how the networks physically evolve are described and analysed by relating the observed evolution with the specifications of the scenarios. Firstly, some general findings which hold for (almost) all scenarios are discussed in section 5.2.1. Hereafter, similarly to section 5.1, the impacts that the spatial structure of the urban area, demand distribution, operational costs and multimodality have on the evolution process are discussed in sections 5.2.2 – 5.2.5 respectively. The full visual breakdowns of different phases in the evolution process for each scenario are shown in Appendix C.

5.2.1 General findings

Firstly, it is observed that the networks need some sort of critical mass in order to evolve. Each scenario starts with an initial network consisting of one single link. However, in the first few iterations the benefits generated by potential new links is limited due to the fact that only the initially connected two nodes gain travel time reductions. In early iterations it is therefore observed that the investment scores are below 1.0 as the costs of new potential links outweigh these limited benefits. After the network consists of a certain number of links, new potential links become beneficial up to the point that there were no beneficial links to be constructed anymore in the end. The critical mass is therefore described as the number of initial links necessary in the network for it to evolve in a stable manner. While the threshold value of this critical mass varies per scenario, this phenomenon is observed in almost all scenarios. For all scenarios therefore an initial condition is added: regardless of if the investment score is below 1, until 1% of the maximum possible number of links is constructed, the model chooses to invest in the highest scoring candidate. The exceptions for this rule are the Tokyo scenarios, which are unstable (see section 5.1.1).

Secondly, it is observed that the modal share of PT increases rapidly up to a certain equilibrium and almost stabilizes there. While it does still increase slightly after this equilibrium, the increase per iteration is insignificant in comparison to the first phase where it increases rapidly. Visualisations of how the modal share of PT increases per iteration for all scenarios are shown in Figure 5.26.

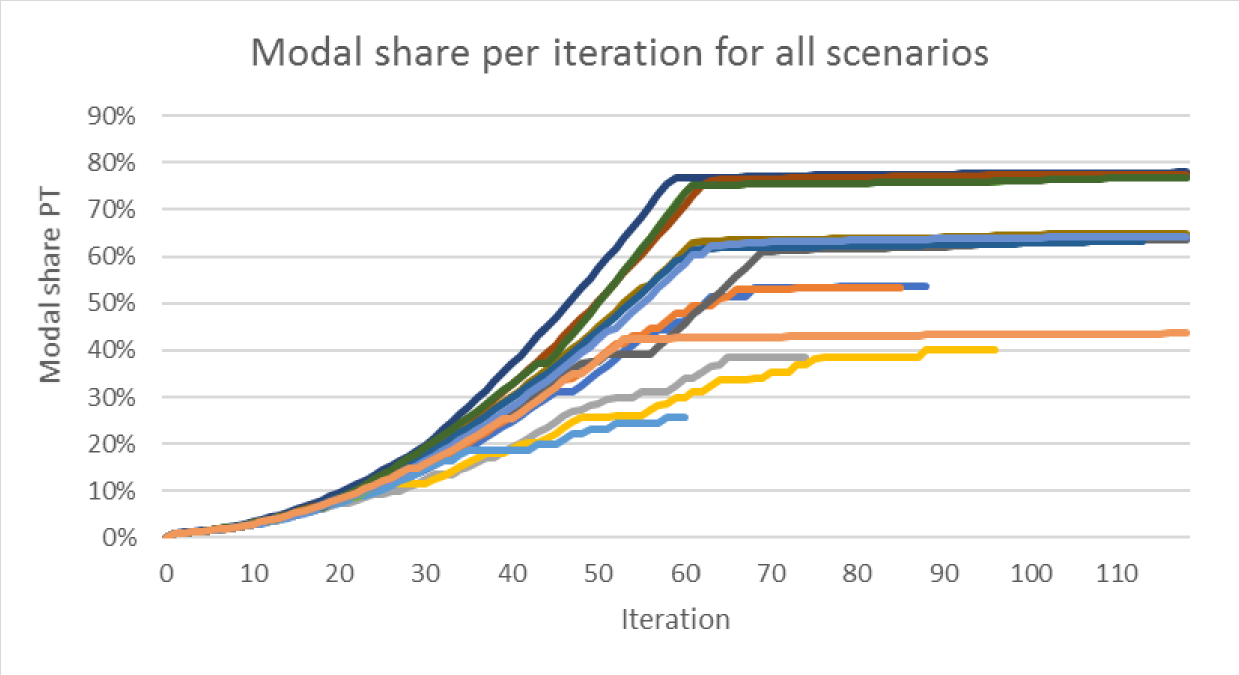

Figure 5.26: Modal share of PT per iteration for all scenarios

While each scenario differs in how rapidly the modal share of PT increases and at what iteration number and percentage it reaches its equilibrium, it is clear that all scenarios have such an equilibrium point. For all scenarios in which all nodes are connected, the equilibrium is reached at the point that the disconnected last node is connected to the PT network.

In terms of the evolution process there are three types of investments identified:

- *Expansion:* A link connecting a node that is part of the existing PT network to a node which is disconnected from the network; the network is expanded.
- *Densification:* A link connecting nodes which are already part of the network; the network is densified
- *Bulking:* The increase of frequency on an existing link; the link is 'bulked'

It should be noted that in the remainder of this thesis, these terms are used for the descriptions of investments.

5.2.2 Impact spatial structure of urban area

For different spatial structure prototypes, the manner in which the networks evolve differ. When comparing the four prototypes, it is observed that each prototype has a distinct evolution pattern. Lastly, an effect referred to as 'hurdle distance' is observed in a number of evolution processes. This effect is briefly discussed at the end of this sub-section.

'London' prototype

The four notable evolution phases in the LLNM scenario are shown in Figure 5.27 and are similar to those of the LENM scenario. In both London scenarios, the network expands from the center towards the outer areas in a radial, tree-like manner. After all nodes are connected to the PT network, the network densifies further. At a certain point the network stops densifying and the evolution process is finished with a number of bulking investments.

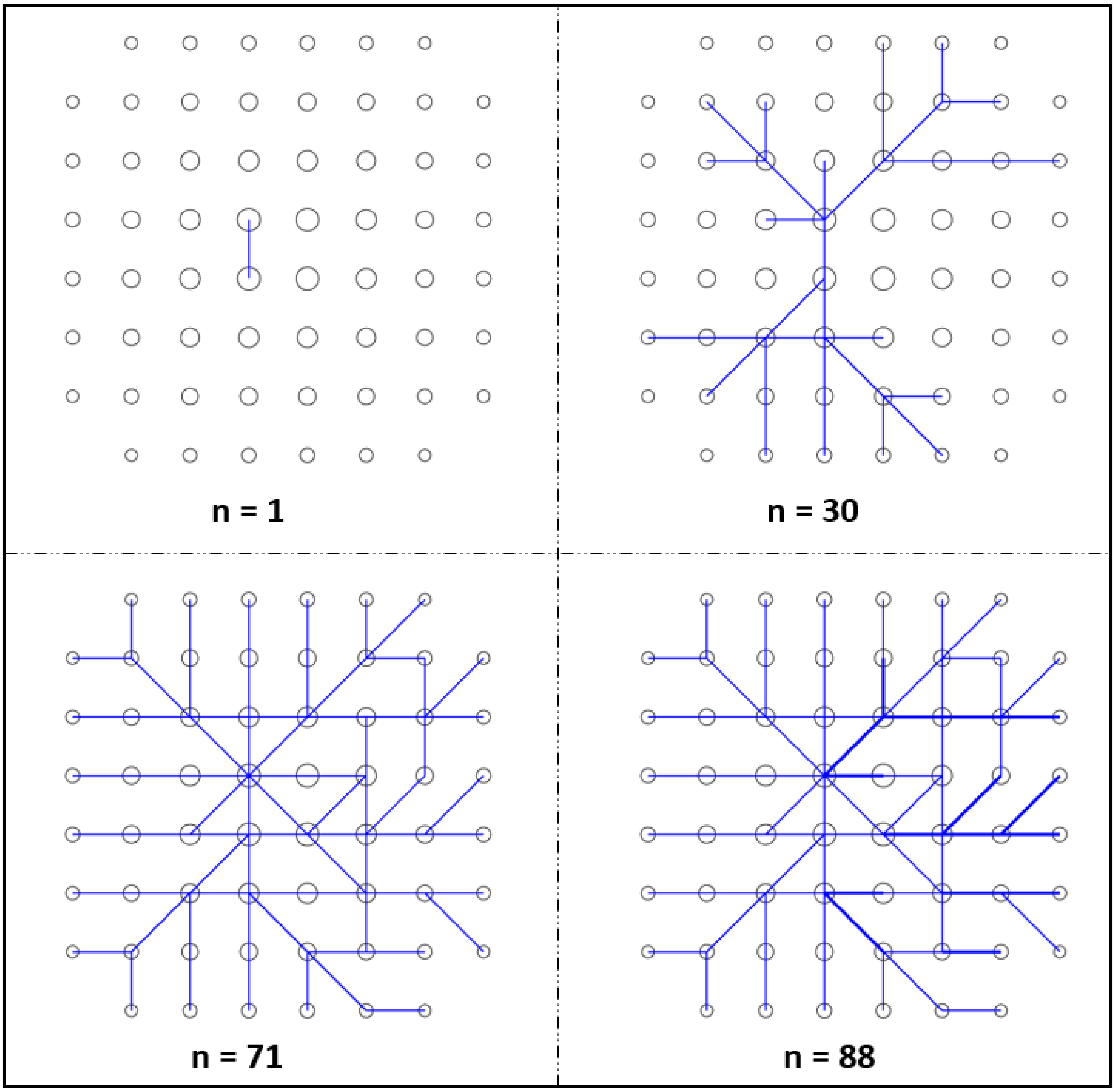

Figure 5.27: Evolution phases LLNM scenario

To provide further insight into the exact type of investments made during the evolution process, Figure 5.28 shows a timeline of the investments made at each iteration.

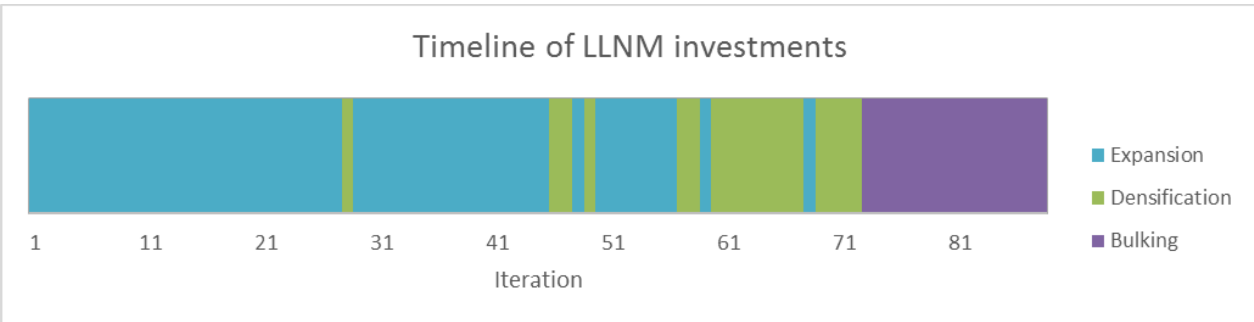

Figure 5.28: Timeline of LLNM investments made during the evolution process

Here it is clearly observed that the first part of the evolution process consists mainly of expansion investments until iteration 56. Hereafter, mainly densification investments are made, with an exception of two expansion investments, until iteration 72. The final part of the evolution process consists solely of bulking investments.

When looking at the investment scores of the LLNM scenario (Figure 5.29), it is observed that the critical mass is reached at iteration 8 and the decline in scores starts at iteration 71. The latter point corresponds to the start of the bulking phase at the end of the evolution process. The peaks in the investment scores (iteration 60 and 66) correspond to the construction of certain links that have a large impact on the travel time reductions. An example of this is shown in Figure 5.30 where the investment made at iteration 60 is highlighted with a red circle. To travel from any node in the North-East to any node in the South-East (and vice versa) at iteration 59, you must travel through the central area. The link constructed at iteration 60 then reduces the travel time significantly for a number of OD-pairs and therefore has a peak investment score. This type of link is described as a 'missing link' in the network.

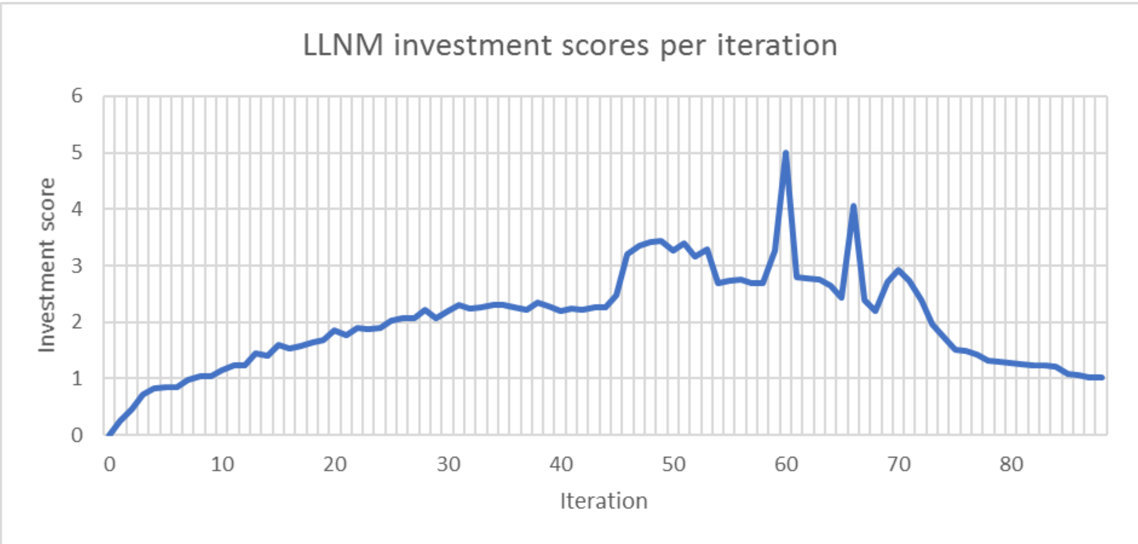

Figure 5.29: Investment scores per iteration of LLNM scenario – peak score at 60 corresponding to 'missing link'

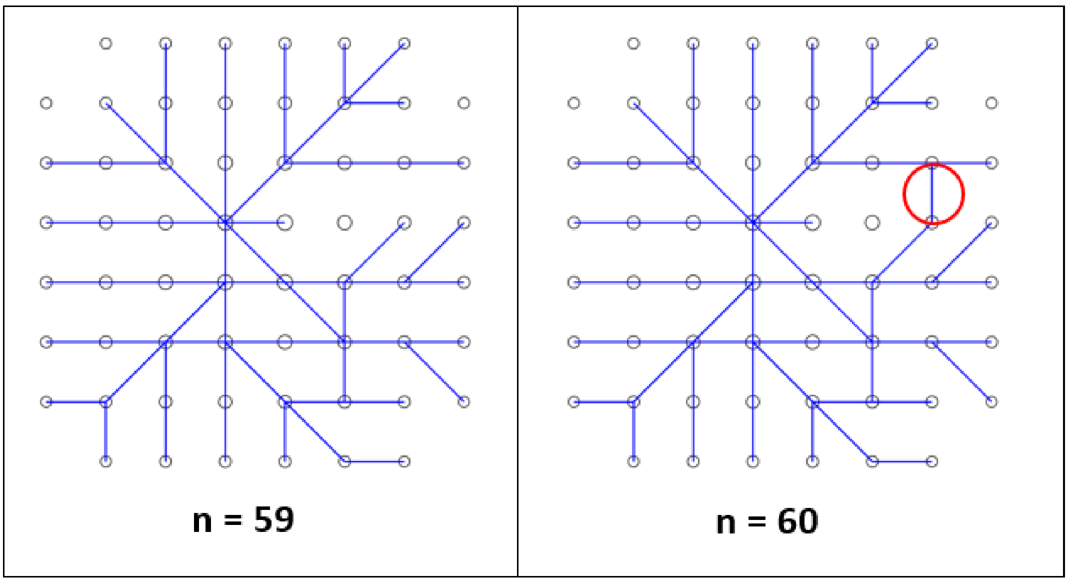

Figure 5.30: Example of high investment score in LLNM scenario

'Tokyo' prototype

As stated in section 5.1.1, the 'Tokyo' scenarios are unstable and it is therefore also difficult to make any statements regarding the evolution process of these scenarios. The example used for discussing the instability and evolution process of the 'Tokyo' scenarios is the TLNM scenario.

The four main evolution phases of the TLNM scenario are shown in Figure 5.31. The highly populated nodes in the North-east and South-west are firstly connected, after which a number of agglomeration links around these nodes are constructed in a star-like shape. The highly populated nodes in the North-west and South-east are later connected as well, with the interregional link from the North-east to North-west being constructed in iteration 30. The highly populated nodes in the four corners of the network however do not get connected directly to one another. In fact, the connection between the North-east and South-east is made with a network of agglomeration links. The connection between the South-west and North-west is not invested in; these trips are made over the existing interregional links between South-west and North-east, and North-east and North-west.

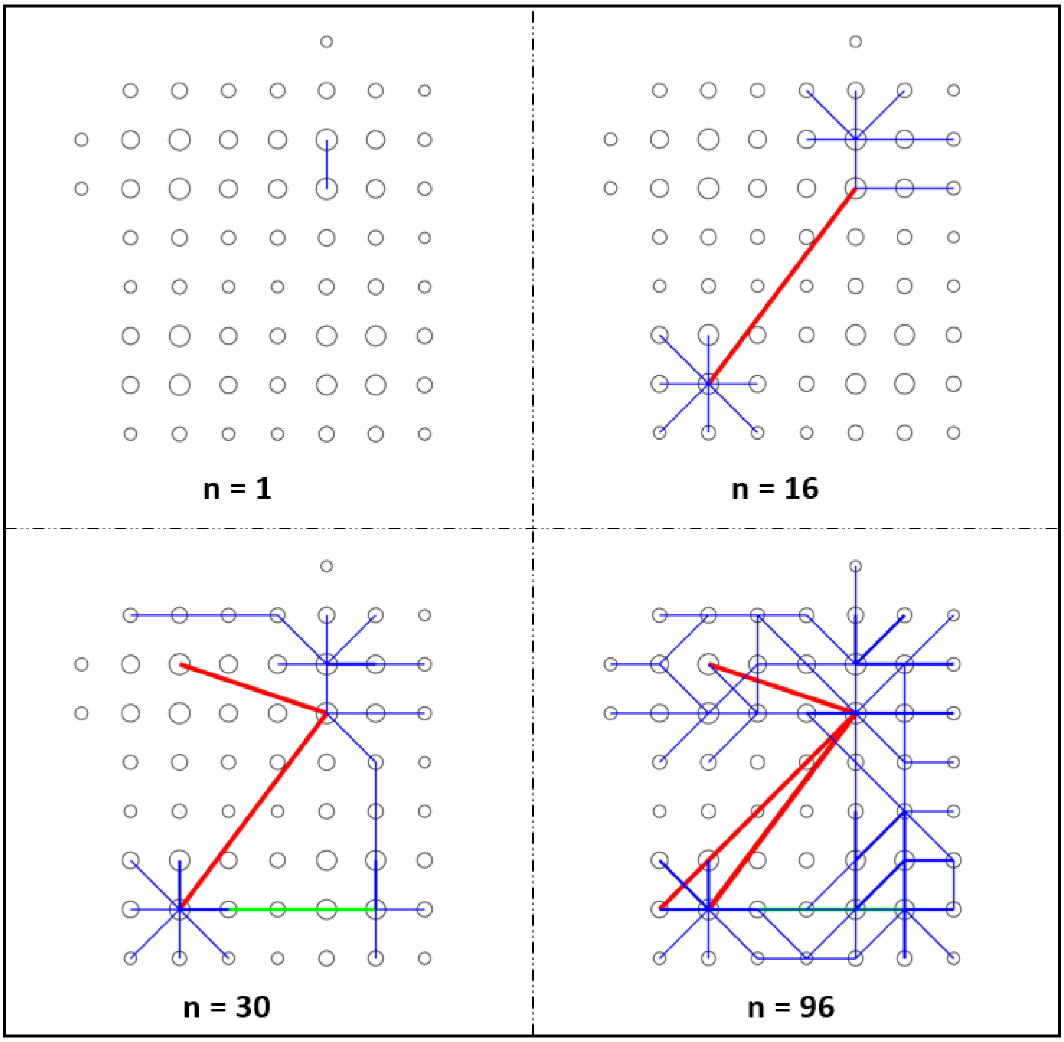

Figure 5.31: Evolution phases TLNM scenario

To provide further insight into the exact type of investments made during the evolution process, Figure 5.32 shows a timeline of the investments made at each iteration. For the 'Tokyo' prototype, a distinction is made between inter-agglomeration and intra-agglomeration expansions as there are multiple agglomerations present in this prototype. This also holds for the 'Flemish Diamond' and 'Rhine-Ruhr' prototypes which are discussed in the following sections.

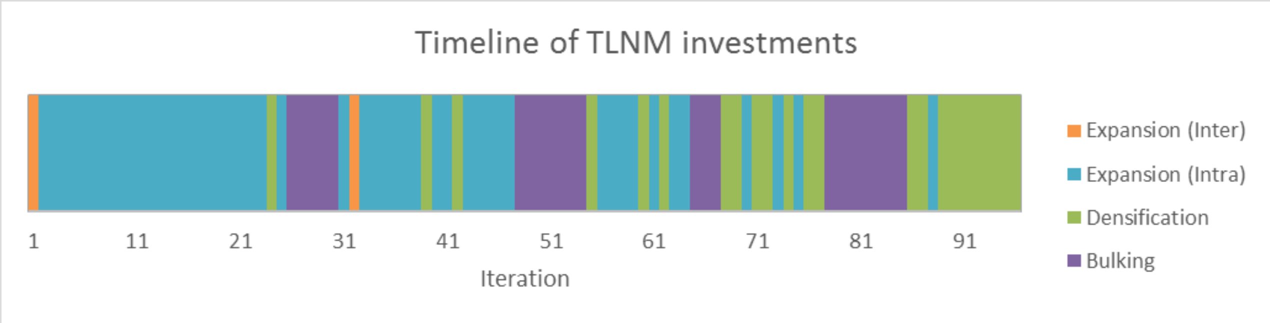

Figure 5.32: Timeline of TLNM investments made during the evolution process

Unlike the 'London' prototype, it is more difficult to identify a distinct pattern within the evolution process. The first phase could be characterized by the inter-agglomeration expansion and intra-agglomeration expansions within these two agglomerations, which ends with a number of bulking investments. Hereafter, a similar phase occurs with the next inter-agglomeration expansion followed by more intra-agglomeration expansions. This phase again ends with a number of bulking investments. Hereafter the existing network continues to expand, densify and bulk. The last part of the evolution mainly consists of densifications and bulking. It is however notable that the evolution process ends with densification investments rather than bulking investments. The combination of the fact that there are no clear patterns observed in the shape of generated network as well as in the timeline of the investments made, leads to the statement that the 'Tokyo' scenarios are unstable.

The TLNM scenario is also notable as it is the only scenario in which a regional link is constructed. This is possibly due to the fact that the highly populated nodes in this case are in the range of the regional link so that it can be constructed. For lower demands this link is possibly too expensive.

When considering the investment scores of the TLNM scenario (Figure 5.33), it is observed that the investment scores have downward peaks below 1.0 at certain moments and a number of high peaks. These high peaks correspond to interregional links that connect a disconnected node with high demand to the existing network (with an exception of the first one constructed). The low downward peaks however are what also make the 'Tokyo' scenarios unstable as there is also no clear critical mass reached.

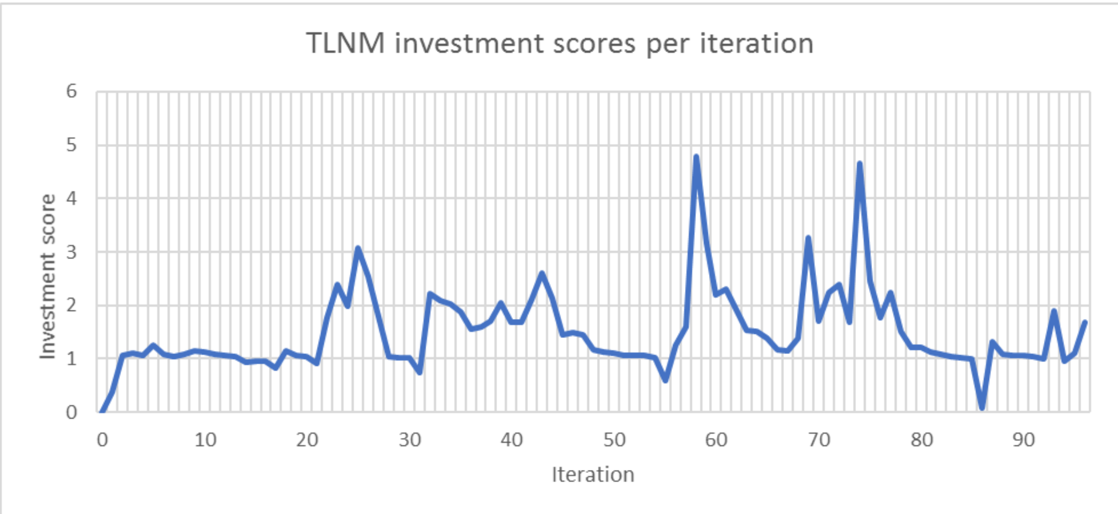

Figure 5.33: Investment scores per iteration of TLNM scenario

'Flemish Diamond' prototype

For the 'Flemish Diamond' scenarios there is a distinct evolution pattern which holds for all 'standard' scenarios with this spatial structure prototype. The main evolution phases are shown in Figure 5.34, where the FUNM scenario is used as example.

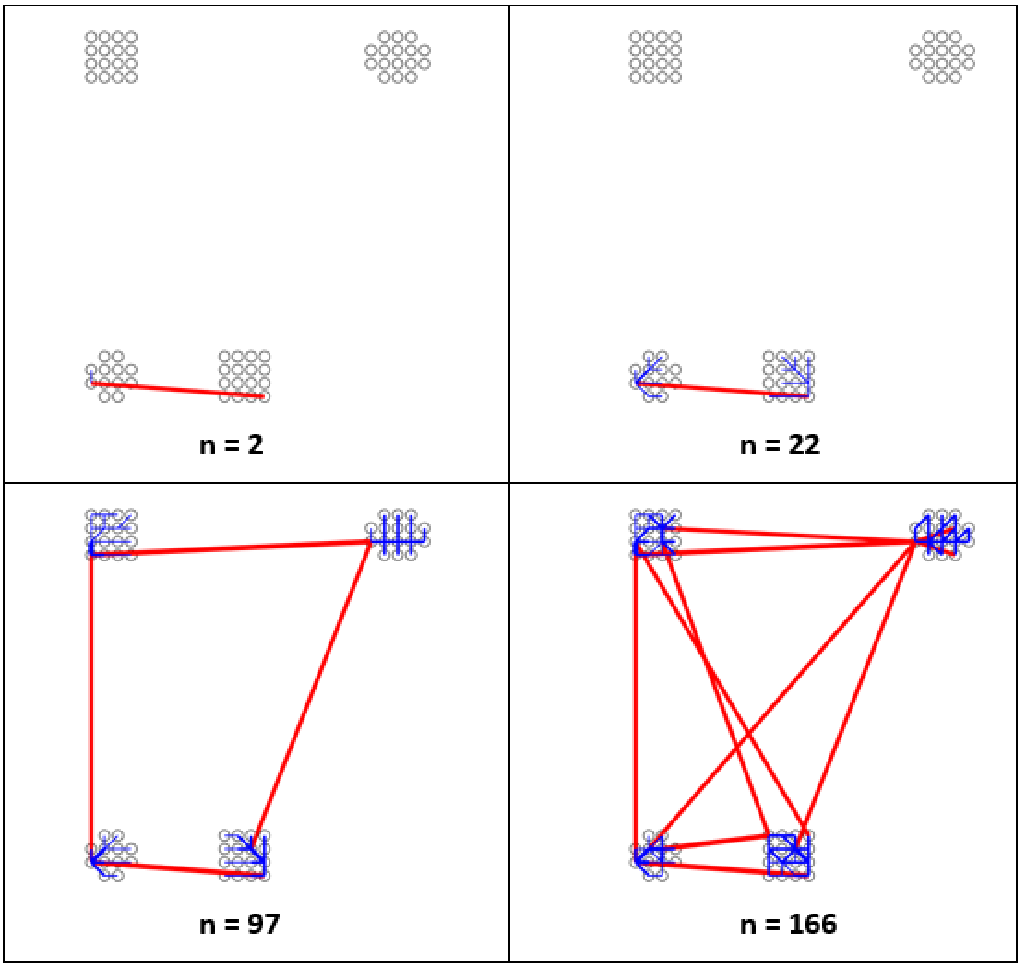

Figure 5.34: Main evolution phases FUNM scenario

The first investment is always in an interregional link that expands the network to the closest agglomeration, as the costs are lower while demands in the different agglomerations are similar. The network within the two agglomerations then start to develop by expanding within the agglomerations with agglomeration links. After a number of agglomeration links are constructed, the network is expanded towards a disconnected agglomeration with an interregional link. The network then again starts to expand within this agglomeration with agglomeration links. The previous process continues until all agglomerations are connected to each other in a ring-form. Hereafter, the network within and between agglomerations is densified and existing links are bulked. Similar to the London prototype, the evolution process ends with bulking investments as well. However, unlike in the London prototype where the bulking investments are only made at the end of the evolution process, bulking also occurs in earlier phases of the evolution process in the 'Flemish Diamond' scenarios.

To provide further insight into the exact type of investments made during the evolution process, Figure 5.35 shows a timeline of the investments made at each iteration.

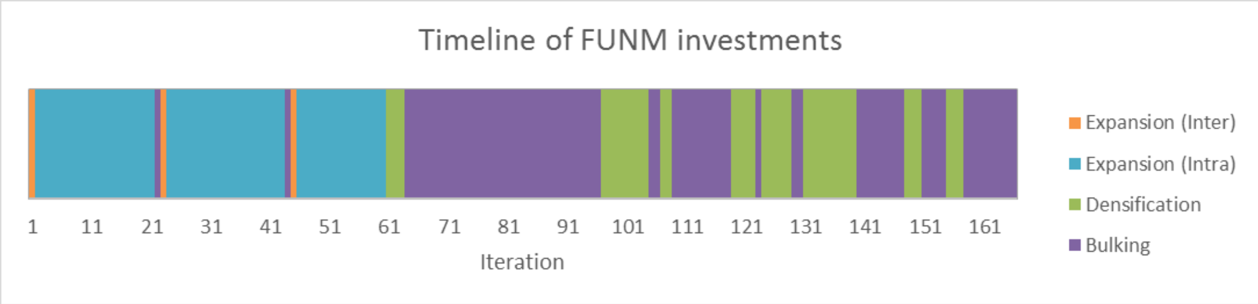

Figure 5.35: Timeline of FUNM investments made during the evolution process

The first part consists of the expansion process between and within agglomerations as described and is clearly visible up to iteration 61. Hereafter, three densification investments are made after which a period of bulking occurs up to iteration 97. The last part of the evolution process consists of additional densification and bulking investments.

When relating this evolution process to the investment scores (Figure 5.36), the peaks at iteration 33 and 45 correspond to agglomeration links. Figure 5.37 shows the link corresponding to this peak score.

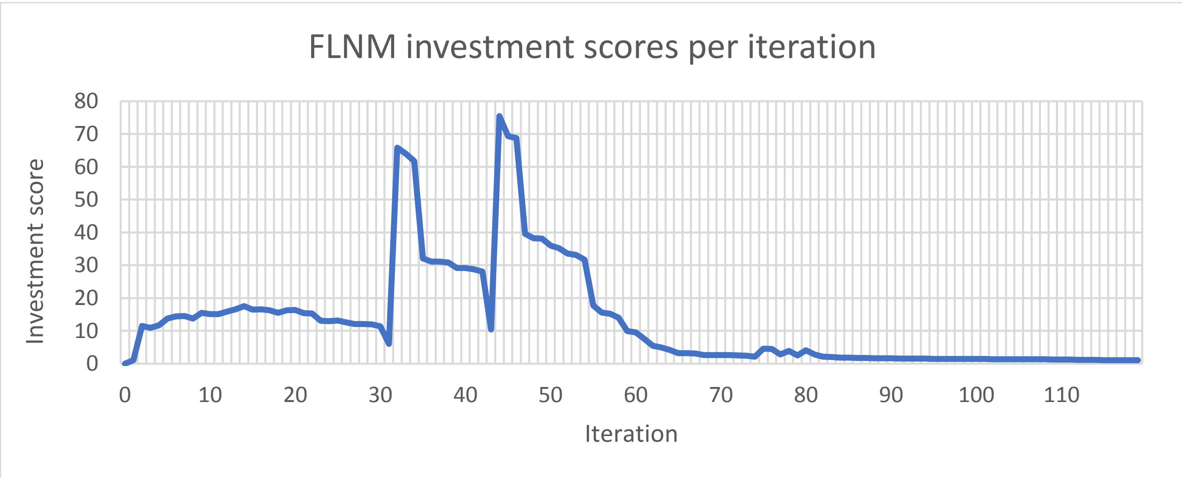

Figure 5.36: Investment scores per iteration of FLNM scenario

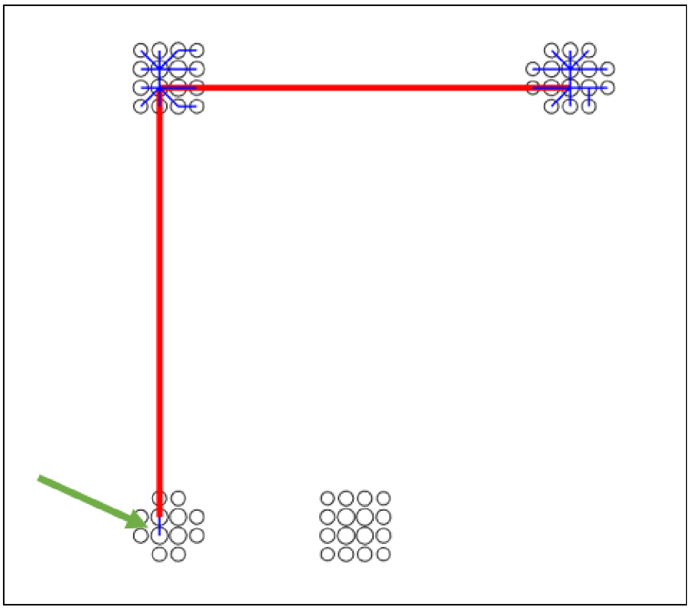

Figure 5.37: Peak score investment at iteration 33 in FLNM scenario

While the interregional link connecting North-West with South-West is very beneficial, the costs are also very high. This leads to an investment score which is relatively low. The agglomeration link constructed in iteration 33 however also provides many benefits while it is much cheaper. It connects a high demand node to all the nodes in the North, while before this moment the travel times by alternative mode were very high due to the low speed and long distances. The peak at iteration 45 corresponds to the first agglomeration link constructed in the South-Eastern agglomeration. It is even higher than that of iteration 33 as it does not only provide a connection to the Northern two agglomerations, but also to the South-Western agglomeration. Once all the nodes are connected to the PT network, the investment scores become much lower. Due to the long distances in this prototype and relatively low alternative mode speed, connecting disconnected nodes to the PT network provides much higher benefits than in other prototypes (factor between 2 and 15 higher).

'Rhine-Ruhr' prototype

The evolution process in the 'Rhine-Ruhr' scenarios is similar to that of the 'Flemish Diamond'. The main evolution phases of the 'Rhine-Ruhr' scenarios are shown in Figure 5.38, where RLNM is used as example. The difference however in this prototype is that the interregional link constructed at the start does expand the PT network to the closest agglomeration. This is possibly because the distance to the neighbouring agglomeration is too short. As the distance increases, so do the costs and benefits. Apparently the optimal benefit-cost ratio is at a distance similar to that of the length of the first interregional link constructed. The furthest agglomeration is apparently too far so that the costs then outweigh the benefits more. The closest agglomeration is apparently too close, so that the benefits outweigh the costs less. The shorter distances are also less beneficial due to waiting times which weigh heavier on travel times over shorter distances.

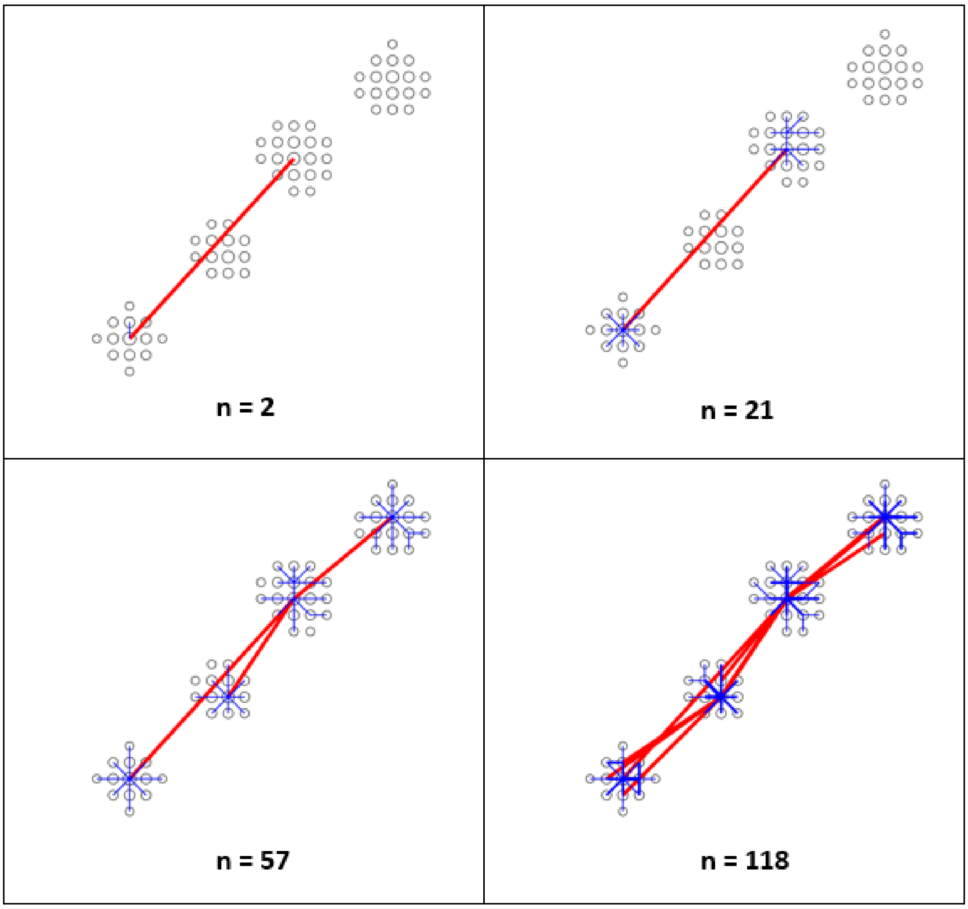

Figure 5.38: Main evolution phases RLNM scenario

To provide further insight into the exact type of investments made during the evolution process, Figure 5.39 shows a timeline of the investments made at each iteration.

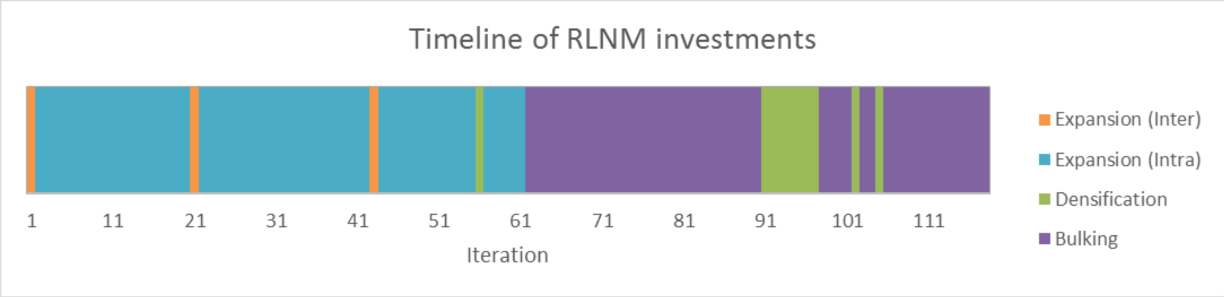

Figure 5.39: Timeline of RLNM investments made during the evolution process

Here it is seen that the manner in which the network evolves is similar to that of the 'Flemish Diamond' scenarios. First there are expansions between and within agglomerations, followed by a long period of bulking. Lastly, there are additional densification and (mainly) bulking investments made at the end. Also, the peak scores correspond to the same types of links as shown in Figure 5.37.

'Hurdle distance'

As briefly explained in the previous sub-section on the 'Rhine-Ruhr' prototype, there is a minimum distance necessary for an expansion to have the maximum investment score. This is referred to as the 'hurdle distance'. Visualizations of this effect are shown in Figure 5.40, where the FUNM and RUNM are taken as example.

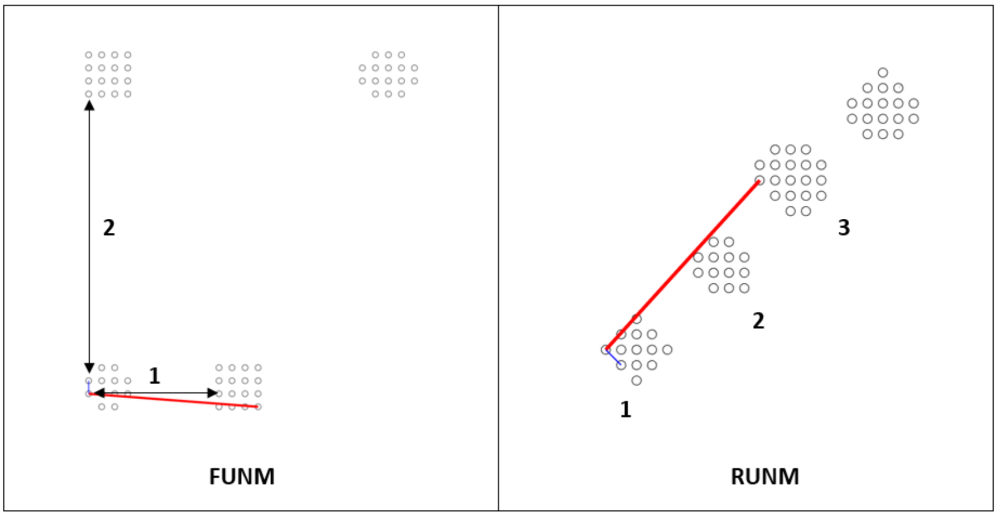

Figure 5.40: Examples of 'hurdle distance' in FUNM and RUNM

While the interregional links in FUNM generally expand to one of the outer nodes of a disconnected agglomeration, which has the shortest distance, for the first interregional link this is not the case. The 'hurdle distance' in this case lies somewhere between distance 1 and 2, as 1 was too short and 2 is too long. The same is the case for the first interregional link of RUNM. All nodes in agglomeration 2 are too close, while in agglomeration 3 the highest investment score for an expansion is found at the closest node. The 'hurdle distance' in this case therefore lies somewhere between agglomerations 2 and 3. If in the RUNM scenario a node in agglomeration would have been connected, it is plausible that the final resulting network would also be different. This 'hurdle distance' therefore impacts the investments made in the network, and thus the resulting network. This implies that within different prototypes, the differences in generated spatial structures may also impact the resulting network.

5.2.3 Impact demand distribution

In terms of how the network evolves, there are not many differences between the different demand distributions apart from the nodes within an agglomeration that get connected to the network. In the uniform demand distribution, the nodes on the outer areas of the agglomerations are more relevant, as also mentioned in section 5.1.3. In terms of the first expansions made to a disconnected agglomeration, for the linear and exponential cases these expansions are firstly made towards the central node with high population. For the uniform cases however, the expansion tends to generally go to the closest node of the disconnected agglomeration. As the populations are equal in all nodes, the benefits of connecting to any node in the disconnected agglomerations are roughly the same. Therefore, the investment which has the lowest cost (thus highest investment score) is made. Naturally, as the distance is lower, so are the costs. However, when the distances are too low, the benefits are not high enough to have the best investment score. As is also explained for the 'Rhine-Ruhr' prototype in the previous sub-section, a so-called 'hurdle distance' is necessary for the investment to become beneficial enough.

When looking at the investment scores per iteration, there are clear differences to be observed between the different demand distributions (Figure 5.41 and Figure 5.42). Both the 'standard' linear scenarios (xLNM) and 'standard' exponential scenarios (xENM) have higher investment score peaks than the 'standard' unimodal scenarios (xUNM). However, the peaks of the latter scenarios are broader. The reason for this is that the xLNM and xUNM scenarios have higher peaks in population. When travel time gains are provided to these nodes, the benefits will be higher as more people profit from these benefits. In the xUNM scenarios however, where there are no peaks in population, the benefits will not be as high. As for the width of the peaks; in the xLNM and xENM scenarios, providing travel time gains to the nodes in the outer areas of the agglomeration is less beneficial than in the xUNM scenarios. The populations per node are smaller in the outer area nodes in the xLNM and xENM scenarios, while in the xUNM scenarios the population is equal in all nodes. This combination leads to investment scores with higher but narrower peaks for the xLNM and xENM scenarios, and lower but broader peaks for the xUNM scenarios.

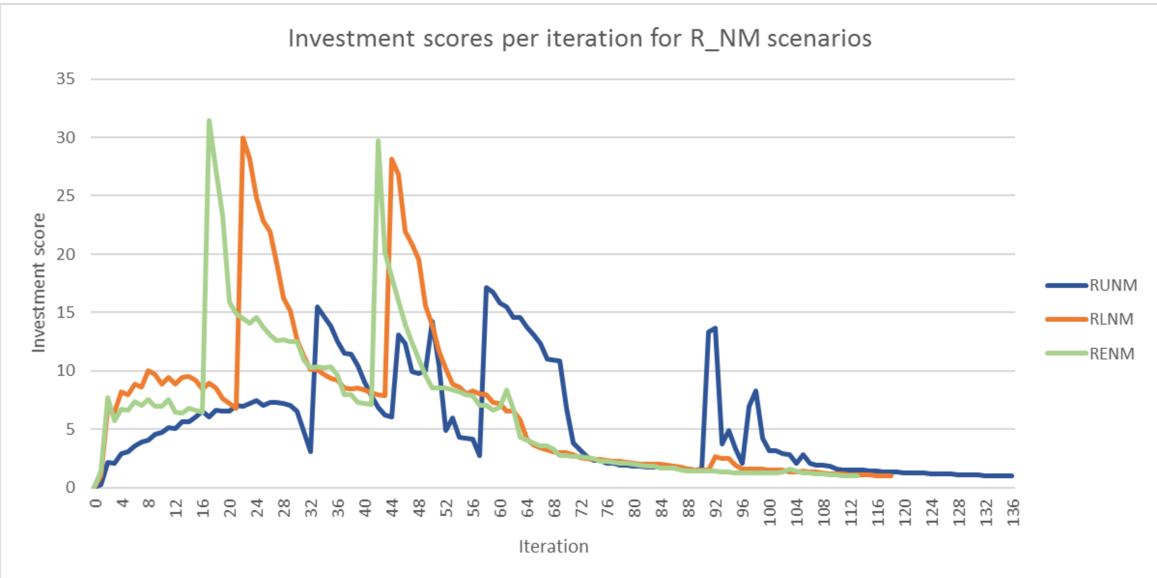

Figure 5.41: Investment scores per iteration for the 'standard' Rhine-Ruhr scenarios

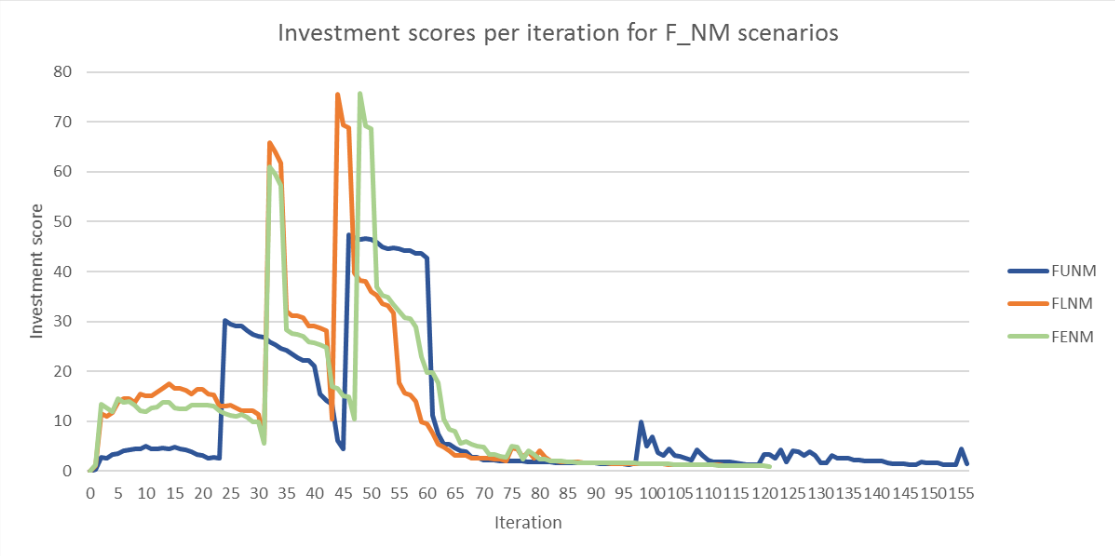

Figure 5.42: Investment scores per iteration for the 'standard' Flemish Diamond scenarios

Lastly, it is observed that when there are multiple central nodes with the highest population in the linear or exponential scenarios, there is still a difference in hierarchy that occurs during the evolution. Dependent on which of the nodes gets expanded to first from the existing network, this node becomes better developed and new expansions are more likely to start or end at these nodes. A visualization of this is shown in Figure 5.43, where the FLNM scenario is taken as example.

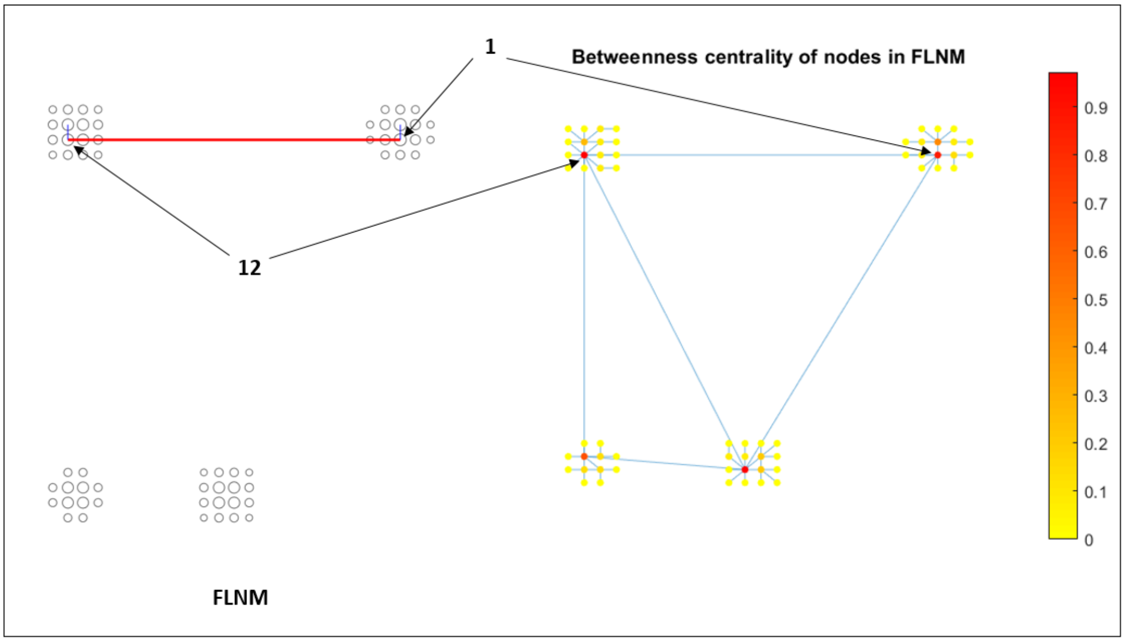

Figure 5.43: Example of emergence node importance

The node directly North of node 1 has the same population as 1 and the same holds for node 12 and the node directly North of node 12. As at the start of the evolution node 1 connects to node 12, these two nodes get developed better than their respective neighbouring nodes to the North. This is seen in the betweenness centrality values of these nodes, as the higher value indicates that more shortest paths pass through these nodes. This emergence of hierarchy in nodes is dependent on the nodes that get connected first and is inherent to the evolution process, as slight differences made in investment choices at the start of the process may lead to different resulting networks. It is however noted that the assumption made for node choice for interregional expansions affects the choices made as to what nodes can be expanded to.

5.2.4 Impact operational costs

As discussed in section 5.1.4, the resulting networks of the FUNM and FUAM scenarios are similar. The exception is that in the FUAM scenario more investments are made as a result of the lower operational costs and thus higher investment scores.

In terms of the evolution processes of both scenarios, they are also very similar with some differences. Figure 5.44 shows the investment scores per iteration for both scenarios. The main difference is observed at around iteration 20, where the network in the FUAM scenario expands towards the third agglomeration while the first and second agglomerations are being densified more in the FUNM scenario before the expansion is realized. Hereafter, the expansion towards the fourth agglomeration is realized at around the same point in both scenarios. It is observed that apart from this difference at around iteration 20, the same patterns in terms of investments occur in both scenarios. It is also clear that the investment scores are higher in the FUAM scenario due to the lower operational costs. Lastly, it is observed that around 50 more investments are done in the FUAM scenario in comparison to the FUNM scenario.

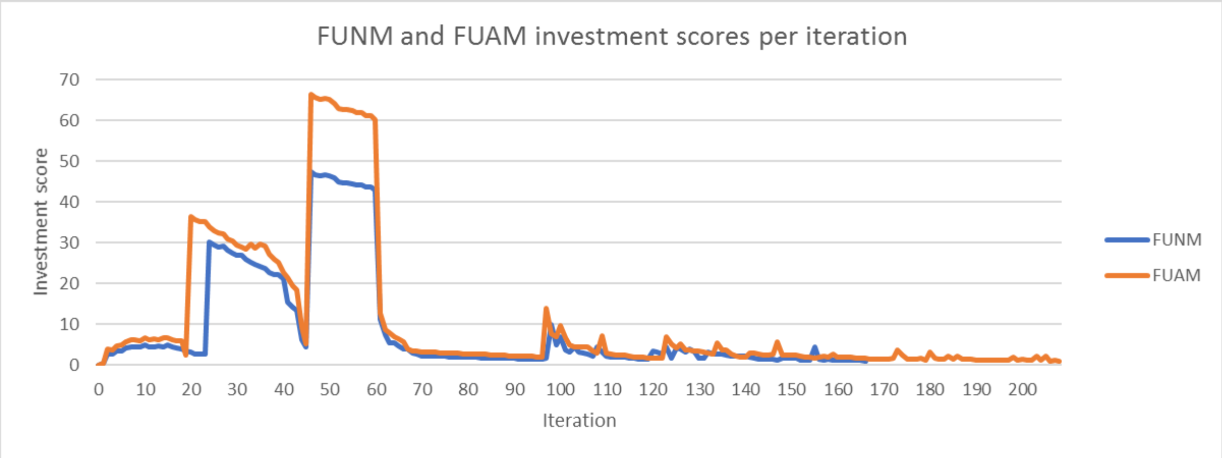

Figure 5.44: Investment scores per iteration for FUNM and FUAM scenarios

Lastly, the comparison between the investments made during the evolution process of the FUNM and FUAM scenario are shown in Figure 5.45.

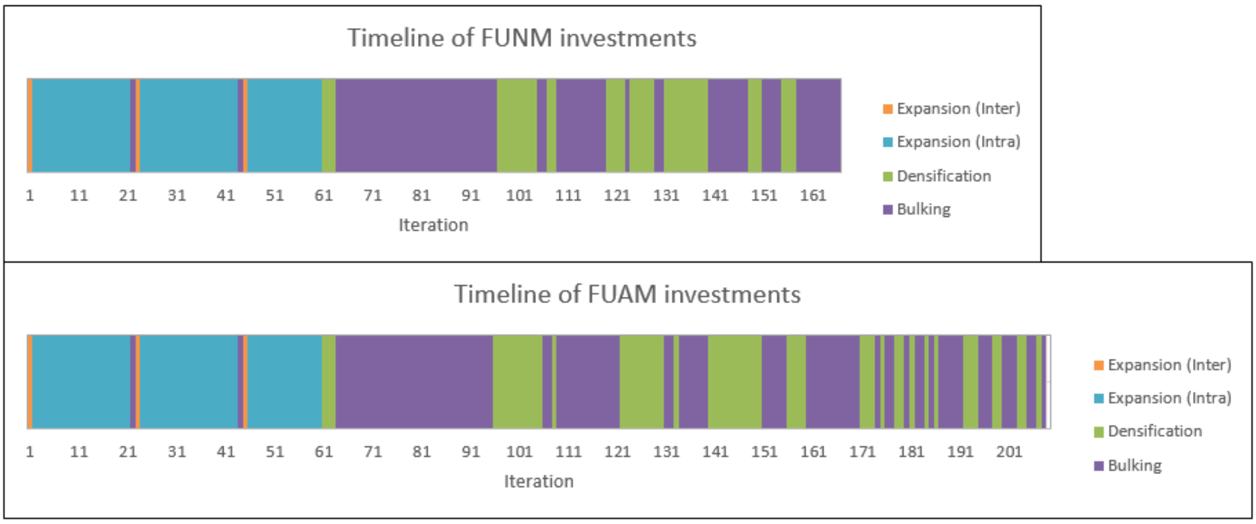

Figure 5.45: Timelines of FUNM and FUAM investments made during the evolution process

It is observed that both timelines are almost identical up to iteration 97, where the bulking phase ends. Arguably, this is the end of the phase in which the 'basic network' is completed. For both scenarios it holds that the last part of the evolution process consists of densification and bulking investments to further improve the network. While the FUAM scenario consists of all investments made in the FUNM scenario, the order in which these are made differs in the FUAM scenario as there are also additional investments made.

In short, it can be stated that the evolution process is extended when operational costs are lowered.

3.3.2.5 Impact multimodality

For both unimodal scenarios it is observed that the evolution process is different to their respective multimodal scenarios.

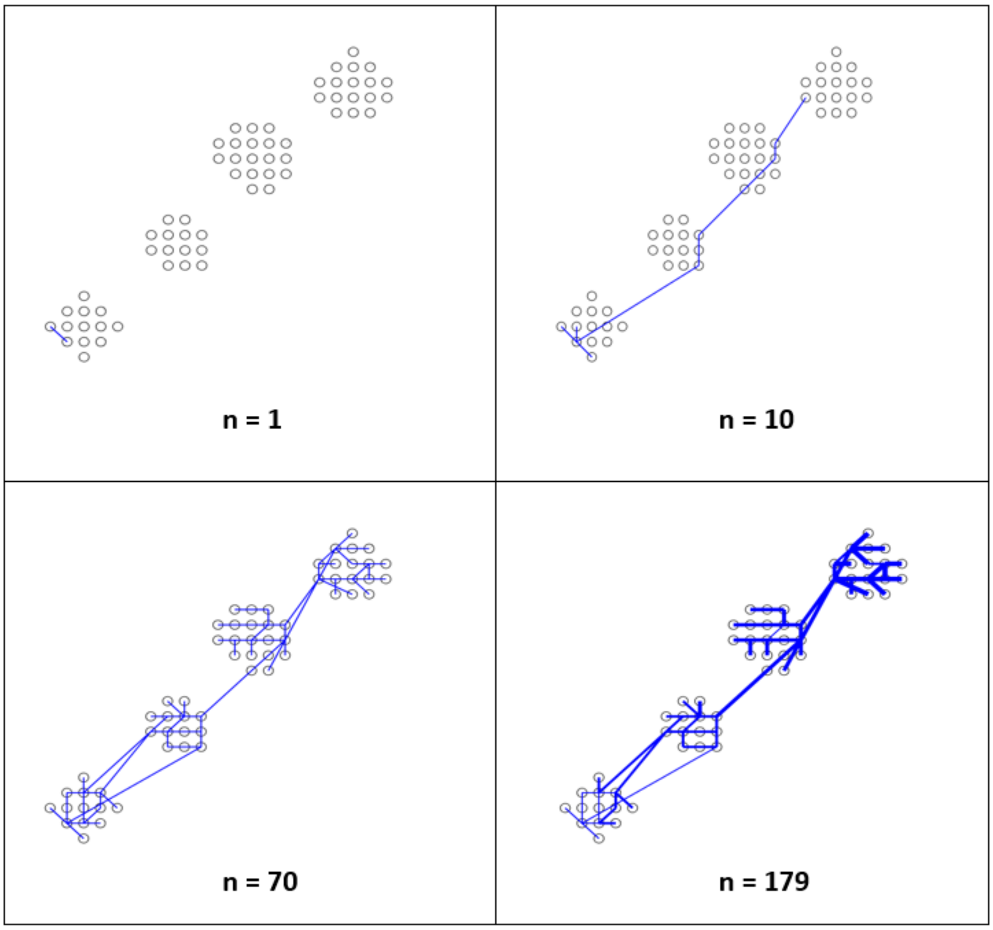

Figure 5.46: Main evolution phases RUNU scenario

The main evolution phases of the RUNU scenario are shown in Figure 5.46, which is similar to how the RLNU scenario evolves. In the multimodal scenarios two agglomerations get connected, after which the PT network expands within these agglomerations. Hereafter the networks are expanded to other unconnected agglomerations and this process continues until all agglomerations are connected. In the RUNU scenario it can however be seen that the network initially expands towards the unconnected agglomerations first. Hereafter, the network expands within and between the agglomerations. The final phase then consists of network bulking.

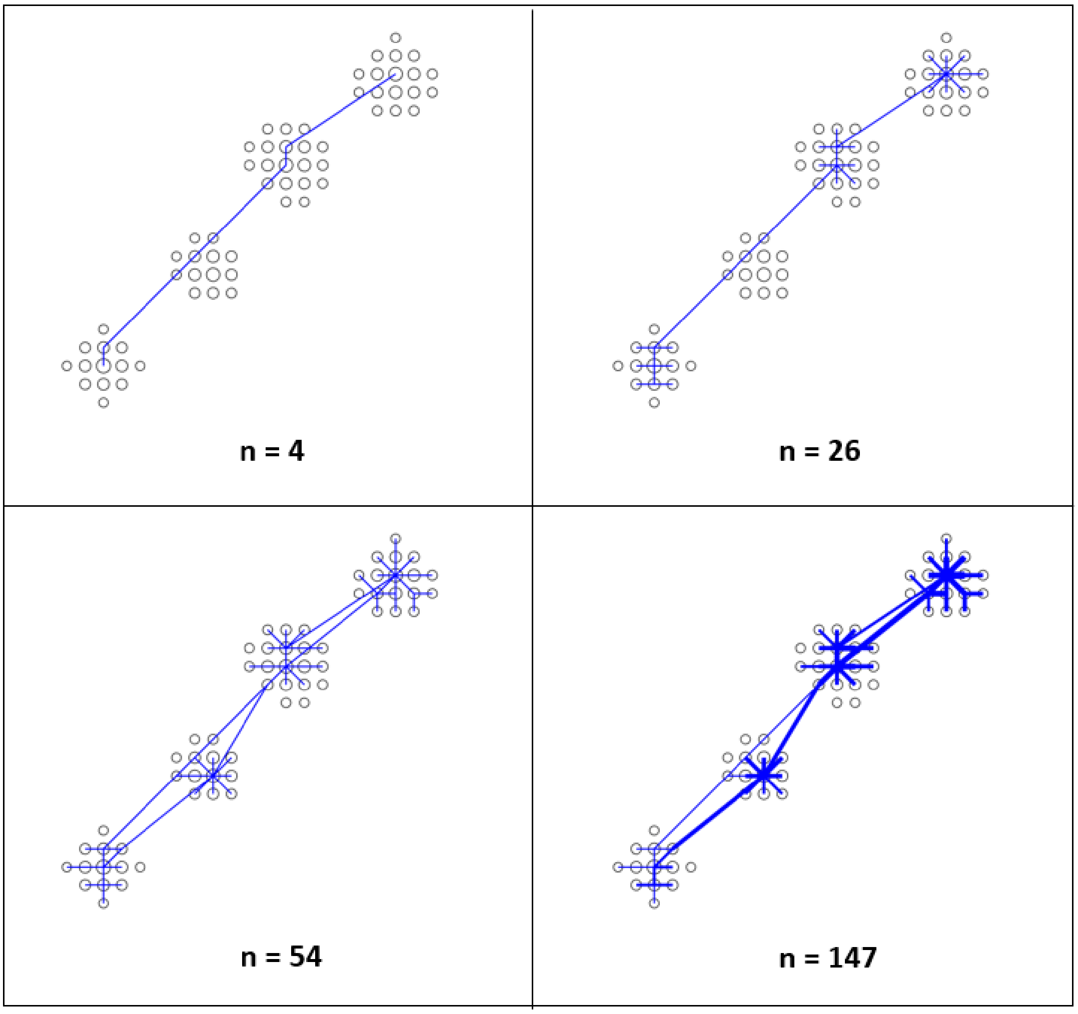

Figure 5.47: Main evolution phases RLNU scenario

While the RLNU scenario evolves similarly to the RUNU, there is also some similarity with the RLNM scenario. The network expands to unconnected agglomerations, just as in the RUNU scenario, but similarly to the RLNM scenario it initially does not connect to the second agglomeration. Only after 26 iterations (Figure 5.47), when expansions have been done within the other three agglomerations as well, the network expands to this unconnected agglomeration. Hereafter, the network densifies between agglomerations, but hardly within, and the evolution finalizes with bulking. Certain nodes stay disconnected from the network and densifications within agglomerations are hardly done.

When considering the timelines of the investments made during the evolution process of both the RUNU and RLNU scenario (Figure 5.48 and Figure 5.49), it is seen that the pattern is similar.

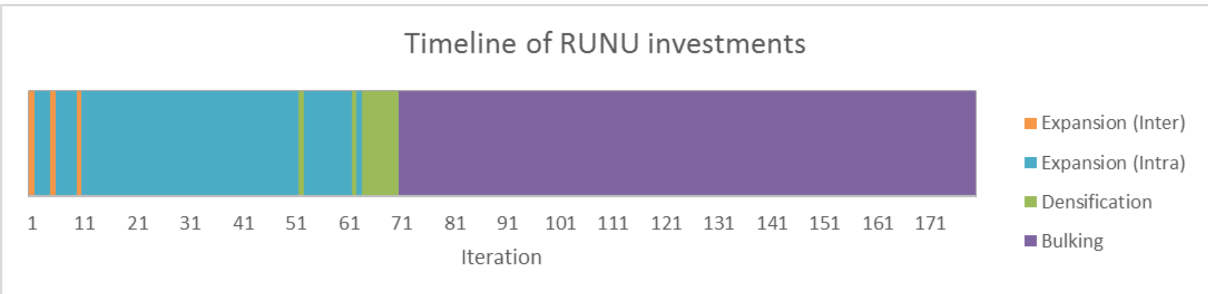

Figure 5.48: Timeline of RUNU investments made during the evolution process

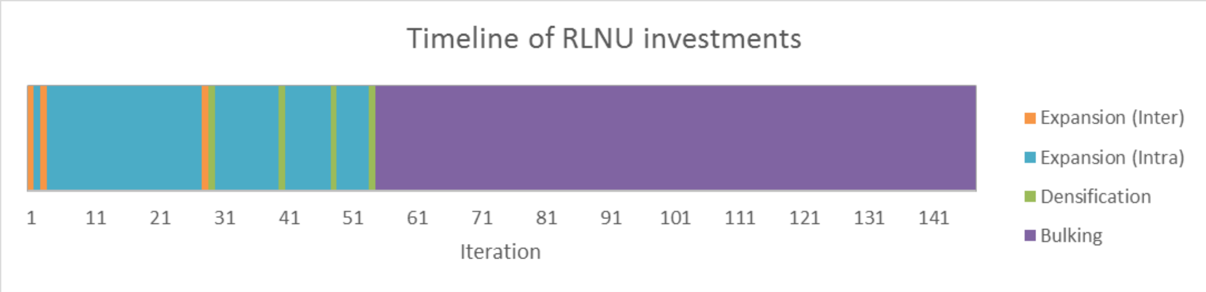

Figure 5.49: Timeline of RLNU investments made during the evolution process

In both scenarios the evolution process starts with expansions between and within agglomerations. Hereafter, there are some densification investments made after which a long period of bulking occurs. This long period of bulking can be explained by the fact that the operational speed of this PT mode is relatively low. It is expected that bulking investments provide relatively more benefits by reducing waiting times for a lower cost than investing in additional densifications for a higher cost. Additional densifications with interregional links, as was the case in the RUNM and RLNM scenario, would have been realized with the agglomeration links. However, due to the low operational speed of this PT mode, this link type provides less benefits over longer distances. Furthermore, when comparing the timelines of the RUNU and RLNU scenario, it should be noted that the expansion period of the RLNU scenario finishes earlier than that of the RUNU scenario. This is due to the fact that certain nodes stay disconnected from the network in the RLNU scenario.

5.3 Sensitivity analysis

To investigate the impact that the assumptions made with regard to input have on the resulting network evolution, a sensitivity analysis is done. The network evolution is expected to be impacted by differences in investment scores, which potentially lead to different investments being made. It is therefore chosen to vary the population size, the speed of the alternative mode and the cost components of the PT modes, which all have an impact on the potential benefits but in a different manner. The population size is directly linked to the potential benefits due to the number of passengers which can benefit from an investment. The speed of the alternative mode is indirectly linked to the potential benefits, as it has an effect on the travel time differences between the alternative mode and PT. The cost components of each PT mode are also directly linked to the investment scores. The varying population sizes are discussed in section 5.3.1, followed by the discussion on varying the speed of the alternative mode in section 5.3.2 and the discussion on varying cost components in section 5.3.3. Finally, based on these three sections, additional findings on network instability are discussed in section 5.3.4.

5.3.1 Population size

For the numerical experiments, a total population of 2.4 million was assumed. For the sensitivity analysis the population sizes are varied in two scenarios: FLNM and TENM. For the FLNM scenarios, a ‘low’ and ‘high’ scenario are considered in which a total population of 1.6 million and 3.2 million respectively is assumed. For the TENM scenarios, a ‘high’ and ‘very high’ scenario are considered in which a total population of 3.2 million and 4.8 million respectively is assumed. As the TENM scenario appeared to be ‘unstable’ during the numerical experiments, a ‘low’ scenario did not seem to make sense as the benefits would then be even lower (thus making it more ‘unstable’). While the choice was made to consider both a ‘stable’ and ‘unstable’ scenario, the choice of these two scenarios in specific was arbitrary, and it is plausible that with other scenarios the results may differ.

The resulting networks of the FLNM scenarios are shown in Figure 5.50.

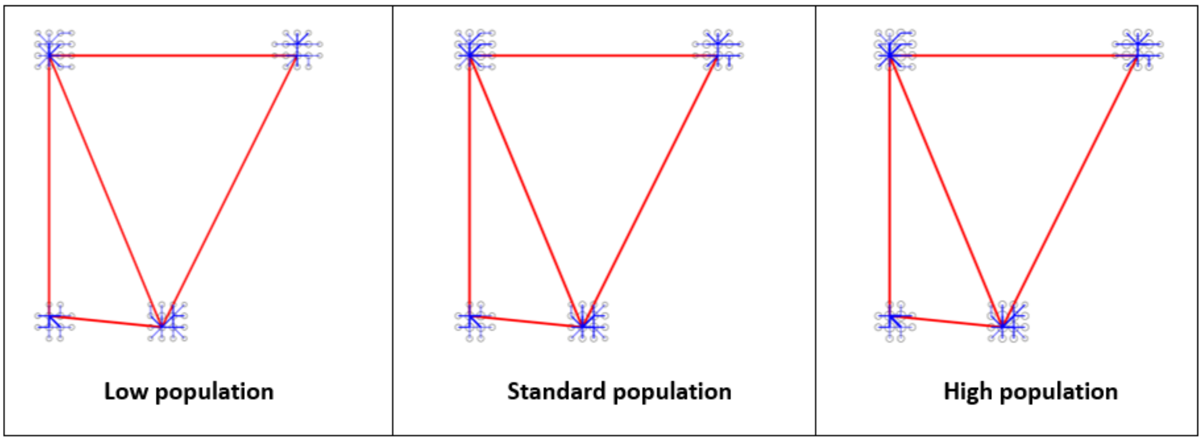

Figure 5.50: Visualizations of generated networks for the FLNM scenarios with varying population sizes

In all three scenarios, the network in terms of constructed links and the evolution processes are the same. The only differences observed are the number of bulking investments made. As the population increases, so does the number of bulking investments. These bulking investments are all made in the last phase of the evolution process, and as the population increases this phase is also extended. This process is similar to what is seen in the FUAM scenario in comparison to the FUNM scenario, where the operational costs were lower in the FUAM scenario. This decrease in costs led to an extended evolution period as the investment scores stayed above 1.0 for a longer period of time. This is also the case when the population is increased, as more people can benefit from the investments made. This in turn leads to higher investment scores as well, which leads to an extended evolution period.

In this specific case, the additional investments were only bulking investments at the end of the evolution process. In the FUAM scenario however, also additional densification investments were made in comparison to the FUNM scenario. While it can be expected that similar differences would be observed when lowering operational costs or increasing population, this does not seem to be the case. An explanation for this could be the difference in demand distribution considered in both cases. If the same sensitivity analysis would be done with the FUNM scenario, it is possible that different types of additional investments are made rather than only bulking investments.

The resulting networks of the TENM scenarios are shown in Figure 5.51

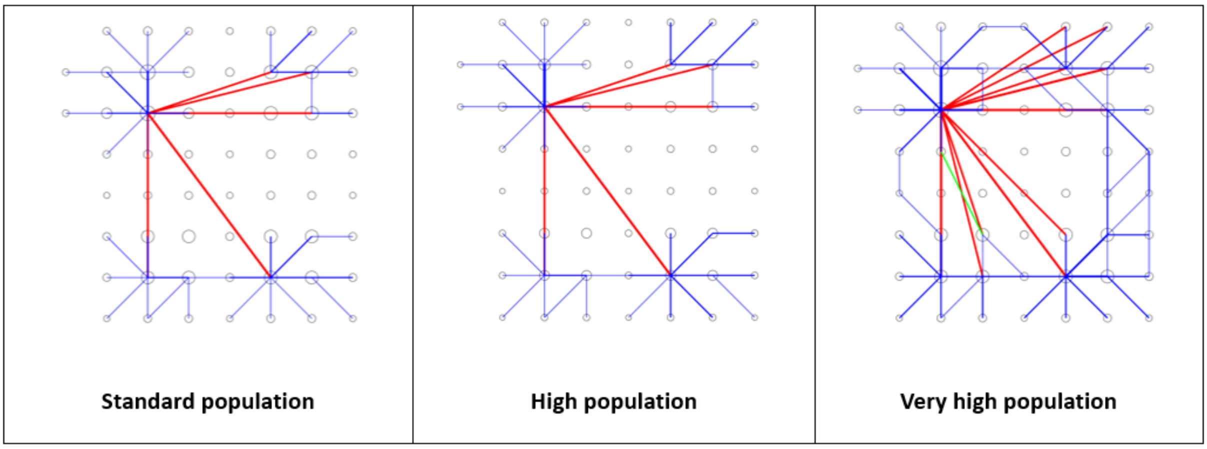

Figure 5.51: Visualizations of generated networks for the TENM scenarios with varying population sizes

Similar to the comparison between the 'standard' and 'high' scenario of FLNM, the difference between these two for the TENM scenario is that the only additional investments are bulking investments. However, for the ‘very high’ scenario it is observed that as well as bulking investments, additional expansion and densification investments are made. A population value somewhere between the ‘high’ and ‘very high’ scenario is the threshold value necessary for the network to invest in an additional expansion or densification investment. This expansion and densification phase occurs after a bulking phase in which the network as seen in the ‘high’ scenario is bulked further. After this additional expansion and densification phase, there is a final bulking phase. This is more in line with the additional investments made in the FUAM scenario compared to the FUNM scenario, due to lower operational costs.

To summarize, these results indicate that an increase in population leads to an extension of the bulking phase due to the higher benefits. However, after a certain threshold value, an additional expansion and densification phase can occur. This additional expansion and densification phase is then followed up by another bulking phase. In general, it can be said that an increase in population leads to an extension of the evolution process.

5.3.2 Speed of alternative mode

In terms of the speed of the alternative mode, the value assumed in the numerical experiments is 15 km/h. For the sensitivity analysis this value is varied in the TENM and FUNM scenarios. For the TENM scenario, a ‘low’ and ‘very low’ scenario was assumed with speeds of 10 km/h and 13.5 km/h respectively. As the TENM scenario appeared to be ‘unstable’ during the numerical experiments, a ‘high’ scenario did not seem to make sense as the benefits would then be even lower (thus making it more ‘unstable’). For the FUNM scenario one ‘very high’ scenario was assumed with a speed of 25 km/h. As also explained in section 5.3.1, the choice was made to consider a ‘stable’ and an ‘unstable’ scenario, but the choice of these two in specific was arbitrary, and it is plausible that with other scenarios the results may differ.

The resulting networks of the TENM scenarios are shown in Figure 5.52.

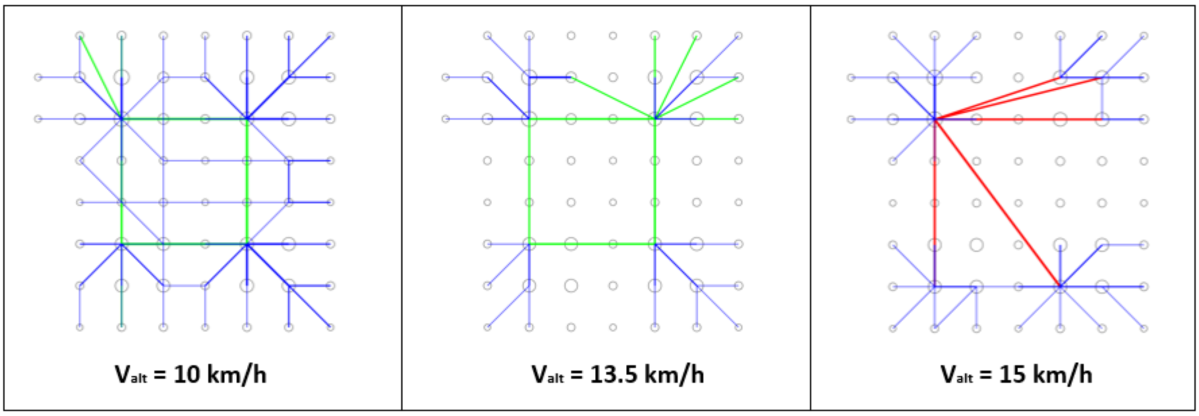

Figure 5.52: Visualizations of generated networks for the TENM scenarios with varying speeds of the alternative mode

The resulting networks are significantly different in all three situations, arguably as the network is ‘unstable’ when a speed of 15 km/h is assumed. As this speed decreases, PT provides more benefits, leading to a more ‘stable’ evolution process of the PT network. With a speed of 13.5 km/h for the alternative mode, the investment scores are still sometimes below 1.0 at certain points, but overall the network is already more ‘stable’. The network which is constructed already seems more logical, with the ring-form of regional PT links between the high population nodes. This behavior is more comparable to that of the ‘Flemish Diamond’ ‘standard’ scenarios. With a speed of 10 km/h for the alternative mode, the network seems ‘stable’ and scores are positive. What is also notable in this case is that all nodes get connected to the PT network, contrary to the other two cases. The evolution process is similar to that of for example the FLNM scenario: first expansions are invested in between highly populated nodes, after which the network expands further until all nodes are connected to the network. Hereafter, the network densifies, and the final evolution phase consists of bulking investments. It is however notable that a decrease in the speed of the alternative mode does not simply lead to an extension of the evolution process as was the case for a higher population size, but the resulting network in its entirety also differs.

The resulting networks of the FUNM scenarios are shown in Figure 5.53.

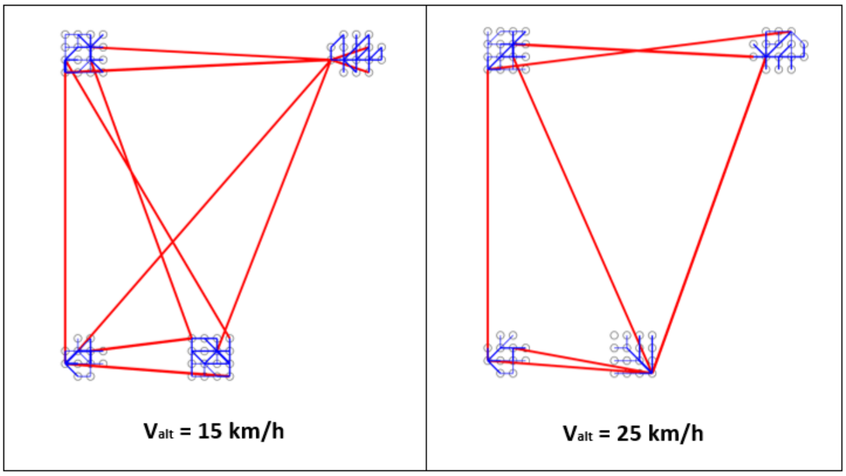

Figure 5.53: Visualizations of generated networks for the FUNM scenarios with varying speeds of the alternative mode

The resulting networks in these scenarios follow the same 'basic pattern' where the evolution process is the same, but again the resulting network in its entirety differs. Both the agglomeration links within, and the interregional links between agglomerations are constructed between different nodes in the two scenarios leading to different structures. In the 'very high' scenario it is observed that more tree-like shapes emerge, rather than more ring-like structures which are a result of densification investments. This is arguably due to the fact that the network does not expand as much within agglomerations, which is also seen in the early stages of the evolution process (Figure 5.54).

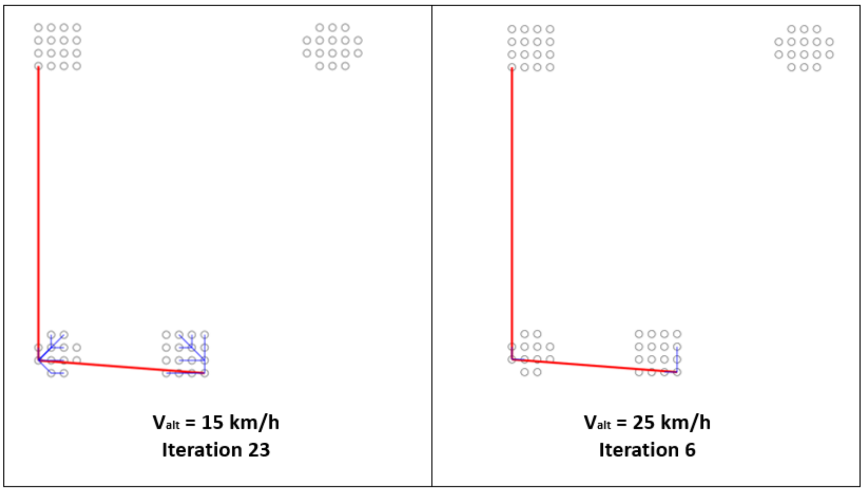

Figure 5.54: Comparison of when second interregional link is invested in between two FUNM scenarios with varying speeds of the alternative mode

In this figure it is seen that the second interregional link (from the South-West to North-West) is constructed much earlier when a higher speed of the alternative mode is considered. The network within the agglomerations are less developed before the inter-agglomeration expansions are invested in. It is expected that due to these differences at the start, the resulting networks also differ. Notable differences are also visible after the fourth interregional link (from the North-East to South-East) is constructed (Figure 5.55).

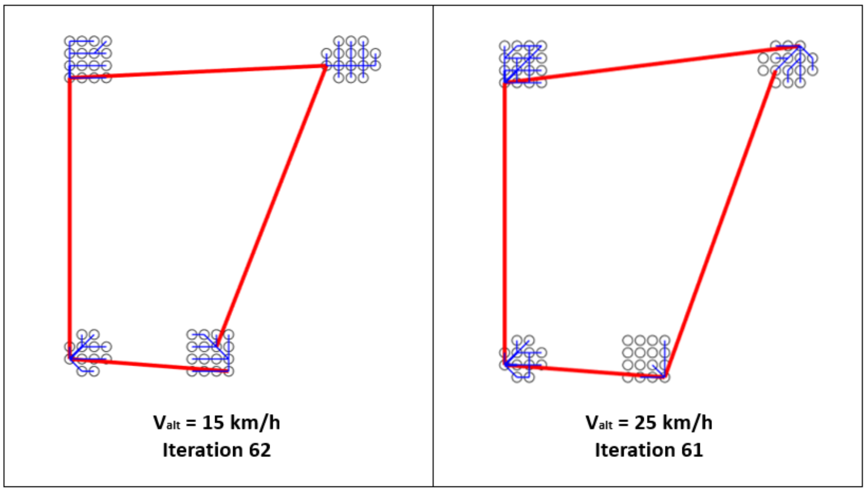

Figure 5.55: Comparison of when fourth interregional link is invested in between two FUNM scenarios with varying speeds of the alternative mode

Here it is seen that in the 'high' scenario the North-West agglomeration is much more developed than in the standard scenario, while the South-East agglomeration is much less developed than in the standard scenario. An explanation for this phenomenon is currently missing and could perhaps be found in future research.

Contrary to varying population sizes, the network evolution process differs in its entirety with varying speeds of the alternative mode. While the general pattern does not differ with varying speeds of the alternative mode (i.e. expansions between and within agglomerations), the exact investments made do differ. When the population size is increased for a certain scenario, in this new scenario the same investments are still made but the evolution process is simply extended. However, when the speed of the alternative mode is decreased, the investments made in the earlier stages already differ. These differences in early investments in turn lead to differences in the final states of the generated networks. This indicates that the assumption made for the speed of the alternative mode does not only impact the length of the evolution process, but also the generated network in its final state. Furthermore, it is observed that a variation in the speed of the alternative mode has more of an impact on the final network state in the 'Tokyo' prototype than in the 'Flemish Diamond' prototype. This indicates that the variation of the speed of the alternative mode differs in sensitivity based on the spatial structure considered. It seems that for spatial structures in which there are relatively longer distances to be covered, the same variation in the speed of the alternative mode has less of an impact on the final network state than for spatial structures in which there are relatively shorter distances to be covered.

5.3.3 Cost components

For the numerical experiments, values of the three cost components (infrastructure costs, rolling stock costs and operational costs) were determined based on literature and expert judgement. However, it was already observed that these values can vary in reality. Therefore, these values are varied as well to investigate the impact of these assumptions. For the sensitivity analysis, the FUNM and TENM scenario are again considered. While the choice was made to consider both a 'stable' and 'unstable' scenario, the choice of the FUNM and TENM scenario in specific was arbitrary, and it is plausible that with other scenarios the results may differ.

For the FUNM scenario, there are two variations: one in which all agglomeration link cost components are increased by 50% and one in which the regional link cost components are decreased by 50%. For the TENM scenario one variation is investigated in which the regional link cost components are decreased by 50%. The reason for increasing the agglomeration link cost components is to investigate if these links would still be constructed as much as with the standard assumptions made. The reason for decreasing the regional link cost components is to investigate whether these would be constructed more in this case, as it was observed that this link type was hardly constructed in the numerical experiments.

The resulting networks of the FUNM scenarios are shown in Figure 5.56.

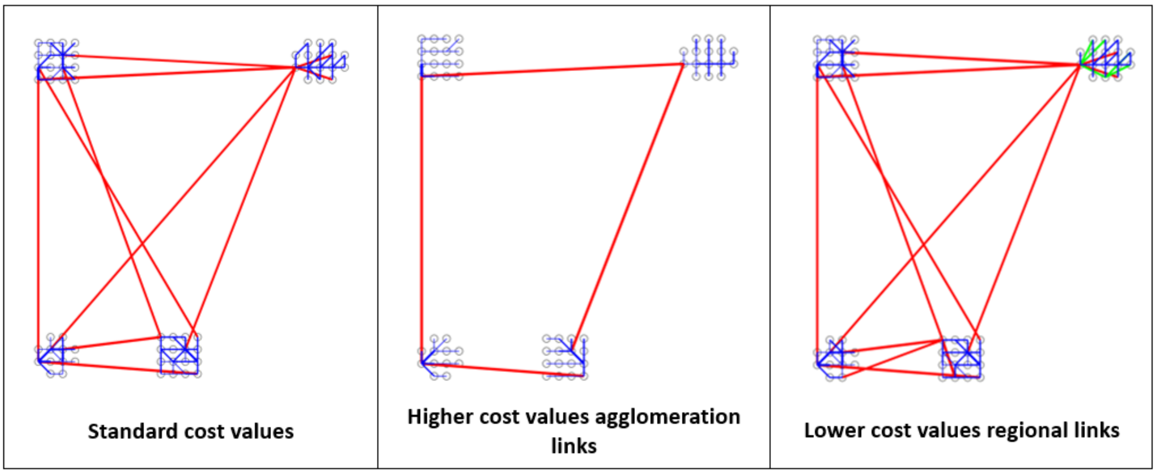

Figure 5.56: Visualizations of generated networks for the FUNM scenarios with varying values of cost components

It is seen that when the cost values of the agglomeration links are increased, 91 investments are made which are the same as the first 91 investments as in the standard FUNM scenario. The standard scenario has some additional bulking investments after these 91 iterations and then commences a new densification and bulking phase. These differences are similar to what is observed in Figure 5.51 where the population was varied.

For the reduction of regional link costs it is seen that the generated network is generally the same in comparison to the standard scenario. The main differences are that 5 regional links are constructed in the north-eastern agglomeration instead of two agglomeration links, which also leads to some additional densification and bulking investments in the other three agglomerations. While the reduction in cost values leads to an extension of the evolution process, it may also impact the final state of the generated network in this case.

The resulting networks of the TENM scenarios are shown in Figure 5.57.

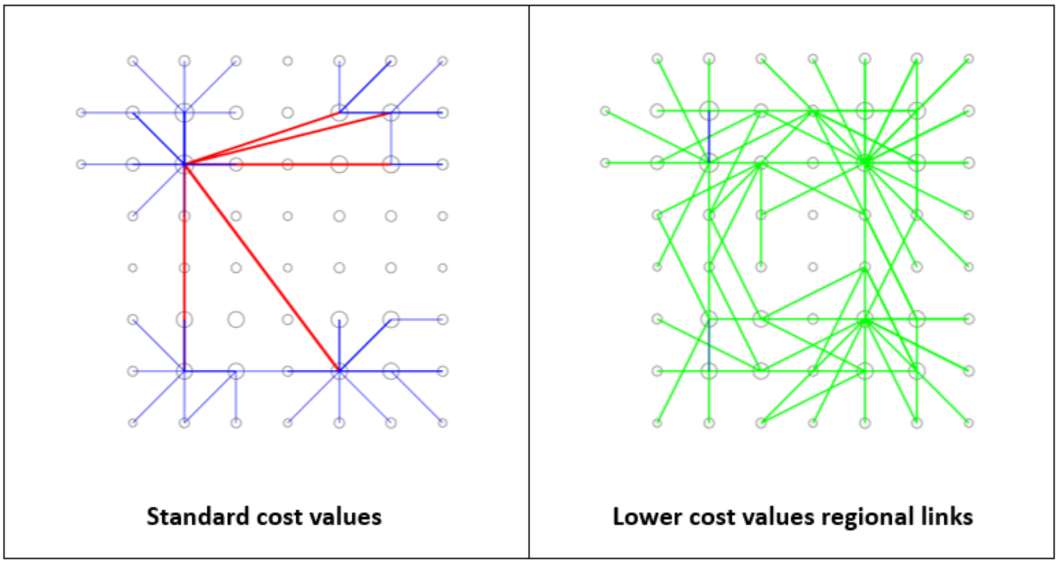

Figure 5.57: Visualizations of generated networks for the TENM scenarios with varying values of cost components

Here it is observed that the generated network consists of regional links almost exclusively. The main pattern however does remain similar, where there are central nodes observable within the four agglomerations as was also the case with a lower speed of the alternative mode (Figure 5.52). The evolution process is also similar as these four central nodes get connected to each other, and from these central nodes, additional expansions are invested in. As the regional links can't be constructed between two directly neighbouring nodes, the observed pattern in links differs from what is generally observed in previously generated networks and the emergence of network levels is not present in this case. The reduction in costs of these regional links has made it beneficial to generate a network with this link type almost exclusively. What is also notable in this scenario is that the evolution phases are very similar to the LLNM, LENM, RUNU and RLNU scenarios (expansion, densification and bulking in this order). All these scenarios have in common that the generated networks (almost) solely consist of one single modality. This may indicate that this specific pattern in evolution phases may be a characteristic to networks with unimodal systems.

For different assumptions regarding the cost values, it is seen that for different spatial structures the impact that this has differs. In the 'Flemish Diamond' prototype, an increase in costs simply shortens the evolution process while a reduction of costs simply extends the evolution process. For the 'Tokyo' prototype, a reduction in the regional link however leads to a considerably different network. The regional link can be constructed between nodes that lie between 3 to 6 km from each other. As these distances are more common in the 'Tokyo' prototype, a reduction in costs of these links makes it a lot more dominant in the generated network. This indicates that an increase or reduction in costs may have varying impacts on the generated network, based on the spatial structure that is assumed.

5.3.4 Network instability

In the previous three sub-sections it is observed that for the 'unstable' scenarios, the generated networks differ considerably more than the generated networks in the 'stable' scenarios. Therefore, additional tests are done to investigate network instability. To investigate the instability phenomenon further, two additional tests are performed in which the network starts with two initial links instead of one. These tests are conducted on the TUNM and FLNM scenario. While the choice was made to consider both a 'stable' and 'unstable' scenario, the choice of these two scenarios in specific was arbitrary, and it is plausible that with other scenarios the results may differ.

The visualizations of the initial and final states of these networks are shown in Figure 5.58. In the initial state, the additional link in TUNM is the regional link, while the additional link in the FLNM scenario is the interregional links which was not constructed in the 'standard' FLNM scenario. For both scenarios it is chosen to add an additional link which was not invested in in the resulting networks found during the numerical experiments. This is done to investigate whether the network still evolves into the same or a similar network when the initial network is steered into a different direction with this additional link. The expectancy is that the more 'stable' a scenario is, the less influence this steering has on the resulting network.

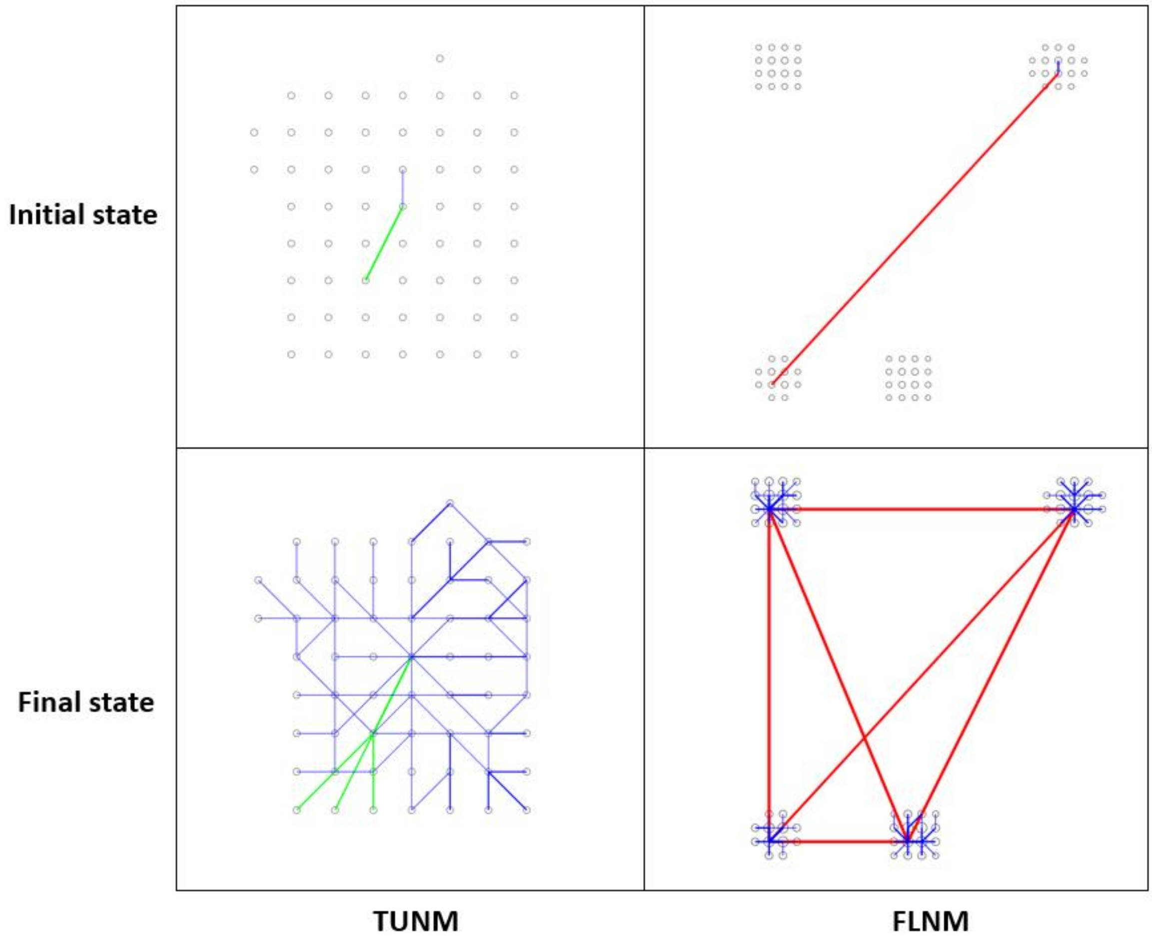

Figure 5.58: TUNM and FLNM scenarios with an additional initial link

The differences between the generated networks in the numerical experiments and sensitivity analysis for both TUNM and FLNM are shown in Figure 5.59.

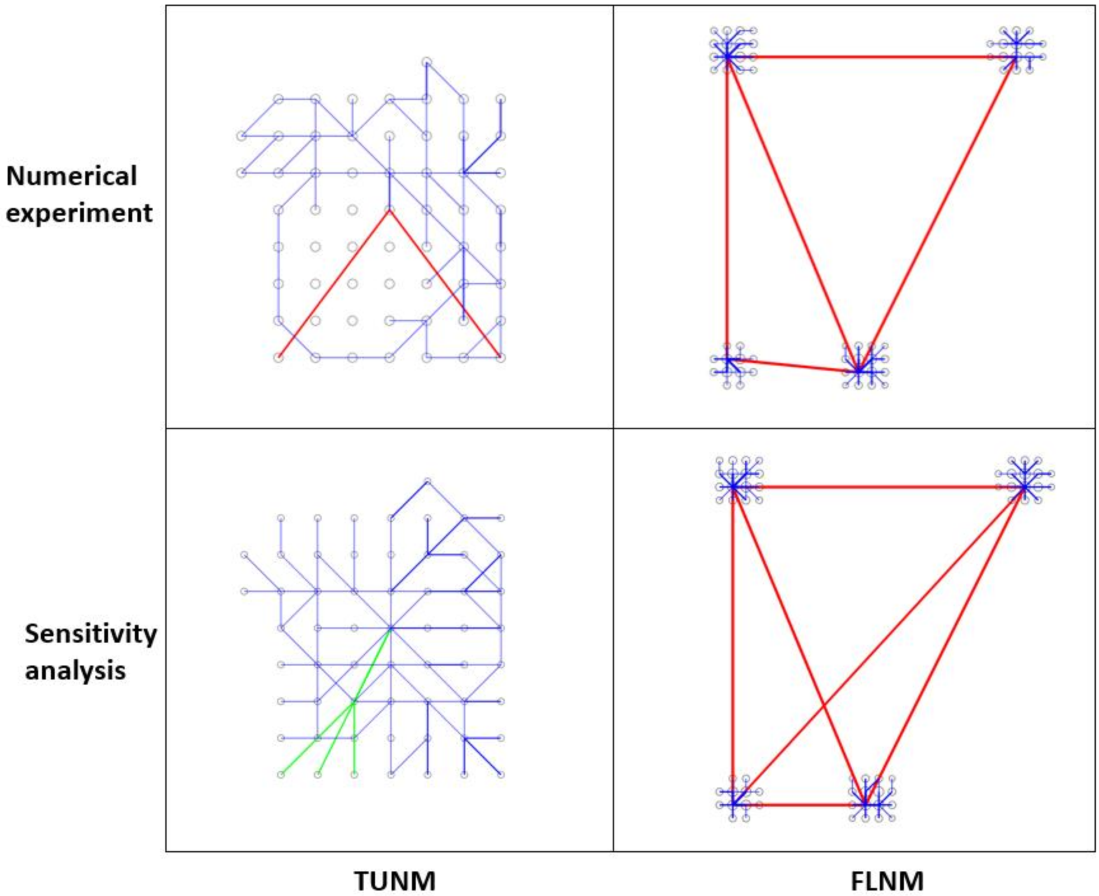

Figure 5.59: Comparison generated networks of TUNM and FLNM scenarios in numerical experiments and sensitivity analysis

For the TUNM scenario it is seen that the resulting PT network is very different from the resulting network generated during the numerical experiments, while for the FLNM scenario the differences are limited. The TUNM scenario has no low scores (< 1.0) during the entire evolution process and all nodes are connected to the PT network when this additional link is introduced. The evolution process of the FLNM scenario with an additional link is similar to the evolution process without the additional link. The only differences in the resulting networks are that a few additional agglomeration links are constructed in the situation with an additional link. Generally, the network evolves into something very similar.

It seems that as there are more distinctly separated agglomerations (FLNM), the generated network is likely to evolve into a state that is always similar. This is arguably due to the fact that a certain link type will always be most beneficial to connect two nodes based on the distance. For example, an interregional link will almost always be the best option to connect two agglomerations that are far apart from each other.

In the case where there are less distinctly separated agglomerations (TUNM), the network seems to have more 'freedom' as to how it evolves. In terms of the longer distances to be covered, there are no clear-cut solutions as is more the case in for example the FLNM scenario. By steering this type of network into a certain direction, it is more likely to evolve into a state that follows this direction.

These findings show that the resulting network determined by the network evolution model can be sensitive to the initial network that is assumed. How sensitive the evolution process is to these assumptions however varies, and further research would be necessary to investigate these effects.

5.4 Conclusions numerical experiments

Based on the results presented in section 5.1 and 5.2 and the sensitivity analysis performed in section 5.3, the main conclusions of the numerical experiments are presented in this section. These conclusions are divided into the impact of the four variables (spatial structure, demand distribution, operational costs and multimodality) and the sensitivity of the model.

Impact of spatial structure of urban area

In terms of how the PT networks evolve, the evolution process varies for different spatial structures. The main differences are observed when there is variation in the geographical distances between different agglomerations. In the case of one agglomeration with a CBD ('London'), the network expands and densifies radially from the central area and starts bulking at the end of the evolution process. In the case of multiple agglomerations ('Flemish Diamond' and 'Rhine-Ruhr'), the network expands to disconnected agglomerations and expands the network further within the connected agglomerations. The network then expands to another disconnected agglomeration and then again expands the network within the agglomeration. This process is repeated until all nodes with sufficient demand are connected to the network. The network then densifies and bulks further. While this process is the same for the 'Flemish Diamond' and 'Rhine-Ruhr' scenarios, the resulting networks do differ. In terms of the different evolution phases, spatial structures with more distinct agglomerations ('Flemish Diamond and 'Rhine-Ruhr') generally consist of a main evolution phase consisting mainly of expansions and bulking. Hereafter, additional densification and bulking investments are made. For the 'London' prototype, where there is one agglomeration, it holds that the evolution consists of expansions, densifications and bulking investments in that order. Furthermore, in the standard scenarios of the 'Tokyo' prototype it is observed that the network evolution is unstable. However, when a lower speed of the alternative mode is considered, the evolution process becomes similar to that of the 'Flemish Diamond'. The main differences observed in the final network states are in terms of betweenness centrality. This indicates that hierarchy of nodes within both types of network differ. In the 'Rhine-Ruhr' prototype where two of the four agglomerations have a geographically central location within the entire urban area, a node in this central location has more potential to become relatively more important in the entire PT network. This is less the case for the 'Flemish Diamond' prototype, as the agglomerations are more 'equally spread'. Besides differences between different spatial prototypes, the evolution process and resulting network are further determined by the spatial structure within a certain prototype. When certain agglomerations are 'too close' to the starting network, they may lie below the 'hurdle distance' threshold. This affects the evolution process in terms of how the network physically evolves and may also lead to different resulting networks for similar structures. The spatial structure of the urban area also has an impact on the user costs. In spatial structures with longer distances to be travelled, the total user costs are higher. Lastly, the spatial structure of the urban area has an impact on the type of mode that is invested in. For different distance classes it is observed that certain modes relatively provide the most benefits. These findings are in line with the statements made by Van den Heuvel (1997) and Van Nes (2002).

Impact of demand distribution

For different demand distributions, the main observation made is that in the uniform scenarios, the networks generally expand to the closest disconnected nodes if the distances to these are above the 'hurdle distance'. As the population is equal in all nodes, the demands from one node to any node in another agglomeration are roughly the same. The best investment is then one for which the costs are minimal, and this is the case for links covering shorter distances. For the linear and exponential demand distributions the network is most likely to expand to the nodes with highest population. However, investment choices made early on have been observed to influence the resulting hierarchy of nodes in the final network state. For equally populated central nodes, the betweenness centrality value of these nodes will vary based on which of the two is connected first to the higher-level network. The node which is connected to the higher-level network at the start is more likely to strengthen its position within the entire network over time.

Impact of operational costs

A variation in operational costs leads to a difference in the evolution process of the PT network. When lower operational costs are assumed, the investment scores increase as this is inversely related to the total costs of investments (which also consist of the operational costs). As these investment scores are higher in each iteration, the evolution process continues longer since the scores stay above 1.0 for a longer period of time. In the numerical experiments it is observed that these extra investments made are further densification and bulking of the network. This indicates that a decrease in operational costs makes it possible to make more beneficial investments in the PT network, which results in a decrease in user costs in the entire network. The exact investments however, do differ from a certain point onwards. This point can be described as the point at which the 'basic network' is completed, after which additional densification and bulking investments are made to further improve the network. Furthermore, due to the extra investments made with lower operational costs, the hierarchy of nodes also shifts when operational costs are decreased. The importance of the most dominant node in the network increases when lower operational costs are assumed. For all the other nodes which are less dominant it holds that their importance becomes more equal when lower operational costs are assumed.

Impact of multimodality

With the consideration of a unimodal PT network with the agglomeration mode, it is observed that the evolution pattern is generally different than when a multimodal PT network is considered. In the multimodal network, the network expands to a disconnected agglomeration first and then expands within the two connected agglomerations. In the unimodal network however, the network rapidly starts expanding the PT network to all agglomerations first (with an exception of the second agglomeration in RLNU). In the unimodal scenarios, there are no high-level PT modes with high operational speeds assumed. The benefits of expanding the network within agglomerations to connect node-pairs of different agglomerations is then also less at the start of the evolution process. While it is beneficial for nodes in a newly connected agglomeration to connect to the node which has an interregional link, this is less the case in the unimodal scenarios. This is due to the relatively lower travel time gains that are provided. In terms of the evolution process, it is observed that in both unimodal scenarios the investments consist of expansion, densification and bulking in that order. While the resulting networks in the unimodal scenarios are comparable to their respective multimodal scenario, certain nodes stay disconnected from the PT network in the unimodal scenario. This is due to the combination of low PT speeds offered and low demands in the nodes. The user costs are higher in the unimodal scenarios. This is a result of low PT speeds and thus high in-vehicle times and a larger share of users for the alternative mode. In terms of the betweenness centrality values for the multimodal and unimodal scenarios, it is seen that the multimodal scenarios are steered more towards a hierarchical network structure.

Model sensitivity

Lastly it is observed that the model is sensitive to inputs that affect the costs and/or benefits and to the initial network which is assumed. The sensitivity of the model to these aspects however differs per scenario. While varying assumptions that affect the benefits have a significant impact on the resulting network in the 'Tokyo' scenario, this is not so much the case for the 'Flemish Diamond' scenario.

An increase in population leads exclusively to bulking investments in the ‘Flemish Diamond’ scenario. In the ‘Tokyo’ scenario however, additional densification investments are also made. Generally, an increase in population leads to an extension of the bulking phase due to the higher benefits. However, after a certain threshold value, an additional expansion and densification phase can occur. This additional expansion and densification phase is then followed up by another bulking phase.

For the assumption of varying speeds of the alternative mode it is found that different investments will be made, and a decrease of this value does not simply lead to an extension of the evolution process as is the case for an increase in population. As different investments are made in early stages of the process, the resulting networks also follow a different evolution path and differ. These differences are more present in spatial structures where relatively shorter distances are covered, such as the ‘Tokyo’ prototype.

For varying values of the cost components of the PT modes it is found that the impact this has on the generated networks also differs for different spatial structures. These differences are again more present in spatial structures where relatively shorter distances are covered, such as the ‘Tokyo’ prototype. Furthermore, by decreasing the values of the cost component of one specific PT mode, this mode can become dominant in the network. This can even eliminate the necessity of having any other PT modes.

Lastly, in terms of the initial network which is assumed, the impact that this has on the final network state is more visible in spatial structures where there are less distinctly separated agglomerations, such as the ‘Tokyo’ prototype. This prototype has more ‘freedom’ as to how it can evolve and has no clear-cut solutions in terms of how to connect the agglomerations. It is expected that by steering this type of network into a certain direction, it is more likely to evolve into a state that follows this direction.

While it is seen that the model is sensitive to these types of input, due to the limited number of tests conducted for the sensitivity analysis it is difficult to comment fully on the varying results. Further research would be necessary to investigate these effects better.

6. Case study: Randstad area

To test the applicability of the network evolution model to a PT network in the real world, it is chosen to apply the model to the Randstad PT network. The choice to apply the model to the Randstad area is made because the Randstad is a prime example of a polycentric urban region. Furthermore, Rijksoverheid (2019) states the current vision of various PT stakeholders on the future of the Randstad PT network and this network's role on a national scale. It is interesting to investigate if there are any missing links in the Randstad PT network and to investigate whether investments suggested by the network evolution model correspond to future visions stated in this document. This chapter firstly discusses the Randstad study area in section 6.1. Besides discussing the Randstad area in general, this section also discusses the PT network within the Randstad. While the model functions the same as in the numerical experiments, different data is used as input and also the assumptions made differ from the numerical experiment. These model specifications are all detailed in section 6.2. Thereafter, the simulation results of the case study and their implications for the Randstad PT network are discussed in section 6.3. Lastly, the conclusions of the Randstad case study are discussed in section 6.4.

6.1 Study area: Randstad

The Randstad area is a large urban region in the central-western part of the Netherlands (Figure 6.1).

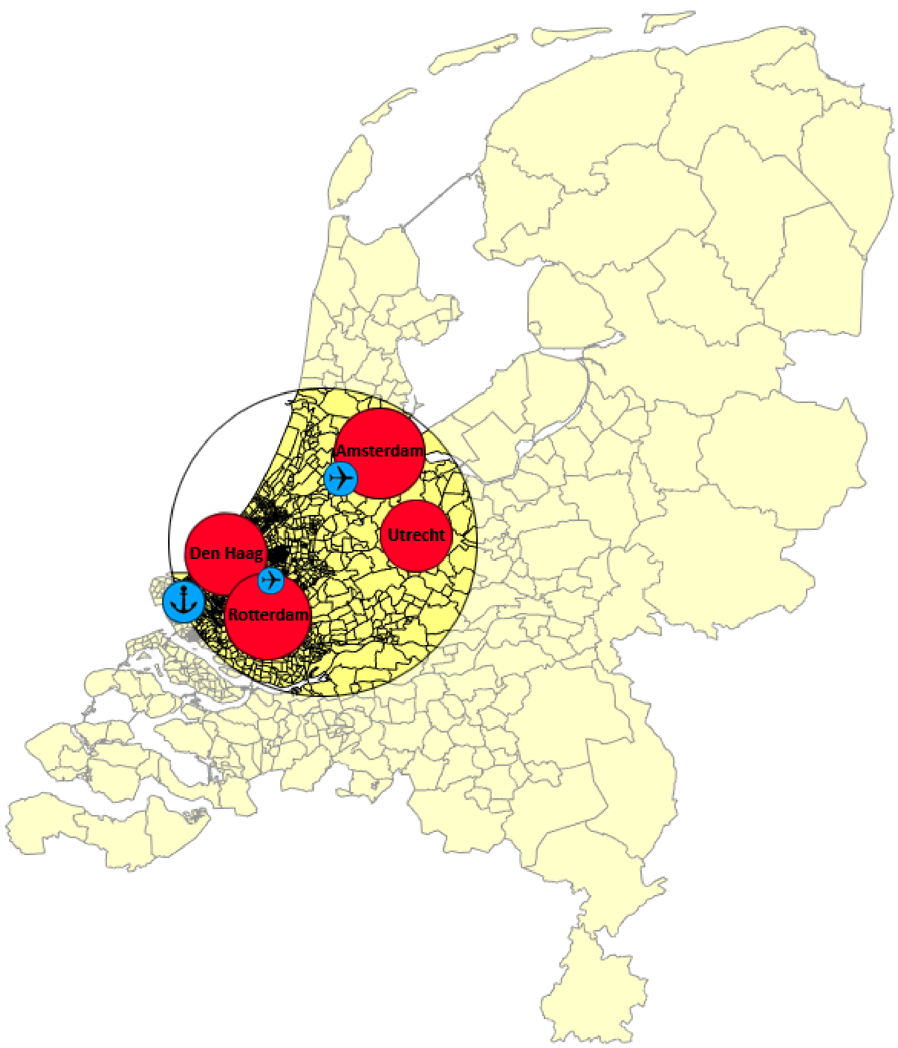

Figure 6.1: Location of the four main cities and notable ports in the Randstad

The Randstad consists of the four largest Dutch cities (Amsterdam, Rotterdam, The Hague (Den Haag) and Utrecht) and a number of other large agglomerations with a population above 100,000 inhabitants such as Leiden, Delft, Haarlem, Dordrecht, Almere and Amersfoort. The entire Randstad area consists of roughly 8 million inhabitants, which is almost half the entire population of The Netherlands.

The main sea- and airports of the Netherlands are located within the Randstad including Schiphol Airport (AMS), Rotterdam The Hague Airport (RTM) and the Port of Rotterdam. Schiphol Airport, which is near Amsterdam, is one of the largest airports in the world and therefore does not only have an important position within the Netherlands itself, but also has international importance serving 68.5 million passengers in 2017 (Schiphol Group (2018)). While Rotterdam The Hague Airport is significantly smaller than AMS, it is still a notable airport which served almost 2 million passengers in 2018 (Rotterdam The Hague Airport (2019)). The Port of Rotterdam is one of the largest ports in the world and the largest port in Europe with a throughput of 469 million tons in 2018 (Port of Rotterdam (2019)). In terms of passenger transportation, the ports are centers of activity which produce and attract many trips (jobs and flight passengers) and are therefore also of importance to the Randstad area.

In terms of the PT network in the Randstad, the national Dutch rail network is most notable. Figure 6.2 shows the part of the network operated by the Dutch Railway (NS) that covers the Randstad area. In terms of the main ports, it is seen that Schiphol Airport has a prominent position in this rail network as well.

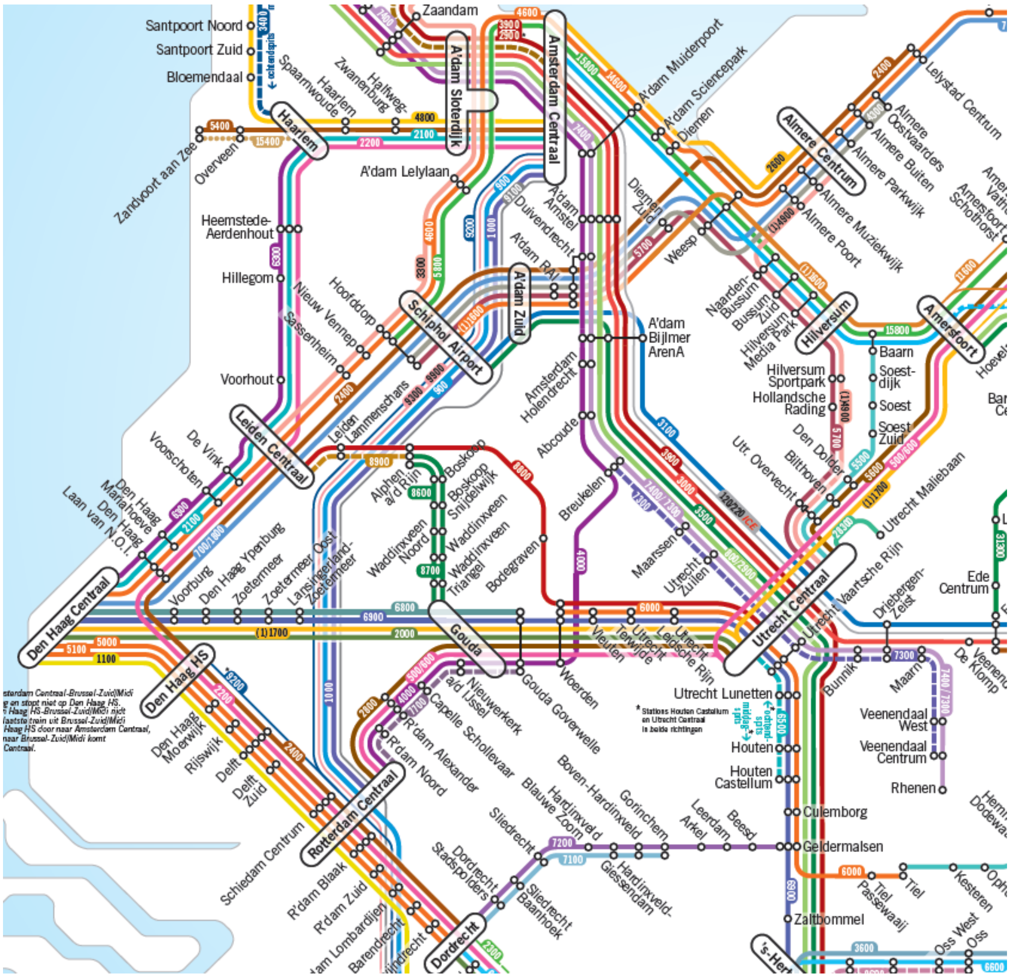

Figure 6.2: Part of the Dutch main railway network that covers the Randstad

All the large cities within the Randstad are served by this network and also the smaller agglomerations between these large cities are served. This railway network can be seen as the higher-level PT network within the Randstad. On a lower network level there are also notable rail networks mainly within and between the large cities. The three most notable networks are the GVB metro network in Amsterdam, the RET metro network in Rotterdam and Den Haag and the HTM tram network in Den Haag (Figure 6.3). A notable aspect of the RET metro network is line E; this is a metro line that operates within Rotterdam, but also connects Rotterdam with Den Haag. This metro line also serves smaller agglomerations between Den Haag and Rotterdam such as Pijnacker and Berkel en Rodenrijs, which are not connected to the main railway network. The choice of including the tram in Den Haag and not including the GVB and RET tram-networks in Amsterdam and Rotterdam respectively, is made because in the latter two cities the metro network is considered to be the backbone of these networks that cover a large part of the agglomerations. In Den Haag however, there is no metro network present. This leads to the existing tram network to function as the backbone of the network within the agglomeration.

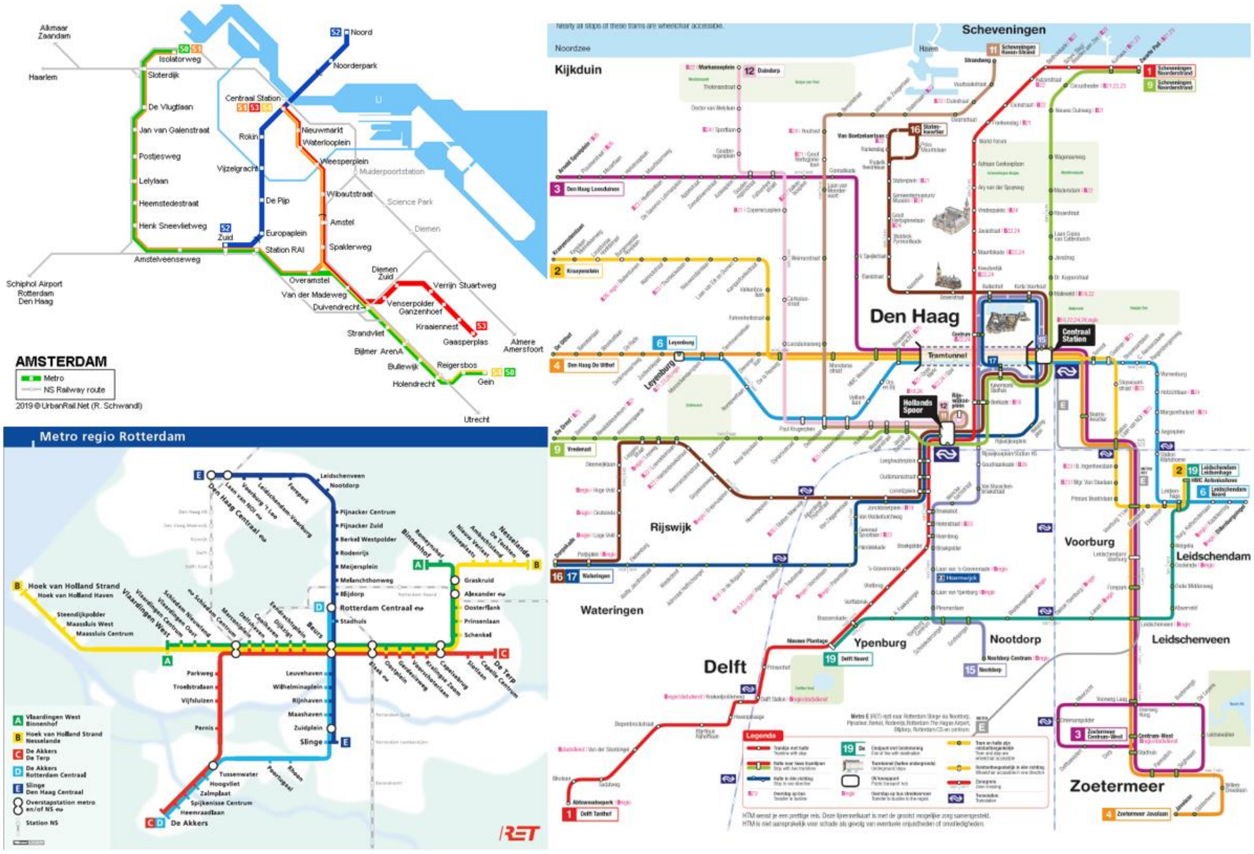

Figure 6.3: GVB metro network (top left), RET metro network (bottom left) and HTM tram network (right)

6.2 Model specifications of Randstad case study

In comparison to the numerical experiment, certain adjustments are made to the model for the case study. As there is already an existing network and data with regard to trips is already available, relevant data is already used as input for the model. This data is discussed in section 6.2.1. Furthermore, certain notable assumptions are made in order to limit computational times. These assumptions are discussed in section 6.2.2. Lastly, section 6.2.3 shows visualizations of the existing rail network in the Randstad area, which was used as starting point for the evolution process.

6.2.1 Input data

The data used as input for the case study is extracted from the 'Verkeersmodel Metropoolregio Rotterdam Den-Haag' (VMRDH). Part of this data consists of OD-matrices of all zones within the Netherlands for PT trips and car trips. The data on OD-matrices is taken from the 2030-High scenario; these are based on predictions for 2030 with high estimates. The scale level of the zones is similar to something between 4-digit postcodes and 6-digit postcodes. As the focus of the VMRDH is on the Rotterdam and the Hague metropolitan region, the zones in this region are closer to 6-digit postcode scale and the zones outside this metropolitan region are more aggregated. The total number of zones in the VMRDH is 7786 zones; to compare, there are 4066 4-digit postcodes and 458,114 6-digit postcodes in the Netherlands (Spotzi (2018)).

Besides these zones, data on the PT network is extracted. This data consists of geographical locations of the stations and information on the PT modalities that operate on the various links of the network. The PT network in the VMRDH which is used in the case study consists of the national Dutch rail network and the RET metro network. As the HTM tram network in the Hague and the GVB metro network in Amsterdam were missing in the VMRDH, stops and links corresponding to important lines in these networks are added based on expert judgement. The reason to add these lines is to avoid unrealistic passenger flows, as these lines are seen as part of the backbone of the network. A list of the added lines and stops is shown in Table 6.1. Besides these added lines and stops, also gateway stops are added outside the Randstad area. These gateway stops, which are all train stations, are the following: Zwolle, Arnhem Centraal, 's-Hertogenbosch, Eindhoven and Breda. Lastly it should be noted that certain stops are removed when they are close to other stops on the same line (e.g. Waddinxveen Noord and Waddinxveen Triangel are removed, while Waddinxveen (in the middle of these two) is not). These removals are done to reduce computational times and are based on expert judgement. A complete list of all 156 stops is shown in Appendix D.

Table 6.1: List of PT lines and stops added

Line	Stops
HTM – Line 1	Den Haag Centraal, Kurhaus (Scheveningen)
HTM – Line 6	Den Haag Centraal, Spui, Leyenburg
HTM – Line 17	Den Haag HS, Rijswijk, Wateringen
GVB – Line 52 (Noord-Zuidlijn)	Amsterdam Noord, Amsterdam Centraal, Vijzelsgracht, Amsterdam RAI (Europaplein), Amsterdam Zuid
GVB – Line 51 (Amstelveenlijn and Uithoornlijn)	Amsterdam Zuid, De Boelelaan/VU, Oranjebaan, Westwijk, Uithoorn

6.2.2 Modelling assumptions

Firstly, as is also assumed in the numerical experiments, access and egress times are not considered in the case study. This means that the trips within the network start and end at the stations. The data on OD pairs however is between zones and thus these zones are firstly aggregated to stations. The first assumption made in this process is that certain zones have a much larger share of car trips than PT trips, for example if there is no frequent PT service near that zone. As the model is used to investigate future evolution of the existing network, and not allowing for new stations to be constructed, it is chosen to leave out the nodes which have a large share of car trips. Both the OD matrix for PT trips as for car trips are used for the 'generalized' OD matrix in the model. When considering nodes with a high share of car trips, it would not be realistic to assign these zones to certain stations as the OD matrix may become too 'biased' towards car trips. Zones which have limited access to public transit have a relatively much larger share of car trips instead of PT trips. If these zones are then aggregated to certain stations, it means that a share of the existing car trips for this zone could potentially become PT trips. The potential PT demand then becomes unrealistically large, since in reality these zones have limited access to public transit. It is therefore chosen to leave these 'biased' zones out of the model. The assumption made to remove these car-biased zones, is to remove them if the share of PT trips is less than 25% of the total number of trips (car and PT). This assumption already reduced the number of nodes from 7786 to 4234 zones. The total number of car and PT trips made per day when considering these 4234 zones is roughly 6.7 million. These 4234 zones are then distributed over the 156 stops in the network. This is done by assigning each zone to stops based on the distance that the centroid of this zone has to the stops. When there is a stop within a 2 km radius of the zone, the zone is assigned to this stop. If there are multiple stops within the 2 km radius, the zone is assigned to all stops within the 2 km radius and the number of trips is then also divided equally between all stops. If there is no stop within a 2 km radius of a zone, the zone is assigned to the closest stop.

The second assumption made was with regard to the different PT modalities. It was chosen to consider 4 different PT modalities which generally correspond to the PT modalities in the Randstad area: High Speed Line (HSL), Intercity (IC), Sprinter (SP) and LRT/Metro (LM). The first three modalities are trains that operate on the main railway network and the LM modality is a generalized modality of the various types of metro, light-rail and tram which operate within the Randstad. The operational speeds of the modalities have been assumed based on travel times between stations in the current network. The cost parameters have been determined with a combination of existing documentation on costs and expert judgement provided by RoyalHaskoningDHV. Lastly, the stop spacing values have been determined based on the 25th and 75th percentile of all distances between stations in the existing network for each modality. The values found have then been adjusted based on expert judgement. A complete overview of the mode attributes is shown in Table 6.2.

Table 6.2: Attribute values for the four PT modes in the Randstad

Attribute	LM	SP	IC	HSL
s_k^{min} [km]	0.5	3	10	30
s_k^{max} [km]	3	10	30	200
$C_{infra,k}$ [€/km]	16 mln.	14 mln.	14 mln.	25 mln.
$C_{RS,k}$ [€/veh]	5 mln.	5 mln.	8 mln.	20 mln.
$C_{OCt,k}$ [€/h]	60	100	120	130
$C_{OCd,k}$ [€/h]	3	10	12	12
f_k [veh/h]	6	3	3	4
v_k [km/h]	45	65	90	110

The third assumption made was with regard to the candidate generation of each PT modality. Similarly to the numerical experiments, the candidates of each modality are dependent on the minimum and maximum stop spacing values. On top of this condition, for the HSL, IC and SP modalities additional conditions were set:

- For the HSL candidates, a pre-defined set of stations was determined based on expert judgement. This set of stations consists of 19 important train stations within the current network: Delft, Den Haag Centraal, Leiden Centraal, Rotterdam Centraal, Amsterdam Centraal, Amersfoort, Gouda, Utrecht Centraal, Rotterdam Alexander, Haarlem, Amsterdam Zuid, Den Haag HS, Schiphol Airport, Breda, Eindhoven, Arnhem Centraal, Zwolle, Almere Centrum and 's-Hertogenbosch.

- For the IC candidates, the stops which can be considered as candidates must already have an existing train link (HSL, IC or SP). If a new train link is realized in the current network, it is more realistic that the stop would serve sprinters first rather than immediately creating an IC station. It should be noted that the list of IC candidates is updated if a new SP station is added during the evolution.
- Finally, for SP candidates an additional condition is set that if there are multiple SP candidates, it only considers the candidate that has the highest demand in a 3 km radius. This is similar to what was done for regional and interregional links in the numerical experiments.

Fourthly, based on the existing links in the network, a detour factor was calculated. While in the numerical experiments the geodesic distance was also assumed as the link length, in the case study it was chosen to make use of a detour factor as it represents more realistic link lengths. The detour factor found in the existing network was 1.11 and this number was multiplied by the geodesic distance between two nodes to calculate the link length.

Lastly, different values for the speed of the alternative mode were used. Based on the average speeds found for different distances to be covered (CROW-KpVV (2015)), it was assumed that the alternative mode has a minimum speed of 20 km/h and this speed linearly increases as the distance to be travelled increases, up to a maximum of 55 km/h for distances over 40 km. A visualization of the speed of the alternative mode in relation to the distance travelled is shown in Figure 6.4.

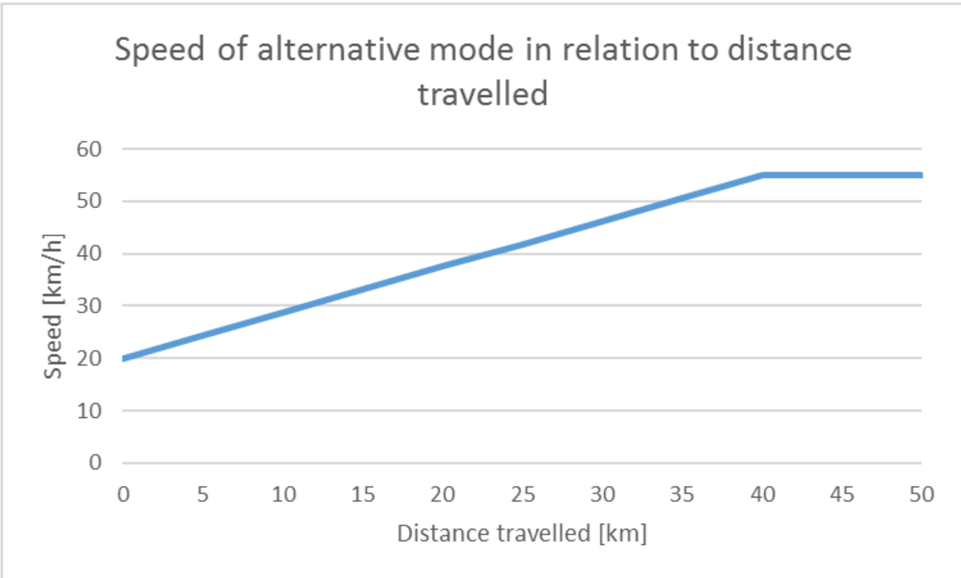

Figure 6.4: Speed of alternative mode in relation to distance travelled

6.2.3 Randstad PT network visualizations

Firstly, a visualization of the considered zones and the PT network is shown on the map in Figure 6.5. The transparent zones are the so-called car-biased zones as discussed in the previous section and are therefore the zones which are not considered in the model.

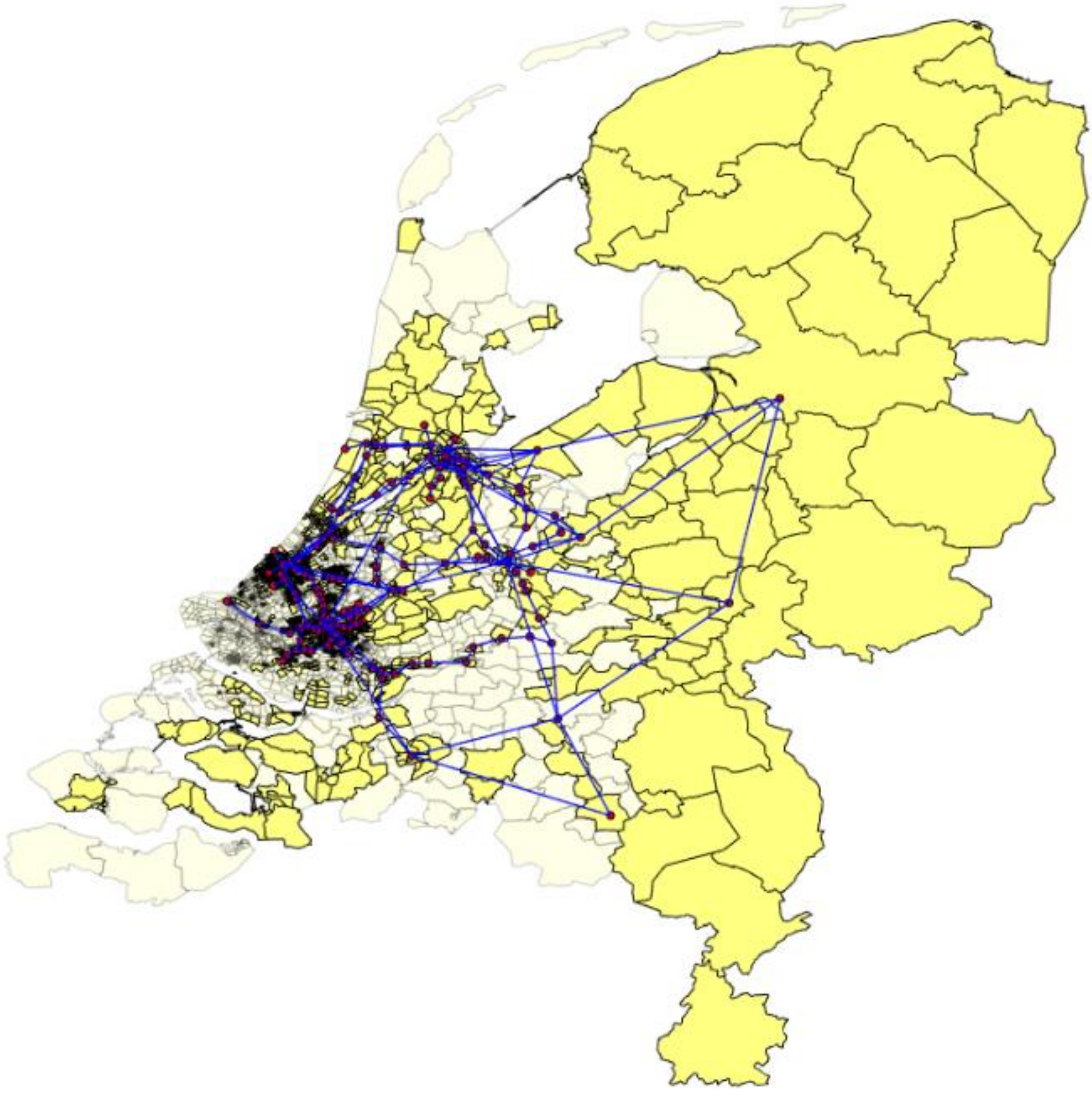

Figure 6.5: Map of the Netherlands with considered zones and PT network highlighted

Secondly, a visualization of only the initial PT network in the Randstad is shown in Figure 6.6. Here the different modalities are shown with different colours.

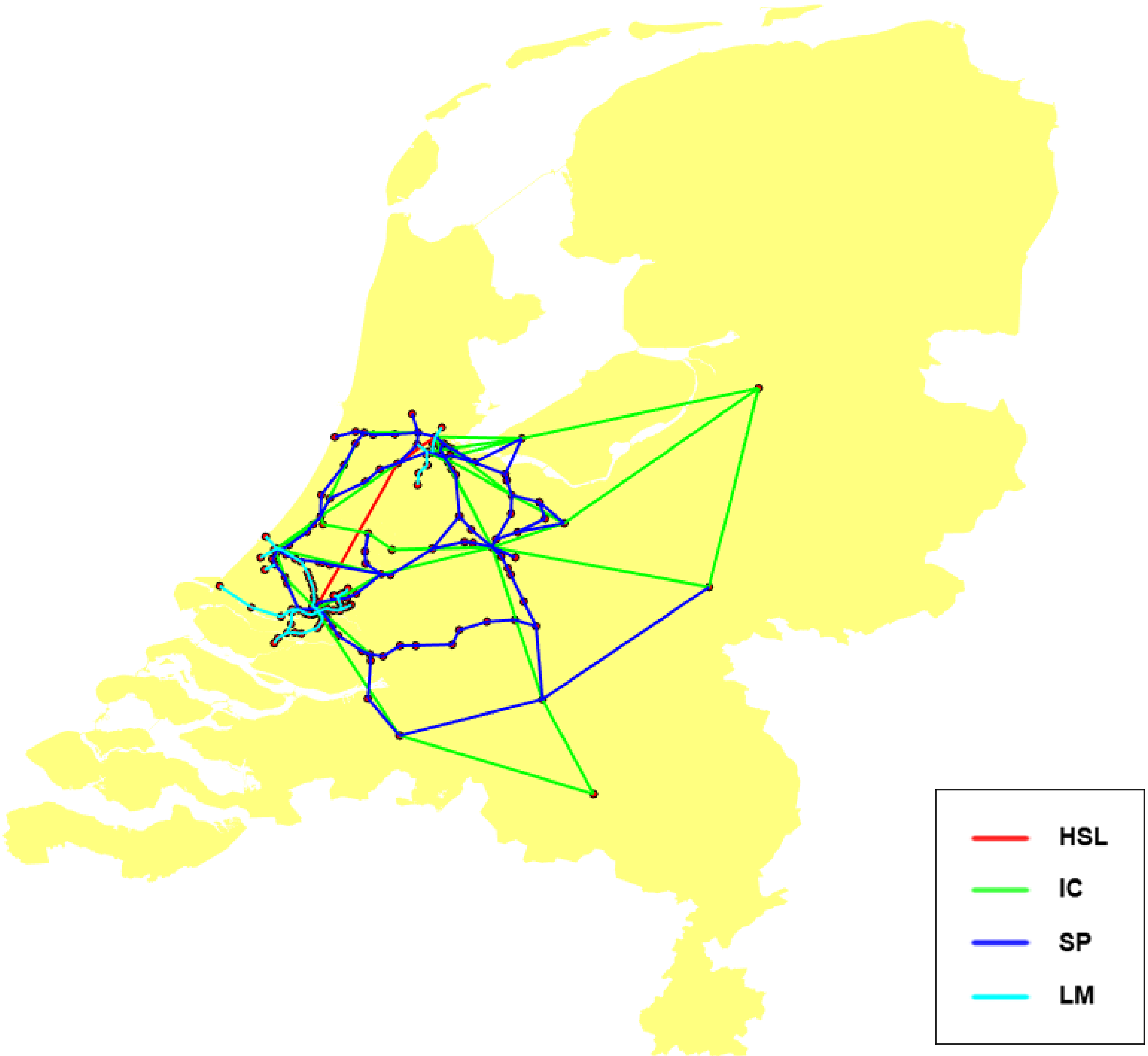

Figure 6.6: Initial PT network Randstad with distinguished PT modalities

The third visualization shown in Figure 6.7 gives an indication of the passenger flow intensities of the initial PT network, as determined by the model. Here the thickness and colour give an indication of the intensity: The thicker the line, the higher the intensity; the redder the line is, the higher the intensity. These intensities are measured in passengers on an average weekday. The largest intensities are around the outer edges of the network. This is because the zones outside the Randstad have been aggregated to the stops on the outer edges of the network. Within the Randstad area, the most notable passenger flow intensities between the four main cities are observed between Amsterdam – Den Haag and Utrecht – Rotterdam. While it is to be expected that Amsterdam – Utrecht would show large passenger flow intensities, these are relatively low. Furthermore, there is a high passenger flow intensity between Utrecht – Amersfoort. Lastly, the passenger flow intensities radiating to and from the central parts of the four main cities decrease more the further away from the center. This indicates some sort of decay in travel demand starting at the CBD's within the four cities. One notable trajectory which is expected to show inaccuracies is Amsterdam – Utrecht. This trajectory is considered as one of the busiest in the Netherlands (Het

Parool (2018)) despite having one of the highest operating frequencies. This relatively low passenger flow intensity could be due to OD data used. As the data is extracted from the VMRDH, where the focus is mainly on the Rotterdam and Den Haag regions, the passenger flows radiating from these regions have been calibrated properly, but it is expected that on the tangential lines (such as Amsterdam – Utrecht) these calibrations are less accurate.

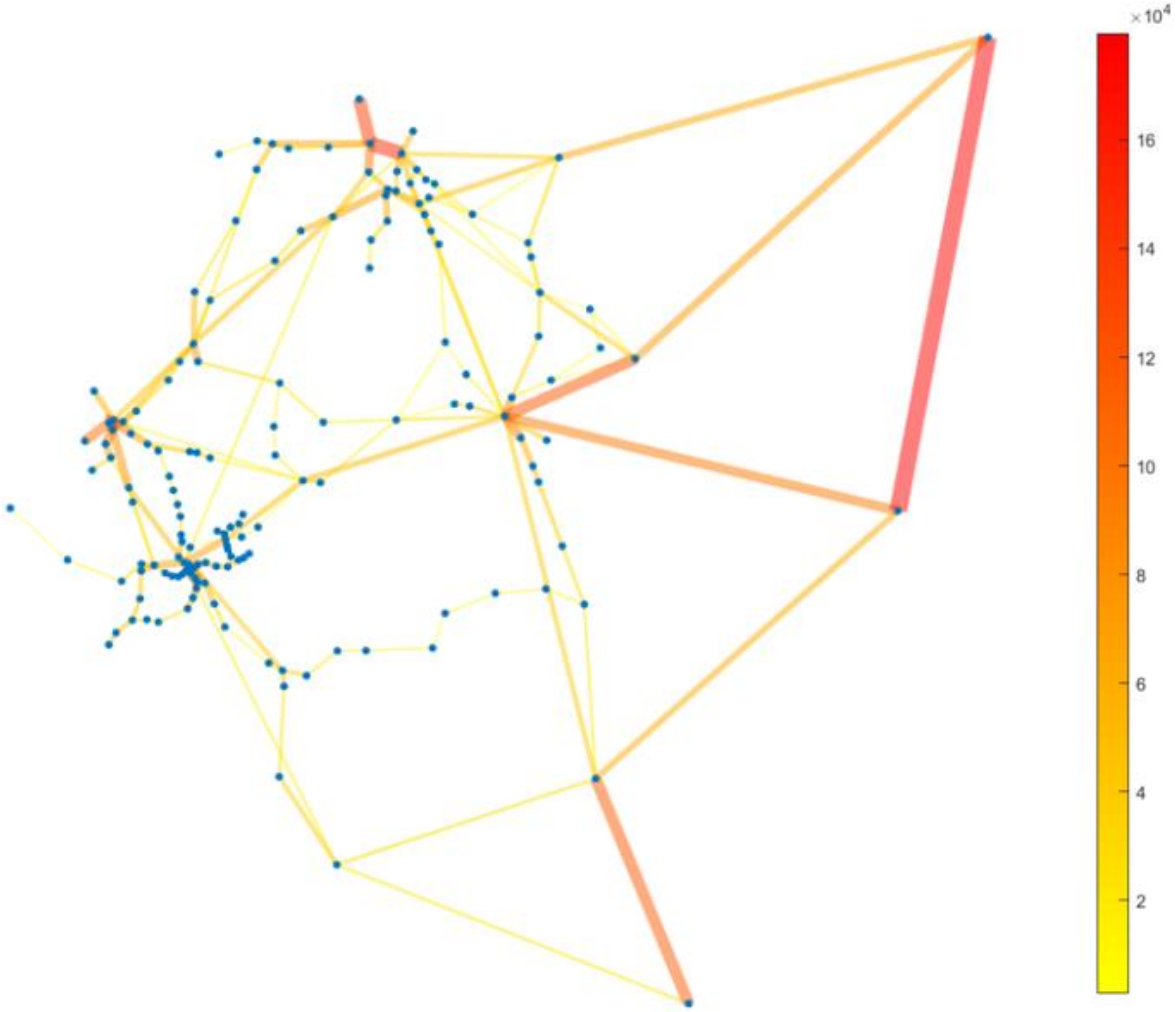

Figure 6.7: Visualization of passenger flow intensities on PT links in initial state for Randstad PT network

In terms of the betweenness centrality, Figure 6.8 shows the distribution of the betweenness centralities of the nodes in the network. In this distribution it is seen that there is one node with a relatively high betweenness centrality value. This value corresponds to Rotterdam Centraal.

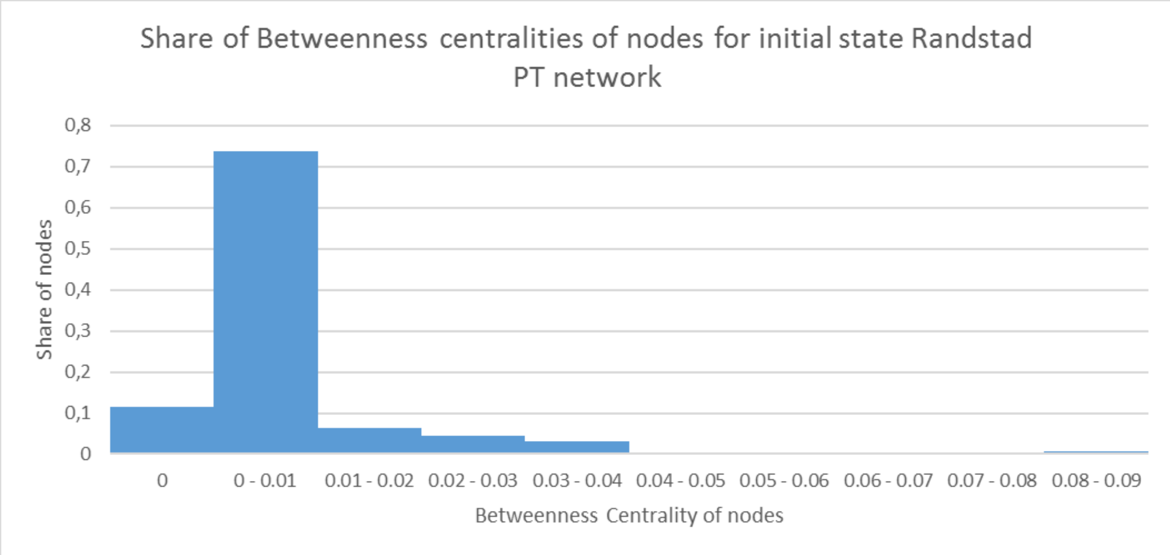

Figure 6.8: Share of betweenness centralities of nodes for the initial state of the Randstad PT network

To get a visual idea of where the nodes with high betweenness centralities are physically located, Figure 6.9 shows the Randstad PT network with the node colour indicating the betweenness centrality value. The redder the colour, the higher this value.

Figure 6.9: Visualization of betweenness centrality of nodes in the initial state for Randstad PT network

6.3 Results of Randstad case study

Firstly, an overview of the investments made is given in section 6.3.1. Hereafter, impact of these investments on the network are discussed in section 6.3.2. Here the differences in terms of topological and performance indicators of before and after the evolution process are analysed. Finally, section 6.3.3 discusses the implications that the results may have on Randstad PT network.

6.3.1 Overview of investments made

The simulation of the Randstad PT network was finished after 17 iterations. To ensure that the network state is not in some sort of local minimum, the simulation is extended. In this extended simulation the model simply chose the highest scoring investment, regardless of it being beneficial or not. After 47 additional iterations (64 in total), it can be seen that the investment scores steadily decrease (Figure 6.10). It can therefore be concluded that the network state is not in a local minimum and is 'saturated' after 17 iterations, as there are no scores above 1.0 after 17 iterations.

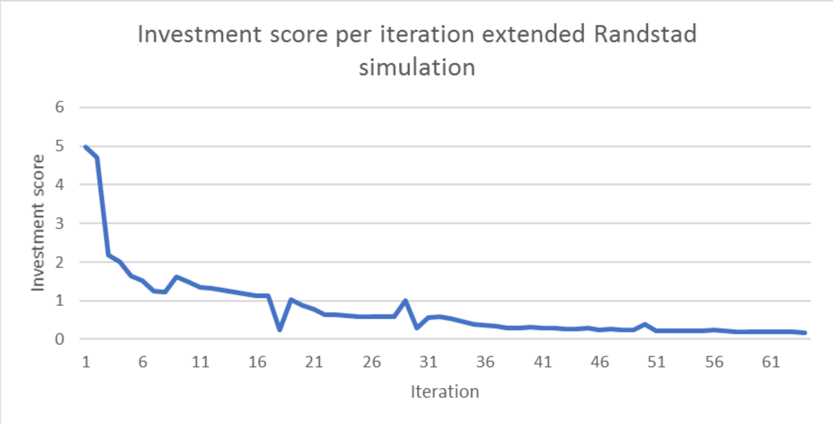

Figure 6.10: Investment scores per iteration for the extended Randstad simulation

An overview of the 17 investments made per iteration are shown in Table 6.3 and are visualized in Figure 6.11 and Figure 6.12.

Table 6.3: List of investments made in Randstad PT network (in chronological order)

Investment type	Start	End	Mode
Bulking	Arnhem Centraal	Zwolle	IC
Densification	Den Haag HS	Den Haag, Spui	LM
Bulking	Amersfoort	Zwolle	IC
Bulking	Den Haag, Spui	Den Haag, Leyenburg	LM
Bulking	Zwolle	Almere Centrum	IC
Bulking	Lage Zwaluwe	Breda	SP
Bulking	Leiden Centraal	Voorhout	SP
Densification	Eindhoven	Arnhem Centraal	HSL
Densification	Rotterdam, Beurs	Rotterdam, Wilhelminaplein	LM
Densification	Amsterdam Zuid	Amsterdam, Vijzelgracht	LM
Densification	Rotterdam, Rijnhaven	Rotterdam Zuid	LM
Densification	Rotterdam, Stadhuis	Rotterdam Noord	LM
Bulking	Arnhem Centraal	Zwolle	IC
Densification	Den Haag Centraal	Den Haag Mariahoeve	SP
Bulking	Naarden-Bussum	Almere Centrum	SP
Bulking	Leiden Centraal	Leiden Lammenschans	IC
Bulking	Overveen	Haarlem	SP

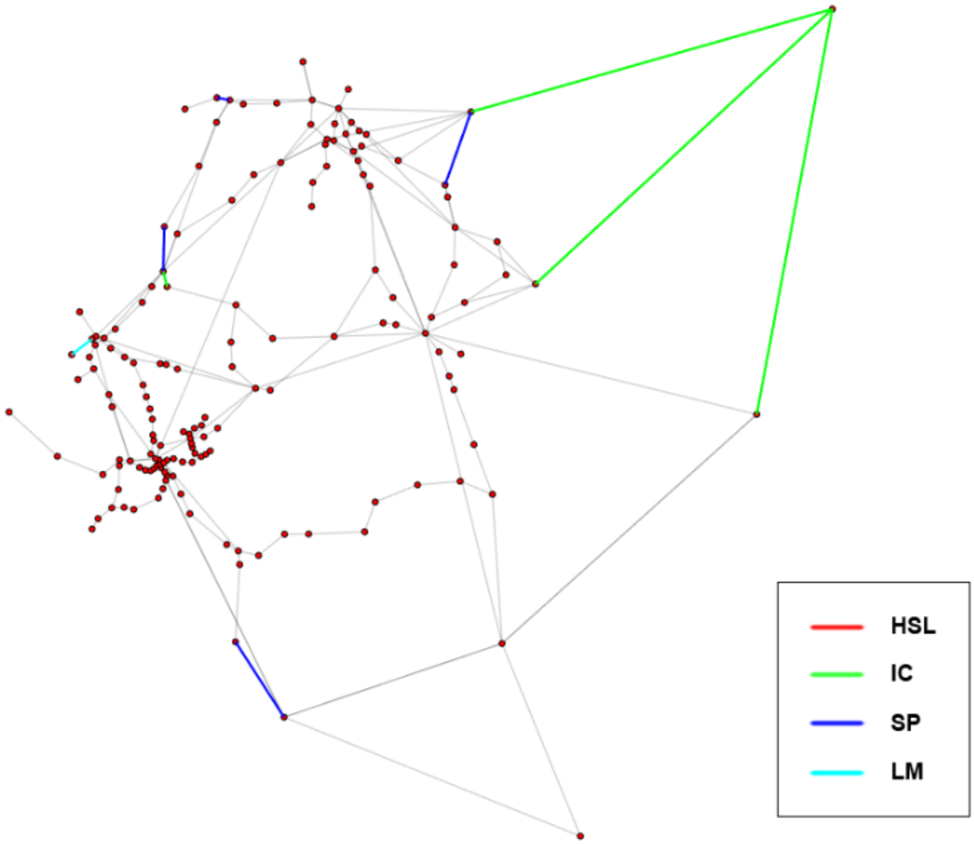

Figure 6.11: Bulking investments made in Randstad PT Network

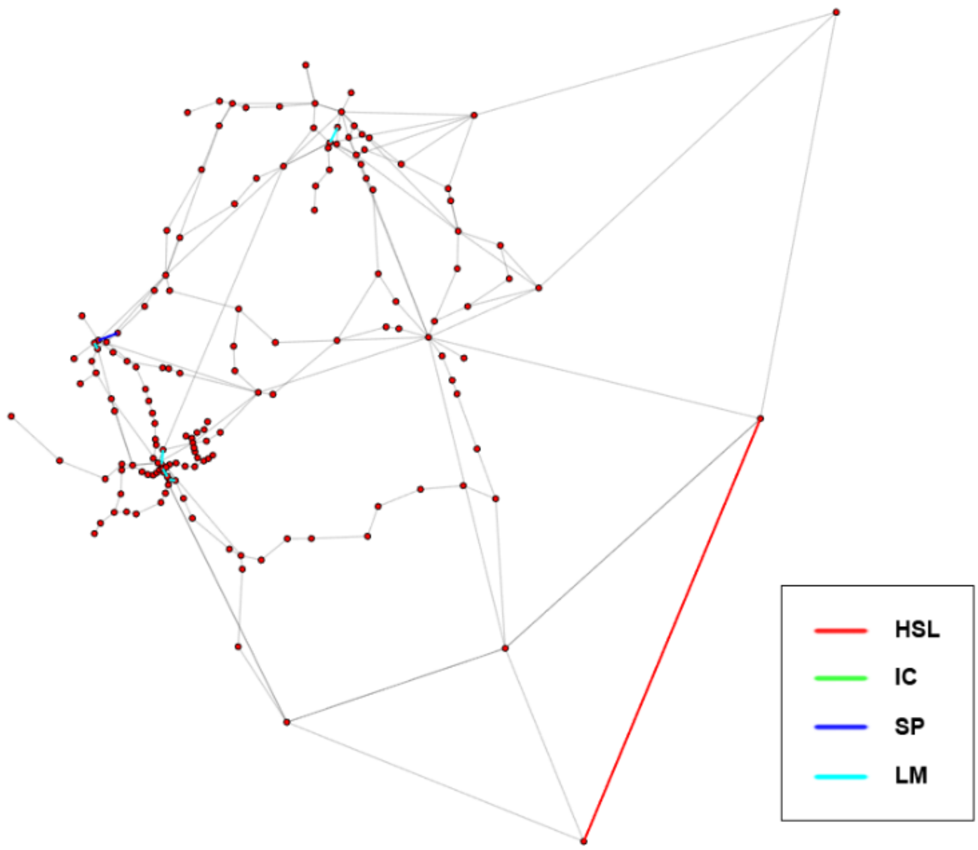

Figure 6.12: Densification investments made in Randstad PT network

As can be seen, the amount of investments made is limited. In terms of the investments made, the bulking investments are done mainly on links towards the outer edges of the network rather than the more central areas of the entire network. This seems logical, as the zones towards the outer edges of the network have been heavily aggregated to these stations. This leads to relatively high demands in the outer areas, making bulking investments more beneficial due to the high number of passengers that benefit from the investment. The most notable example of this is Zwolle, where the three IC connections between Zwolle-Arnhem Centraal, Zwolle-Amersfoort and Zwolle-Almere Centrum are bulked.

As for the densification investments, the two most notable ones are the HSL link between Eindhoven and Arnhem Centraal and the LM link between Rotterdam, Stadhuis and Rotterdam Noord. The other densifications are done on existing lines, where ‘shortcuts’ are realized. An illustration of this is shown in Figure 6.13 where the example of the link Rotterdam, Beurs and Rotterdam, Wilhelminaplein is used. The new link skips Rotterdam, Leuvehaven to reduce the travel times on the entire line, something similar to an express service. The minimal travel time gains that this link provides, are beneficial due to the high usage on this line. This phenomenon has also occurred in the past with for example Amsterdam De Vlugtlaan. This station used to be a stop on the Western railway line of Amsterdam, located between Amsterdam Sloterdijk and Amsterdam Lelylaan. This railway station was however cut out in 2000 due to the limited number of passengers using the station and continued to function only as a metro station. While the phenomenon itself is similar to the ‘shortcuts’, these investments do consider costs for constructing the new link and are therefore not entirely the same as simply cutting out a station on the existing line. Rotterdam, Leuvehaven is also still connected to the network in this case, which is not the same as being cut out entirely.

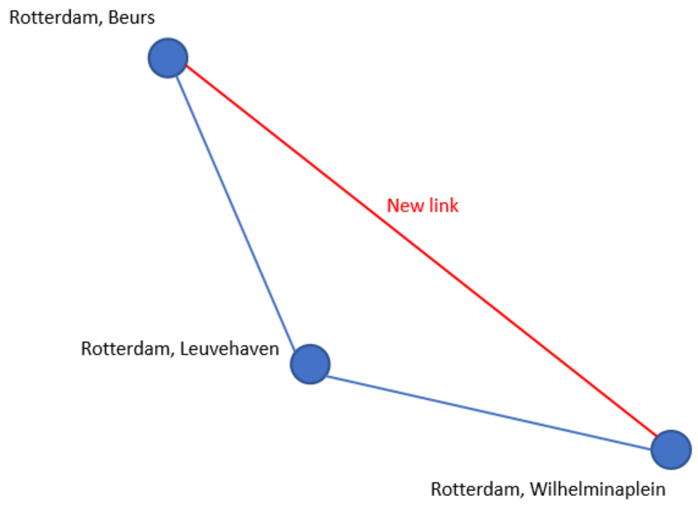

Figure 6.13: Visualization of 'shortcut' expansion link

Regarding the HSL link between Eindhoven and Arnhem Centraal, it is expected that the demands have not been calibrated accurately as it is a tangential line similar to Amsterdam-Utrecht as explained in section 6.2.3. Due to these inaccuracies in demands, this investment is arguably not realistic.

Finally, when considering the investment scores per iteration the bulking of Arnhem Centraal – Zwolle and the expansion of Den Haag, Spui – Den Haag HS score relatively high at the start (Figure 6.14). These high scores can be explained by the high intensities on these paths in the initial state of the network. The high intensities indicate that many passengers will benefit from travel time gains, leading to high scores.

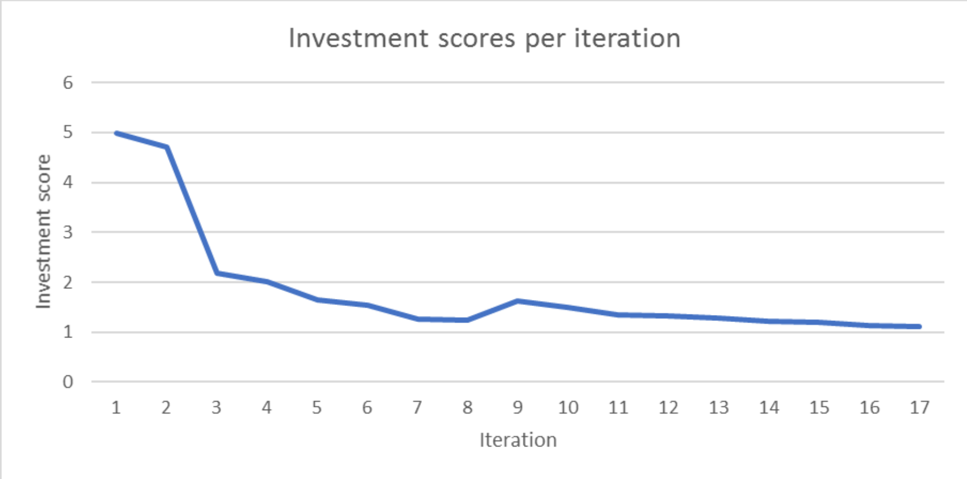

Figure 6.14: Investment scores per iteration for Randstad PT network

6.3.2 Impact of investments on the PT network

The investments made in the Randstad PT network have an impact on the network as a whole. As all stations were connected to the PT network in the initial state, it is expected that the modal share of PT was already at the equilibrium state (as described in section 5.2.1). The increase in modal share of PT is therefore very limited and increases by 0.7% (from 33% to 33.7%) over the evolution process. With a total of 6.7 million trips per day, this increase in modal share translates to roughly 47,000 additional PT trips made per day due to the investments made in the PT network. A large share of this increase is however attributed to the HSL link between Eindhoven and Arnhem Centraal. As this link is arguably constructed due to model limitations and is not realistic, it is expected that the modal share increase would also be significantly lower than 0.7% as this link is arguably not a realistic investment.

In terms of the user costs, the total user costs have decreased by €0.25 million per day (Figure 6.15). As the modal share increased by 0.7%, the number of trips made with the alternative mode decreased. This decrease in alternative mode trips translates to a decrease in user costs of €170.000 per day. At the same time, the additional trips made by PT increases the in-vehicle time. This increase amounts however to only €80.000. Furthermore, the transfer time costs and waiting time costs have been reduced by €5000 and €158.000 per day respectively.

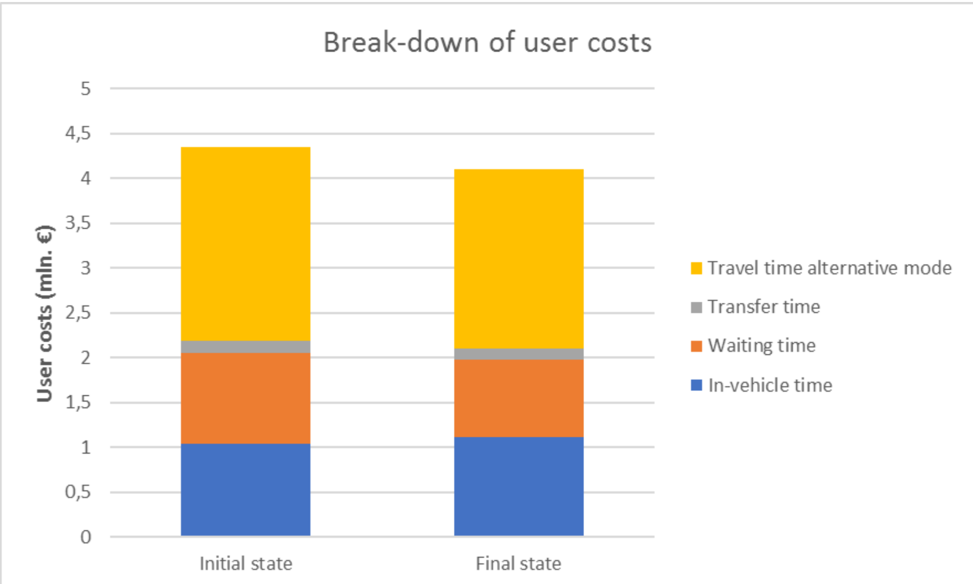

Figure 6.15: Break-down of user costs in initial state and final state of Randstad PT network

In terms of the intensities of passenger flows in the PT network, some differences can be observed as well (Figure 6.16). It should be noted that the line thicknesses have been made thicker in comparison to Figure 6.7. This is done to make the differences clearer. The red colour indicates an increase in passenger flow and the green colour indicates a decrease in passenger flow.

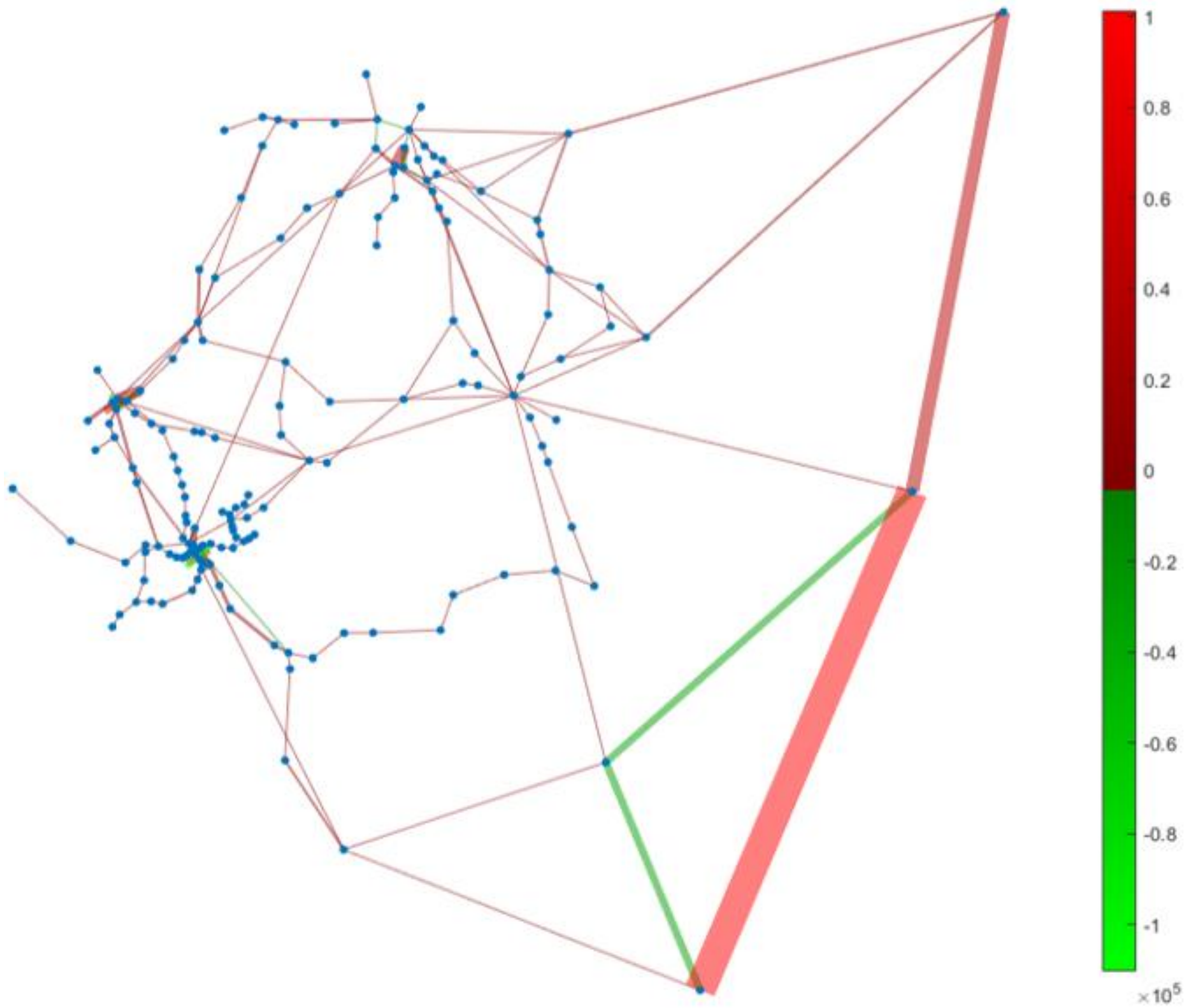

Figure 6.16: Visualization of differences in passenger flow intensities on PT links between initial state and final state for Randstad PT network

The first observable difference is in the South-Eastern part of the network. This is due to the HSL link constructed between Eindhoven and Arnhem Centraal and relieves the links ‘s-Hertogenbosch – Eindhoven and ‘s-Hertogenbosch – Arnhem Centraal. This link is however arguably unrealistic and is therefore considered to be a limitation of the model input.

The second observable difference are observed in Amsterdam, Rotterdam and Den Haag. These changes are mainly due to the ‘shortcuts’ that were realized. As an example, (Figure 6.17) shows the differences within Den Haag. The new LM link between Den Haag, Spui – Den Haag HS means that passengers do not have to first travel to Den Haag Centraal from Den Haag, Spui and Den Haag, Leyenburg to get to Den Haag HS. In the old situation a transfer was necessary at Den Haag Centraal between LM and IC/SP, while there is now a shorter route without transferring from LM. The new SP link Den Haag Centraal – Den Haag Mariahoeve can be seen as a ‘shortcut’ since the old route Den Haag Centraal – Den Haag Laan van NOI – Den Haag Mariahoeve was also served by SP.

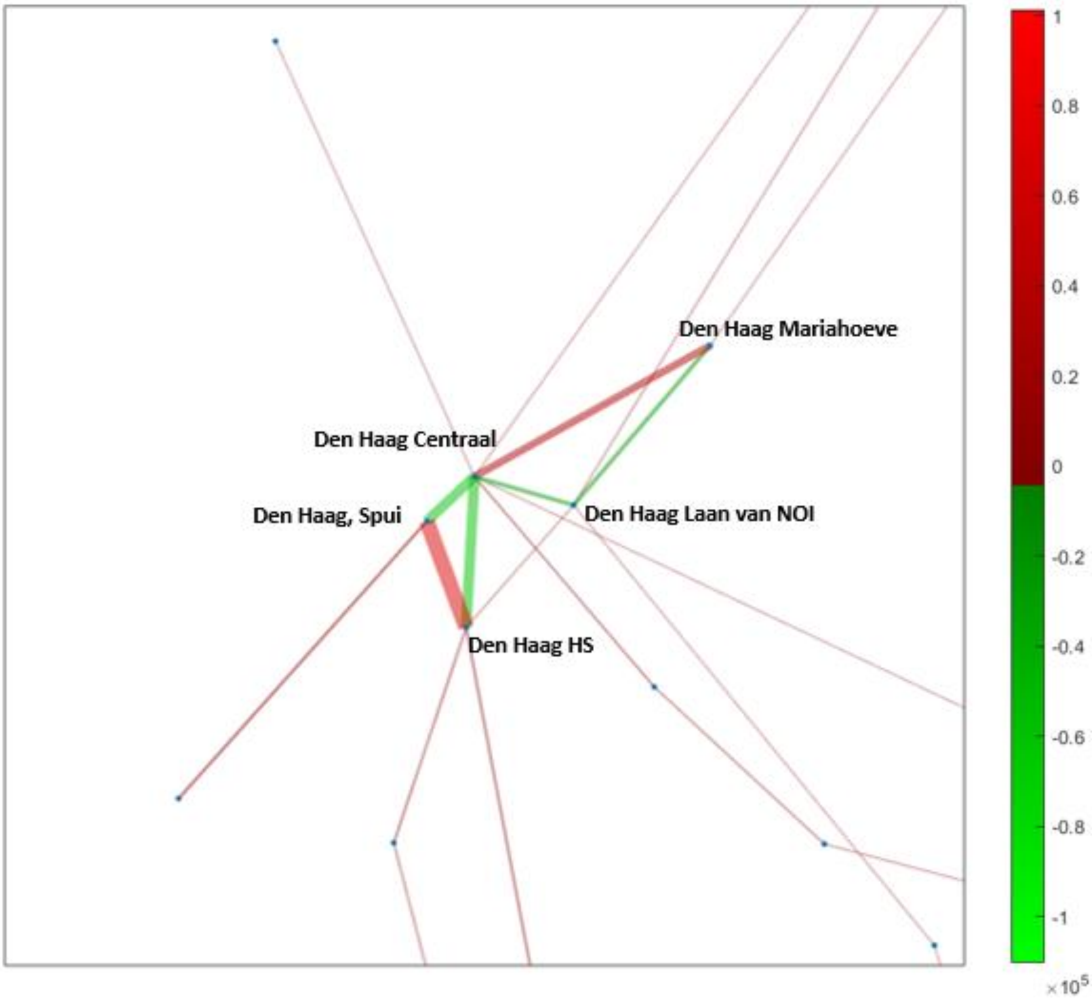

Figure 6.17: Visualization of differences in passenger flow intensities on PT links between initial state and final state in Den Haag

In terms of betweenness centrality it is observed that there are very minimal differences between the two states.

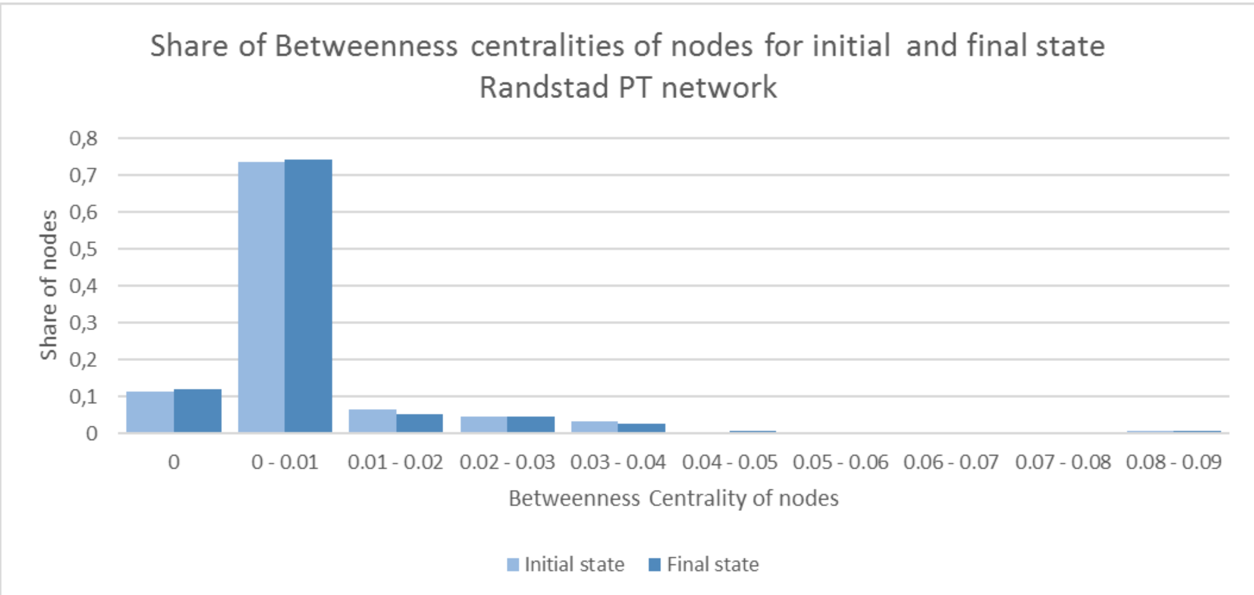

Figure 6.18: Share of betweenness centralities of nodes for the initial and final state of the Randstad PT network

This indicates that for the network as a whole network, the investments made do not have a notable impact on the hierarchy observed in the network. This can be explained again by the fact that the network is already in a 'mature' state with clear central nodes where multiple network levels come together.

Within the various LM and/or train sub-networks in Amsterdam, Rotterdam and Den Haag however, it is observed that these networks are relatively less 'mature'. There are beneficial densification investments that were made within these agglomerations, which indicates that these sub-networks are less 'mature' in comparison to the Randstad PT network as a whole.

6.4 Conclusions Randstad case study

Based on the results found during the case study, conclusions with regard to the implication of these results for the Randstad PT network are discussed in section 6.4.1. Furthermore, there are limitations regarding the application of the model to the Randstad PT network. These are discussed in section 6.4.2.

6.4.1 Implications of results for Randstad PT network

First and foremost, when analyzing the implications of the results on the existing Randstad PT network it is important to acknowledge that the model is built on certain simplifications and assumptions which may not hold in practice. The suggested investments should therefore not be interpreted directly as investments that should be made in practice; they merely give an indication as to where the network could possibly be improved. The limitations of the model with regard to the case study are discussed in the following section.

In terms of potential investments to be made in the network, the following investments are notable:

- The investment with the highest potential of being beneficial is the densification of the tram network in Den Haag by connecting Den Haag HS to Den Haag, Spui.
- Investments to increase the frequencies of trains between Zwolle and the central Randstad area are potentially beneficial to realize.

In general, the limited number of investments made indicates that the PT network in the Randstad is already in a 'mature' state for serving the high-scenario demand anticipated in 2030. The question may then arise as to why the government is currently planning to improve the network with the visions stated in Toekomstbeeld OV. This can be explained by the fact that the network considered in the model is on a relatively high network-level within the Netherlands, as it is the backbone. When considering lower network levels which are more regionally focused, it is plausible that new investments would be made which are similar to for example HOV (high-quality PT) lines, as is also one of the visions stated in Toekomstbeeld OV. There are however still some similarities to be found in terms of development directions for public transportation in the Netherlands (Rijksoverheid (2019)). The bulking of IC links between the Randstad and Zwolle corresponds to the vision of reducing the travel times between the Randstad and the northern part of the Netherlands. The second similarity is the vision of having fast and frequent PT between Eindhoven and Arnhem-Nijmegen (Figure 6.19). This is in line with the HSL link constructed between Arnhem Centraal and Eindhoven in the model. This link may however not be a realistic outcome of the model as discussed previously.

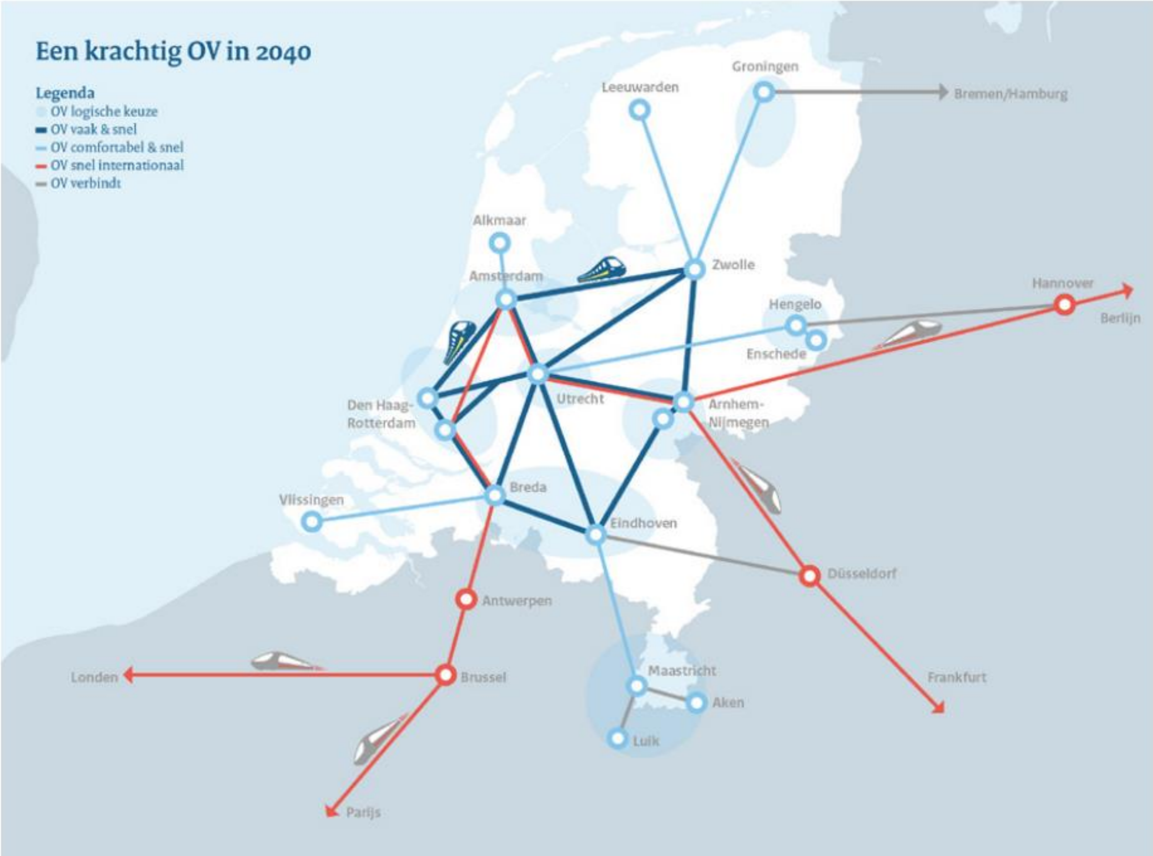

*Figure 6.19: Vision of 'powerful' public transportation in 2040 (*Rijksoverheid (2019)*)*

In terms of the topology and performance of the Randstad PT network, the investments that are made in the evolution process barely impact the existing network. The main impact is the reduction in total user costs. Within the sub-networks of Amsterdam, Rotterdam and Den Haag, the impacts are however relatively higher than within the Randstad PT network as a whole. While investments in 'shortcuts' on existing lines are potentially beneficial, these are less realistic to realize.

6.4.2 Limitations of model on Randstad PT network

As the developed model is built on certain simplifications and assumptions, there are a number of limitations with regard to its application to the Randstad PT network. These limitations are discussed in this section.

Aggregation of zones to stations

The model is built on the assumption that all trips start and end at stations. To apply the model to the Randstad PT network it is then also necessary to model the pre-defined demands between the different stations. As the data on the demand used for the case study is zone-based as opposed to PT station-based, it was necessary to aggregate the zones to stations. While it is attempted to do this in a realistic manner, there are still ambiguities with regard to this process. Firstly, the model assumes that there are no access and egress costs, while this is the case in reality. This means that especially for zones located further away from the station they are assigned to, travelling by public transit becomes more attractive than it would be in reality. It is therefore expected that the aggregation process which is performed has an impact on the results of the simulation. Secondly, the manner in which the zones are distributed over the stations is expected to lead to inaccuracies in passenger flow intensities of PT. A notable example of this are the passenger flow intensities between Amsterdam and Utrecht. These inaccuracies are expected to have an impact on benefits calculated for potential investments and influence the choice of whether an investment would be made or not.

Cost parameters
While the model makes use of generalized values for infrastructure, rolling stock and operational costs, it is expected that the costs associated with each specific investment are different. It is therefore possible that the costs for certain investments may be over- or underestimated. This in turn has an impact on the investment score and determines whether an investment would be made or not.

Waiting times and transfer times
For the waiting times and transfer times, also generalized assumptions are made as to what they are. These values could however be calculated more accurately by using the actual timetable information on departures and arrivals and walking distances for transfers. These calculations will have an impact on the calculations of the travel times within the network, which in turn affect the benefits calculated for investments. As there may be a potential change in the calculated benefits, the investment made in the evolution process may also differ.

Vehicle capacity and overcrowding
The effects of vehicle capacity and overcrowding are not considered in the model. As stated in section 4.3, the value of β_{IVT} may increase with crowding effects. Similarly to the previous limitation, this will affect the benefits calculated for investments and potentially lead to other investments made.

Shortest path calculations
As the shortest path calculations are done in a simplified manner considering only in-vehicle time, it is expected that this has an effect on the calculated travel times. The shortest path algorithm currently determines the shortest path for each node pair based on the in-vehicle time, but it is possible in certain situations that the determined shortest path is not the 'actual' shortest path due to transfers that may have to be made. These potential differences in calculated travel times could have an impact on the calculated benefits, and thus also the choice of investments.

Computational times
As one iteration in the evolution process takes a minimum of 7.5 hours, the computational times can be considered to be large. Especially if a number of scenarios or large number of iterations are to be run, the computational time may form a hurdle as it may potentially take weeks before getting any results.

OD matrix
For the application of the model on the Randstad PT network, data on OD matrices from the VMRDH was extracted. These OD matrices are however expected to be calibrated mainly in a radial manner from the Rotterdam and Den Haag region as the VMRDH is focused on this region. The data on trips made on the tangential lines such as Amsterdam-Utrecht are expected to be calibrated less accurately, and therefore may not be representative for the actual situation. More accurate data on these trips is expected to lead to different results than those found in the case study.

7. Conclusions and recommendations

The final part of this thesis consists of the conclusions and recommendations that are made based on this research. Firstly, conclusions of this research are discussed in 7.1 where answers are provided to the research questions. Based on these conclusions, the scientific and practical contributions of this research are discussed in sections 7.2 and 7.3 respectively. Section 7.4 then consists of a discussion with regard to the limitations of this research and the network evolution model and also discusses impact of these limitations. Finally, recommendations with regard to future work are made in section 7.5 based on the discussions in the preceding sections of this chapter.

7.1 Conclusions

Reflecting back on the introductory chapter, the main objective of this research was to gain insights into how the spatial distribution of nodes, travel demand distribution and operational costs in a PT network with multiple modalities have an impact on the topological evolution of this network in a polycentric urban region. To gain these insights, a network evolution model was developed which incorporates all the variables to be investigated. The basis of this model was provided by Vermeulen (2018) in which demand distribution and operational costs were incorporated. The network model further developed during this research also incorporates different spatial structures of the urban area and multiple modalities within the PT network.

While this model is capable of providing insights into the various aspects, it can also have a practical use in the overall planning process of networks. A first step towards the practical application of such a model was taken by applying it to the Randstad PT network. This practical application was done to reach the secondary objective of this research. The secondary objective was namely to investigate how current predictions on the future travel demand in the Randstad area have an impact on the topological evolution of its PT network.

Main research objective

Regarding the main research objective of this thesis, in the introductory chapter the main research question was posed:

> *When considering a polycentric urban region, what is the impact of the spatial distribution of nodes, the travel demand distribution and the operational costs on the topological evolution of a public transit network consisting of multiple transit modalities?*

As this research question consists of several distinct components and is difficult to answer in one part, five sub-questions were posed to find answers to these components. These five sub-questions are firstly answered, after which the main research question is reflected back on to provide a complete answer to it.

1. What network indicators can be used to quantify the topological evolution of a public transit network in a polycentric urban region?

In this research a number of topological indicators have been discussed. While none of these indicators can exactly quantify the topological evolution of a public transit network in a polycentric urban region, choices were made to choose indicators which can be related to the topological evolution of such a network. Furthermore, performance indicators were determined to quantify and compare various generated networks. All topological and performance indicators are listed in Table 7.1.

Table 7.1: List of topological and performance indicators considered during this research

Topological indicator	Performance indicator
Connectivity	Total travel time
Directness	User costs
Average node degree	Modal share
Network length	Investment score
Average link length	
PT infrastructure shares	
Betweenness centrality	

Lastly, visualizations of the networks have been used to explain certain evolution behavior and to compare the various generated networks.

2. What is the impact of the spatial distribution of nodes in a polycentric urban region on the topological evolution of a public transit network?

This sub-question was accompanied by a sub-sub question to support the answer to this sub-question:

What are the parameters that can be used to describe the spatial distribution of nodes in a polycentric urban area?

To describe the spatial distribution of nodes in a polycentric urban area, four spatial structure parameters have been determined during this research. These four parameters are: Number of agglomerations, radius, distance between neighbouring nodes and the separation between agglomeration centers.

Returning to sub-question 2, firstly four spatial structure prototypes were determined based on these spatial structure parameters. Based on these four spatial structure prototypes, the following conclusions were made with regard to the impact of the spatial distribution of nodes in a polycentric urban region on the topological evolution of a public transit network. In terms of how the PT networks evolve, the evolution process varies for different spatial structures.

Based on the number of agglomerations and the separation between agglomerations, the main differences are the manner in which the networks evolve and the type of PT mode used. For spatial structures with distinctly separated agglomerations such as the 'Rhine-Ruhr' and 'Flemish Diamond' prototypes, separate agglomerations are first connected, after which the sub-networks within the agglomerations start to evolve. Once most of the nodes in the agglomerations are connected to the PT network, the network connects to another disconnected agglomeration and this process continues. The evolution process then ends with the network densifying and bulking. For spatial structures with one agglomeration with a CBD, it is observed that this network expands and densifies radially from the center. At the end of the evolution process the network bulks. During the evolution phases it was observed that hierarchy among nodes starts to form during the evolution process, as nodes with a central location or nodes that are connected early on to the higher-level network tend to become more important. This is due to the fact that it becomes beneficial for disconnected nodes to connect to these nodes which either have a central location within the entire network or have access to the higher-level network. This is in line with the preferential attachment theory of Barabási and Albert (1999). In terms of the type of PT mode used, for different distances it is observed that different types of PT mode are most optimal and there are also certain 'hurdle distances' that a certain mode has to cover before it becomes beneficial to construct. This is in line with what is stated by Van den Heuvel (1997) and Van Nes (2002). Besides the differences in the type of mode that is invested in, distinct network levels seem more likely to emerge in spatial structures in which agglomerations lie further apart from each other. Lastly, the spatial structure has an impact on final state of the network in terms of initial assumptions made. For a structure such as the 'Tokyo' prototype where there are less distinctly separated agglomerations, the network generated is more sensitive to the initial assumptions made. If the initial network is steered towards a certain direction, this type of structure is also more likely to follow this direction than a structure with distinctly separated agglomerations.

3. What is the impact of travel demand distribution in a polycentric urban region on the topological evolution of a public transit network?

For this research variable travel demand distributions were considered: a uniform distribution, a linear decay from a CBD and an exponential decay from a CBD.

For different demand distributions, the main observation made is that in the uniform scenarios, the networks generally expand to the closest disconnected nodes if the distances to these are above the 'hurdle distance'. As the population is equal in all nodes, the demands from one node to any node in another agglomeration are roughly the same. The best investment is then one for which the costs are minimal, and this is the case for links covering shorter distances. The resulting networks are generally a combination of tree-shapes and rings forming within the agglomerations. For the linear and exponential demand distributions the network is most likely to expand to the nodes with the highest population. Similar to what was observed when investigating the impact of the spatial structure, investment choices made early on influence the resulting hierarchy of nodes in the final network state. For equally populated central nodes, the betweenness centrality value of these nodes will vary based on which of the two is connected first to the higher-level network. The node which is connected to the higher-level network at the start is more likely to become more dominant within the entire network over time. The resulting networks generally show star-like shapes forming in the agglomerations, where the outer areas of the agglomerations have a lower node degree.

4. What is the impact of operational costs on the topological evolution of a public transit network in a polycentric urban region?

This sub-question was accompanied by 2 sub-sub questions to support the answer to this sub-question:

4.a. What are the operational cost variables that are mode-dependent?

In terms of the mode-dependent operational cost variables, there were time dependent operational costs and distance dependent operational costs identified. The distance dependent operational cost variable was also dependent on the speed of the mode: the mode operates for a certain number of hours per day and the higher the operational speed, the more distance would be covered. Furthermore, both the time dependent and distance dependent operational costs were determined by the frequency of the mode as both costs were expressed per vehicle. Together with the infrastructure costs and rolling stock costs, the operational costs formed the total construction costs considered.

4.b. What is the effect of vehicle automation on the operational costs?

Based on literature found it was determined that the operational costs are reduced by 35% with vehicle automation. As there was hardly any literature found on the effect of vehicle automation on the infrastructure and rolling stock costs, these were assumed to stay equal to the non-automated situation.

Returning to sub-question 4, the main impact of a variation in operational costs is on the difference in the evolution process of the PT network. When lower operational costs are assumed, the investment scores increase as this is inversely related to the total costs of investments (which also consist of the operational costs). As these investment scores are higher in each iteration, the evolution process continues longer since the scores stay above 1.0 for a longer period of time. In the numerical experiments it is observed that these extra investments made are further densification and bulking of the network. This indicates that a decrease in operational costs makes it possible to make more beneficial investments in the PT network, which results in a decrease in user costs in the entire network. The exact investments however, do differ from a certain point onwards. This point can be described as the point at which the 'basic network' is completed, after which additional densification and bulking investments are made to further improve the network. Furthermore, due to the extra investments made with lower operational costs, the hierarchy of nodes also shifts when operational costs are decreased. The most dominant node in the network becomes more dominant when lower operational costs are assumed. For all the other nodes which are less dominant it holds that these become more equal in importance when lower operational costs are assumed.

5. When considering a polycentric urban region, what is the impact of the consideration of multiple transit modalities on the topological evolution of a public transit network opposed to the consideration of a single modality?

To investigate the impact of a unimodal PT network rather than a multimodal PT network, the assumption in the numerical experiments was made to only consider the agglomeration mode in the unimodal case. With this consideration, it was observed that the evolution pattern is generally different than when a multimodal PT network is considered. In the multimodal network, the network expands to a disconnected agglomeration first and then expands within the two connected agglomerations. In the unimodal network however, the network rapidly starts expanding the PT network to all agglomerations first (with an exception of the second agglomeration in RLNU). The evolution phases are however similar to those of the LLNM and LENM scenario which consist of one agglomeration. The generated networks in these two scenarios also only consist of the unimodal agglomeration system. This pattern in evolution phases may therefore be characteristic to unimodal systems in general as it is also observed in the TENM network consisting of (almost) solely regional links (Figure 5.57) found in the sensitivity analysis. In the unimodal scenarios, there are no high-level PT modes with high operational speeds assumed. The benefits of expanding the network within agglomerations to connect node-pairs of different agglomerations is then also less at the start of the evolution process. While it is beneficial for nodes in a newly connected agglomeration to connect to the node which has an interregional link, this is less the case in the unimodal scenarios. This is due to the relatively lower travel time gains that are provided. In terms of the evolution process, it is observed that in both unimodal scenarios the investments consist of expansion, densification and bulking in that order. While the resulting networks in the unimodal scenarios are comparable to their respective multimodal scenario, certain nodes stay disconnected from the PT network in the linear unimodal scenario. This is due to the combination of low PT speeds offered and low demands in the nodes. The user costs are higher in the unimodal scenarios. This is a result of low PT speeds and thus high in-vehicle times and a larger share of users for the alternative mode. In terms of the betweenness centrality values for the multimodal and unimodal scenarios, it is seen that the multimodal scenarios are steered more towards a hierarchical network structure.

Based on these conclusions, an answer is provided for the main research question:

When considering a polycentric urban region, what is the impact of the spatial distribution of nodes, the travel demand distribution and the operational costs on the topological evolution of a public transit network consisting of multiple transit modalities?

The spatial distribution of nodes, travel demand distribution and operational costs all have an impact on the topological evolution of a multimodal PT network. These impacts however differ in terms of their intensity and in terms of what they have an impact on. These differences can mainly be found in the various evolution phases that occur in each scenario. The most notable differences are observed for different types of spatial structures.

For spatial structures that have multiple distinctly separated agglomerations a clear distinction can be made in these different phases. In a stepwise manner the network expands to a disconnected agglomeration after which the lower level networks within these agglomerations are expanded. This process then occurs again where the next disconnected agglomeration is then connected to the network. For demand distributions in which there is a strong CBD (e.g. linear and exponential decay), these expansions are mainly constructed to and from nodes in this CBD area. After all or most nodes are connected to the network, additional densifications and bulking investments are made to complete the 'basic network'. Once the 'basic network' is created, additional densification and bulking investments are done. The locations and amount of these investments made are dependent on the demand distribution and operational costs. For demand distributions with a strong CBD, most of these investments are done around these central areas as more benefits can be provided in these more populated areas. Also, when lower operational costs are assumed, the amount of these investments made increases. As costs are reduced, the investments become more beneficial and thus extra beneficial investments can be made to further improve the PT network.

For the spatial structure with one agglomeration that has a CBD, the evolution consists solely of agglomeration links. The phases of this evolution are very similar to the evolution phases in the unimodal scenarios, where expansions, densification and bulking investments are made in this order. This pattern in evolution phases may be a characteristic to networks with unimodal systems.

For spatial structures with less distinctly separated agglomerations it is observed that there is no clear pattern in the evolution phases. This type of structure has more 'freedom' as to how it can evolve and is therefore also more sensitive to the initial assumptions considered for the network evolution.

Furthermore, the spatial structure and demand distribution have an impact on the emergence of hierarchy among nodes in the network. Nodes that are geographically more centrally located have a higher tendency to become more important in the network. This is also the case for nodes located in a CBD area. Besides these two aspects, hierarchy also emerges in nodes that are connected to higher network-levels in early stages of the evolution. In further evolution stages it becomes more attractive for other nodes to then connect to this node. This is also in line with the preferential attachment theory.

In short, the spatial structure determines how the network physically evolves and has an impact on the emergence of hierarchy among nodes in the network. The demand distribution mainly has an impact as to which nodes become better connected to the network and the operational costs mainly impact the amount of investments that are made in the network. Unimodal systems also show a specific pattern in evolution phases, regardless of the spatial structure and demand distribution. For multimodal systems, the evolution pattern is however more dependent on the spatial structure and demand distribution.

Secondary research objective

Besides the application to numerical experiments, a first step towards the practical application of the network evolution model was taken by applying it to the Randstad PT network. The secondary objective of this research was namely to investigate how current predictions on the future travel demand in the Randstad area have an impact on the topological evolution of its PT network. Data on future travel demand from the VMRDH was used to investigate the topological evolution of the current Randstad PT network. To this end, an additional sub-question was posed in the introductory chapter with regard to the topological evolution of the Randstad PT network:

Considering the current future predictions on travel demand in the Randstad area in 2030, what is the impact of these predictions on the topological evolution of the current public transit network in the Randstad area?

After application of the network evolution model while using data on the 'high-scenario' of 2030, there were a number of notable investments made in the Randstad PT network:

- Densification of the tram network in Den Haag by connecting Den Haag HS to Den Haag, Spui.
- Bulking of IC links between Zwolle and the central Randstad area.

In general, the limited number of investments made indicates that the backbone of the PT network in the Randstad is already in a 'mature' state for serving the high-scenario demand anticipated in 2030. In terms of the topology and performance of the Randstad PT network, the investments that are made in the evolution process barely impact the existing network. The main impact is the reduction in total user costs. Within the sub-networks of Amsterdam, Rotterdam and Den Haag, the impacts are however relatively higher than within the Randstad PT network as a whole. There are however still some similarities to be found in terms of development directions for public transportation in the Netherlands (Rijksoverheid (2019)). The bulking of IC links between the Randstad and Zwolle corresponds to the vision of reducing the travel times between the Randstad and the northern part of the Netherlands. The second similarity is the vision of having fast and frequent PT between Eindhoven and Arnhem-Nijmegen. This is in line with the HSL link constructed between Arnhem Centraal and Eindhoven in the model. This link may however not be a realistic outcome of the model as discussed previously.

While there were a number of limitations to this method, it is believed that this first step into the application of the network evolution model in practice has provided insights as to how it can be improved further for it to be used in practice. It is furthermore believed that such network evolution models could be used in an early stage of the planning process of networks in general. In this early stage it is possible to apply such a model for a quick-scan to gain insights into where the network could potentially be improved in the future.

7.2 Scientific contributions

This research and the model that has been developed model has several notable scientific contributions. The main contributions are discussed below:

The impact of spatial structure on the topological evolution of a network

In terms of the relation between spatial structure and the topological evolution of a network in these structures, there is limited literature available. Even more so for PT networks in polycentric urban regions in specific. The developed model is capable of generating various spatial structures which makes it possible to investigate the impact that the spatial structure has on the topological evolution of a network. The results that are presented provide initial insights into how the spatial structure relates to the topological evolution of a network. It is however expected that there is more research that can be done into this aspect, and to this end this research and the developed model can be used as starting point for future research.

The impact of multimodality on the topological evolution of a network

Research done by Van den Heuvel (1997) and Van Nes (2002) provided insights into how different types of PT modalities are most suitable for different distance classes. These claims have been strengthened further by this research. While in this research only one specific spatial structure was considered to investigate the differences between considering multimodality or unimodality, for future research it could be interesting to further investigate the relation between multimodality and spatial structure in the context of network evolution. This research and the developed model can be used for this type of future research.

Sensitivity of network evolution

As briefly discussed in the sensitivity analysis in section 5.3, it is found that the spatial structure is an important aspect that determines how sensitive the network evolution in this spatial structure is. While some initial insights have been provided in this research, it would be interesting to further investigate how these two aspects relate to each other and whether this may have implications for networks in practice. To this end, this research could be used as a reference for future research.

7.3 Practical contributions

The most notable practical contributions of this research and the developed model are discussed below:

Initial insight into future evolution of Randstad PT network

Based on demand predictions for 2030 and the developed network evolution model, a number of potential future investments in the Randstad PT network have been identified. While the application of the model to the Randstad PT network in 2030 has certain limitations, the results have provided some initial insights as to where the current network can potentially be improved.

Applicability of network evolution model in practice

With the application of the model to the Randstad PT network, several limitations of applying the model to practice have been identified. This provides insights as to what could be changed for future application of the model to other networks in practice. Examples of such networks could be for example the European rail network, the aviation network or a metro network in a city.

A tool for decisionmakers

The model which is developed is expected to be of use for decisionmakers as it can function as a quick-scan tool that roughly determines the CBA for multiple potential investments. The model is namely capable of analyzing multiple investments simultaneously and roughly determining the costs and benefits of each investment. While further improvements would be necessary, the current model does form the basis of such a quick-scan tool.

7.4 Discussion

The discussion with regard to the limitations of this research are divided into two parts. Firstly, the limitations of the model used for this research are discussed. Hereafter, the limitations with regard to the practical use of the model is discussed.

Network evolution model

Firstly, the sensitivity analysis performed showed that the resulting network that is generated by the model can be sensitive to the input data. It is therefore acknowledged that with different assumptions of for example the cost parameters or the mode attributes, different PT networks may be generated by the model.

Secondly, the network evolution model in its current state consists of a number of simplifications made in certain calculations and assumptions. The most notable simplifications are the following:

- *Shortest path calculations:* The current algorithm used, only considers the in-vehicle time for determining the shortest paths. Including the waiting times and transfer times in the algorithm is expected to lead to more accurate calculations in certain situations.
- *PT mode ranges:* Each PT mode could only connect node-pairs if the distance between these pairs was within a certain range of values. While this was done to save a significant amount of computational times, it does limit the freedom of the model to find investment candidates. Removing these constraints may lead to potentially different structures and may potentially provide indications of the 'hurdle distances' for each PT mode.
- *PT mode candidate nodes:* For higher-level PT modes another assumption was made to reduce computational times. By only considering the most populated node within a cluster of nodes as a candidate node, it is expected that hierarchy towards these nodes was slightly steered especially at the start of the evolution process. It is expected that this mainly affects the early evolution phases, as in later phases it is expected that the hierarchy is determined by the preferential attachment theory.
- *Decision rule for evolution:* The decision rule for the evolution of the network is based on a simplified CBA function. Including more factors into this CBA function may lead to different results. For example, if environment effects are taken into consideration, certain PT modes can become less attractive than others which can lead to potentially different networks generated.

Lastly, the computational times can be considered long. In the current state, the scenarios with roughly 60 nodes took anywhere between 8 and 24 hours. For larger networks or for example if Monte-Carlo simulations are run to investigate the network instability further, this network evolution model would be less suitable. As it is expected that limited computational time gains can be made in the code, possible gains could be found by using a different modeling program.

Practical use of the model

Firstly, a number of assumptions that are built into the model do not hold for realistic scenarios:

- *No physical constraints:* As the graph in which the network is generated is non-planar, it was possible for links to simply overlap each other without assuming additional costs for e.g. tunnels or bridges. This is not a realistic assumption and when taking physical constraints into consideration it is expected that different investments would be made as certain links might cost more while others may cost less.
- *No line operations:* The model distinguishes between different PT modes, but there are no transfers assumed within the same PT mode as there are no line operations. This again is not a realistic assumption. The consideration of line operations may potentially lead to certain modes being less beneficial, as the introduction of line operations means that there will be an additional transfer. It is expected that the total number of investments made would therefore decrease.

- *No crowding effects:* With overcrowding in vehicles, the benefits should be reduced. This effect is however not considered. Introducing crowding effects will potentially lead to different shortest paths as the travel times over the current shortest paths may become longer due to overcrowding. This in turn will lead to different investments being made and thus the generated network would then differ.
- *No access and egress costs:* Passengers are currently assumed to start and end their trips at stations. This is however not a realistic assumption as people have to get to and from the station, which also takes time. When considering nodes of different sizes in terms of the area that it covers, access and egress costs would differ. As the area is larger, arguably the average person has a longer access or egress time when travelling to or from this node.

Secondly, the CBA decision rule used in the model is fairly simplistic. In practice, often other aspects are also considered in the CBA such as environmental effects. Incorporating these additional aspects in the CBA would make the calculations more realistic and thus make the model better applicable in practice.

7.5 Recommendations

Based on the conclusions, contributions and limitations described in the previous four sections, recommendations are made. These are divided into two parts: recommendations for science (7.5.1) and recommendations for practice (7.5.2).

7.5.1 Recommendations for science

In terms of future research, a number of recommendations are made.

Firstly, a number of simplifications and constraints are made in the network. Removing these constraints and simplifications could improve the accuracy of calculations made in the model:

- *Shortest path calculations:* The current algorithm used, only considers the in-vehicle time for determining the shortest paths. Including the waiting times and transfer times in the algorithm is expected to lead to more accurate calculations in certain situations.
- *PT mode ranges:* Each PT mode could only connect node-pairs if the distance between these pairs was within a certain range of values. Removing these constraints may lead to potentially different structures and may potentially provide indications of the 'hurdle distances' for each PT mode.
- *PT mode candidate nodes:* The assumption of only considering the most populated node within a cluster of nodes as candidate node for higher-level PT modes should be removed.
- *Decision rule for evolution:* The decision rule for the evolution of the network is based on a simplified CBA function. Including more factors into this CBA function may lead to different results.

Secondly, it is recommended to further investigate the relation between multimodality, spatial structure and network evolution. There is limited research into the relation between these three aspects and the model developed during this research is expected to be a good tool to do further research into this topic. During this research certain phenomena were observed with regard to these three aspects such as the 'hurdle distance' and network instability. It would be interesting to further investigate these phenomena.

Following the previous point, it may be desirable to develop this model with another program than Matlab. The simulation times per scenario were currently between 8 and 24 hours which was acceptable for the purpose of this research. However, if further research is done into the phenomena discussed above, it may be desirable to reduce computational times as it is expected many simulations would have to be run.

7.5.2 Recommendations for practice

In terms of the practical application of the model, a number of recommendations are made.

For future application of the model in practice, it is firstly recommended that a number of improvements are made to the model. Besides the improvements recommended in the previous section, there are also a few improvements to be made to make the model more applicable in practice. These improvements are mainly to ensure more realistic calculations rather than generalized calculations as is currently the case:

- *Line operations:* The addition of line operations means that within a certain mode, passengers will have to make additional transfers as well. This addition would make the model more realistic as in practice networks also consist of multiple lines. This is expected to lead to more realistic travel times, as transfers and waiting times would then be calculated more accurately.
- *Physical constraints:* By adding physical constraints, the costs and benefits of each potential link would be calculated more accurately.
- *Crowding effects:* Including crowding effects is expected to lead to more realistic benefits.
- *Access and egress costs:* As the coverage area of stations differ in practice, the addition of access and egress costs is expected to provide more realistic travel time calculations.

Furthermore, it is recommended to further test the applicability of the model by applying it to other types of networks as well. Examples of other types of networks are the European rail network, aviation network or the metro network in a city. These applications can provide further insights to help improve the model further for practical application.

Lastly, it is recommended to test other decision rules than the simplified CBA which is applied in the current model. Additional factors such as environmental effects could be implemented to represent a CBA which is more common in practice. While this is a recommendation to improve the model itself, it also makes the results of the model more realistic.

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Appendix A: Model verification

The network evolution model consists of a number of separate modules, which are all part of the backbone of the model: mainFile.m. This is the main script in which the input parameters are listed and is also the file which is executed to run the simulation. This main script recalls numerous other scripts which have all been verified to work as intended. For each script a short description of the script itself and the method of verification is briefly stated.

genNodes.m: Script that generates the spatial structure

Test: Has been verified by generating all spatial structures for various input values.

dijkstra.m: Script that determines the shortest paths in the network. This is a script developed by Joseph Kirk and was retrieved from the Matlab Exchange.

Test: Has been verified by testing 5 small networks for which the shortest paths were also determined manually.

GravityModel.m: Determines the OD matrix based on the travel times in the fully connected network. Production and attractions are balanced iteratively to ensure these are equal.

Test: Production and attractions are equal for multiple tests. Also checked if resulting trips are plausible, based on expert judgement. The total number of trips also corresponds to what it should be.

CalcTT_PT.m: Based on the shortest paths, different modalities are used and it is important that waiting times and transfer penalties are only added to the travel time calculations when necessary.

Test: Has been tested for over 30 instances. Travel times for trip chains with various lengths were manually calculated and compared to script outcomes.

genExpansionCandidates.m: There are three versions of this script. Each version finds node-pairs for which a PT link can still be constructed based on the minimum and maximum stop spacing input values. For the interregional and regional versions, an additional condition was added to only consider the most populated nodes within a cluster of multiple nodes with a certain radius. The original script was provided by Alex Vermeulen.

Test: Tested all scripts for 3 small networks and manually checked if the outcomes are correct

calcScore.m: Calculates the investment scores for each candidate. Both the costs and benefits are calculated and discounted over 30 years. The original script was provided by Alex Vermeulen, but has been adjusted for this research.

Test: For 3 small networks, 4 of the candidate scores were manually calculated (12 instances)

Output.m; OutputCosts.m; OutputEnd.m: All three scripts are meant to calculate the topological and performance indicators. Output.m calculates the outputs per iteration. OutputCosts.m calculates the break-down of user costs at the end of the evolution process. OutputEnd.m also calculates topological and performance indicators at the end of the evolution process.

Test: For all three scripts numerous calculations have been done manually for small networks to ensure the resulting calculations are correct.

Appendix B: Overview of numerical experiment outputs

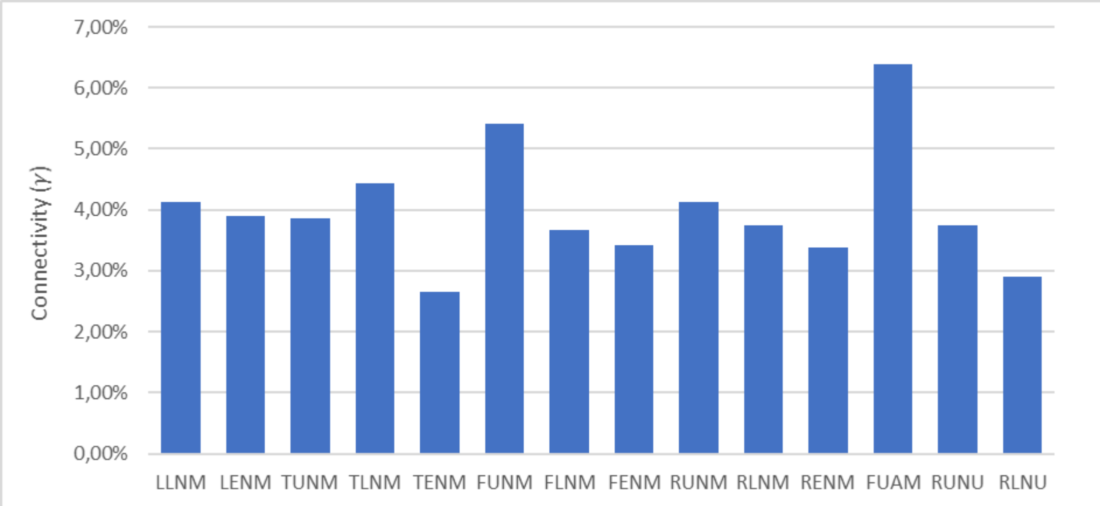


Figure B.1: Connectivity value in generated networks for each scenario

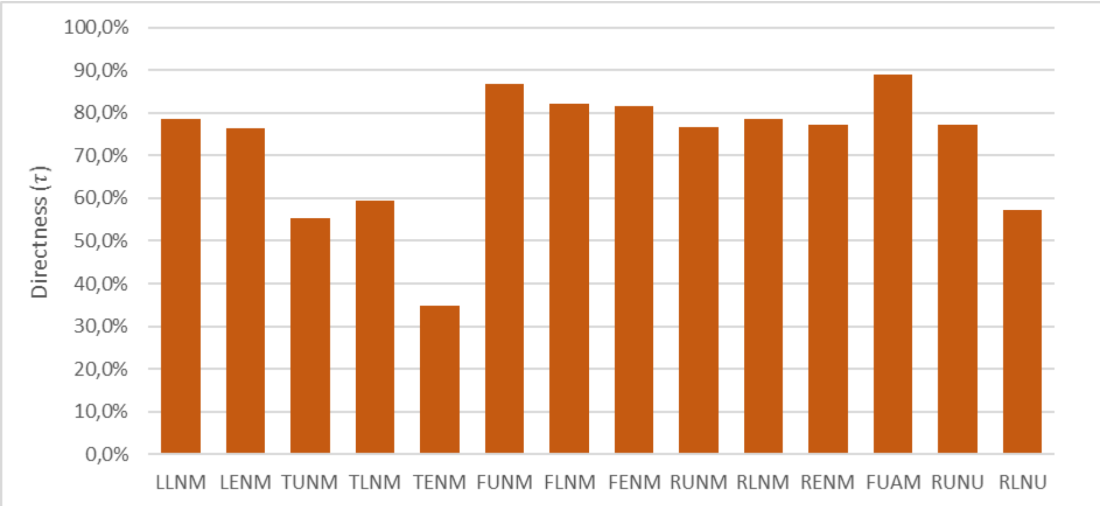


Figure B.2: Directness value in generated network for each scenario

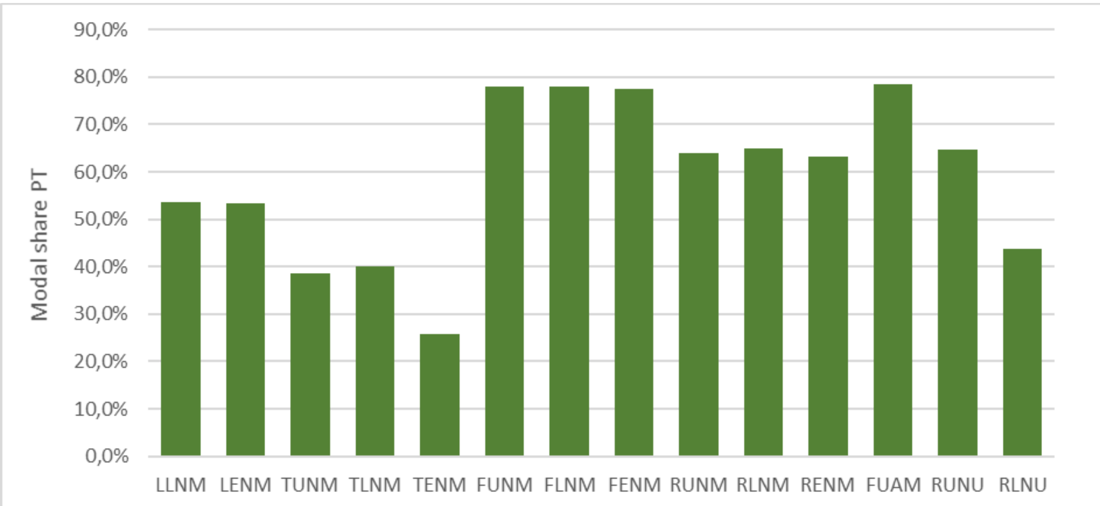


Figure B.3: Modal share of PT in generated network for each scenario

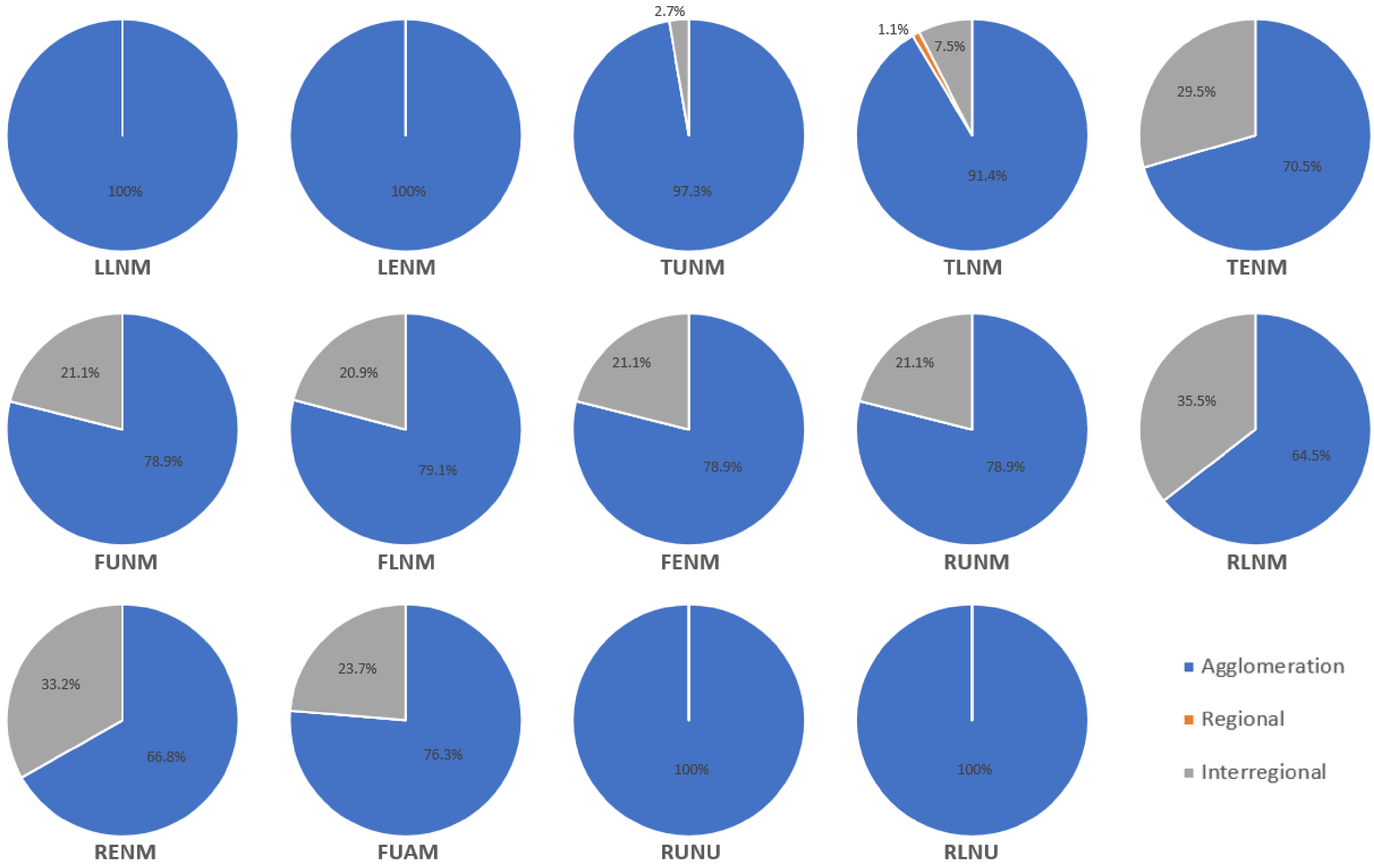


Figure B.4: Modal split within PT network for each scenario

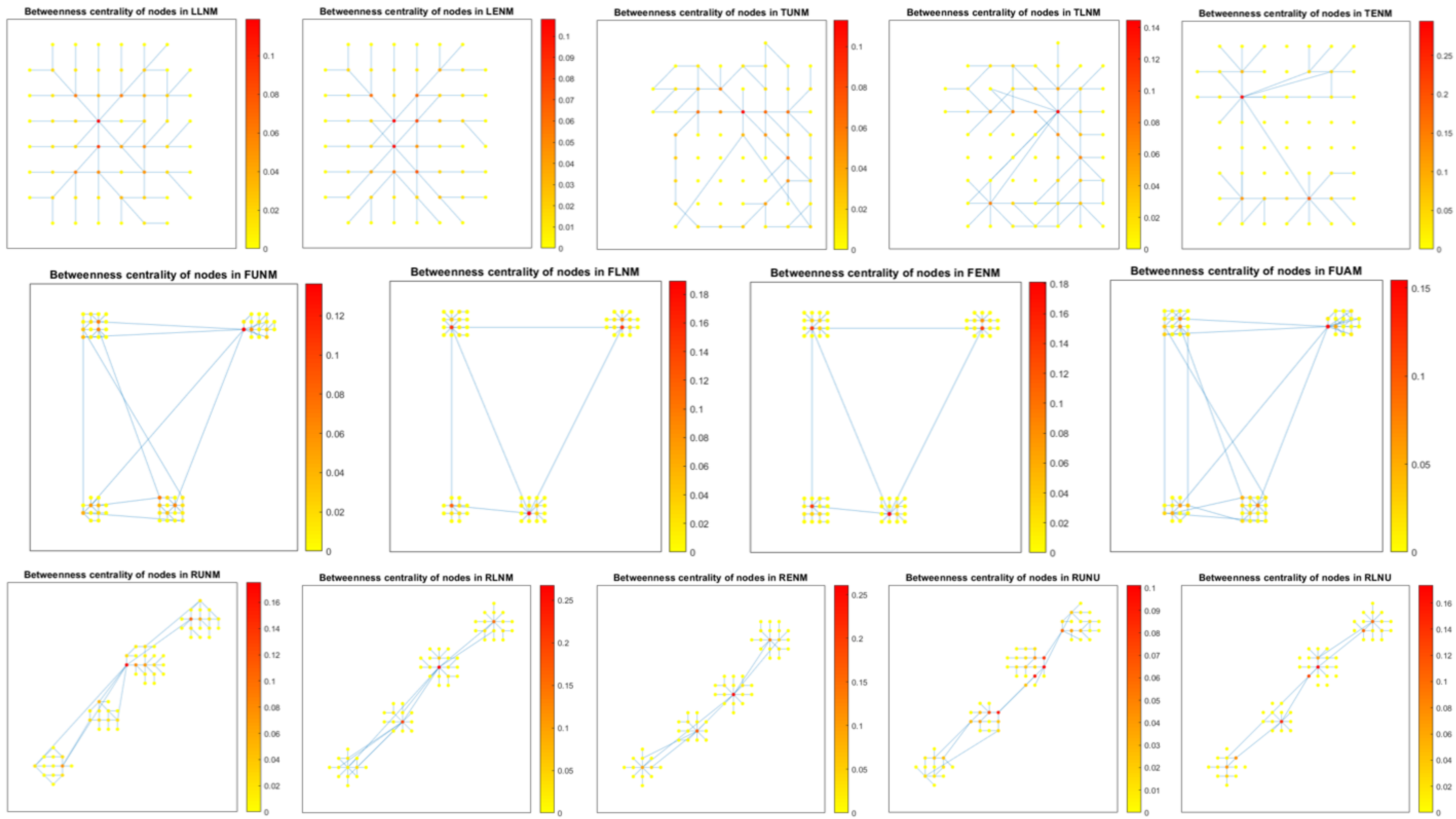


Figure B.5: Visualization of betweenness centralities for each scenario

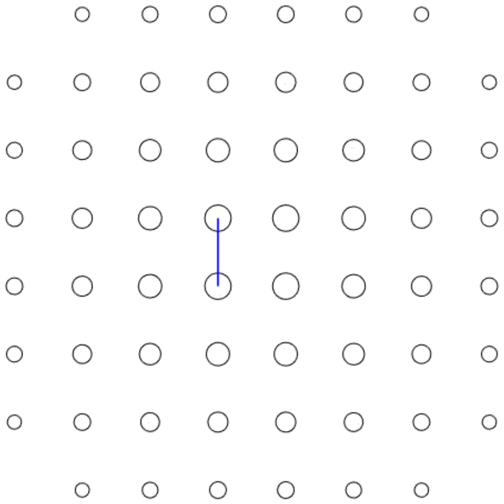
Table B.1: Overview of topological and performance indicators for all scenarios of numerical experiments

Scenario	$\bar{k}$	l [km]	$\bar{l}$ [km]	ψ_{agg}	ψ_{reg}	ψ_{int}	TTT [hrs]	ϕ_{PT}
LLNM	2,433333	160,0833	2,192921	100,0%	0,0%	0,0%	2774213	53,6%
LENM	2,3	153,7401	2,228118	100,0%	0,0%	0,0%	2734428	53,3%
TUNM	2,64	164,5685	2,493463	87,8%	0,0%	12,2%	3427213	38,6%
TLNM	2,980392	205,6627	2,706088	79,5%	2,9%	17,6%	3965181	40,1%
TENM	2,2	129,3403	2,939553	68,6%	0,0%	31,4%	3312293	25,7%
FUNM	3,2	575,8011	5,997928	32,4%	0,0%	67,6%	4970663	78,0%
FLNM	2,166667	348,1918	5,356797	38,0%	0,0%	62,0%	4782146	77,9%
FENM	2,15625	357,0202	5,174206	39,6%	0,0%	60,4%	4819253	77,5%
RUNM	2,516129	281,8585	3,61357	56,6%	0,0%	43,4%	5101872	63,9%
RLNM	2,290323	288,6545	4,065557	48,1%	0,0%	51,9%	4477480	65,0%
RENM	2,064516	222,4464	3,475725	58,1%	0,0%	41,9%	4439955	63,2%
FUAM	3,766667	686,1536	6,072156	31,2%	0,0%	68,8%	4733197	78,6%
RUNU	2,290323	229,9788	3,239139	100,0%	0,0%	0,0%	5775007	64,8%
RLNU	2,115385	191,5789	3,483252	100,0%	0,0%	0,0%	5860971	43,7%

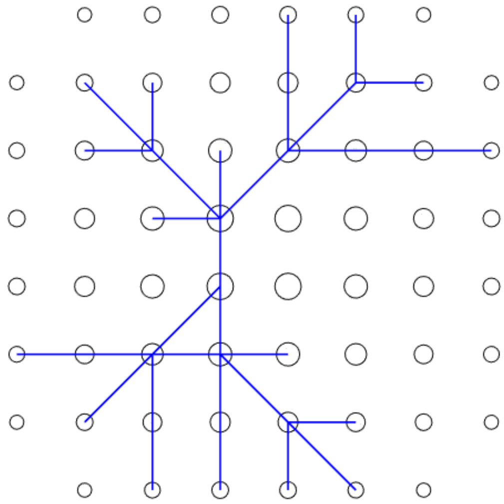
Appendix C: Visualizations of network evolution processes

LLNM

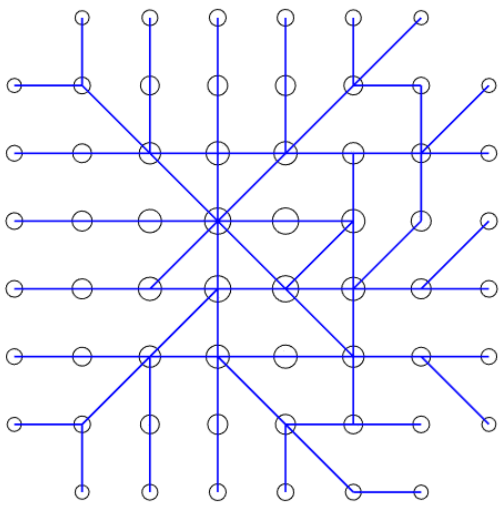
Phase 1 (n=1)



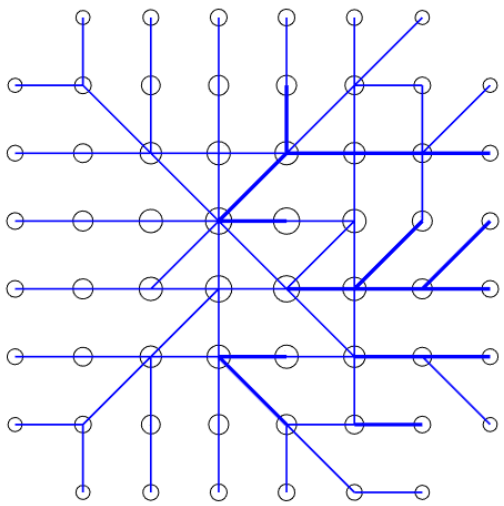
Phase 2 (n=30)



Phase 3 (n=71)

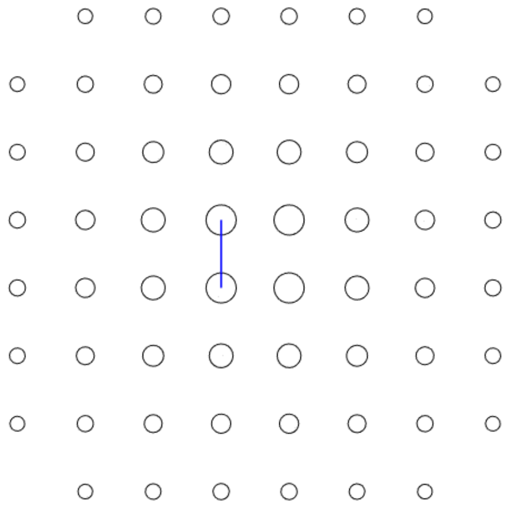


Phase 4 (n=88)

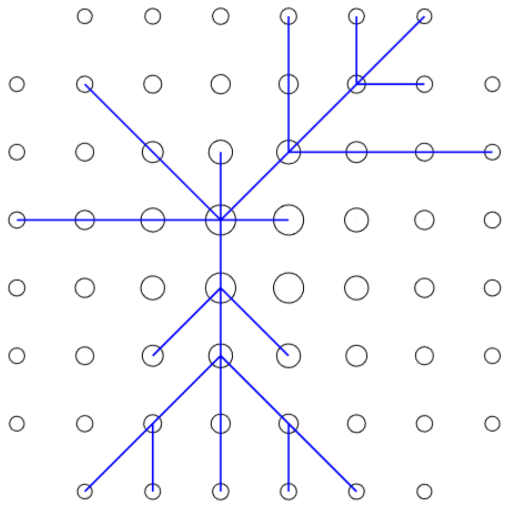


LENM

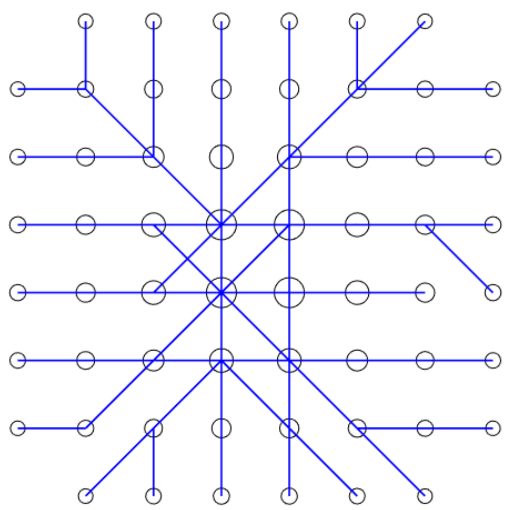
Phase 1 (n=1)



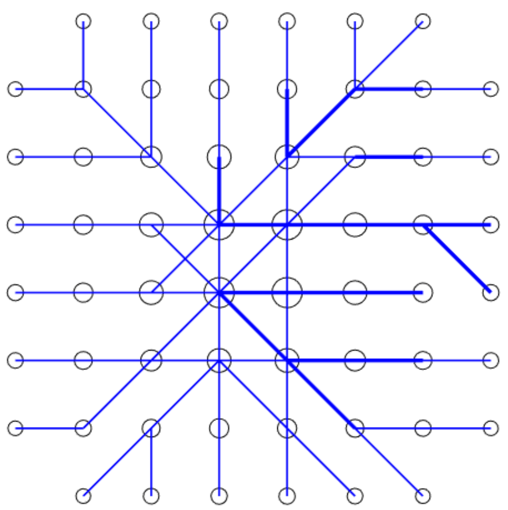
Phase 2 (n=29)



Phase 3 (n=68)

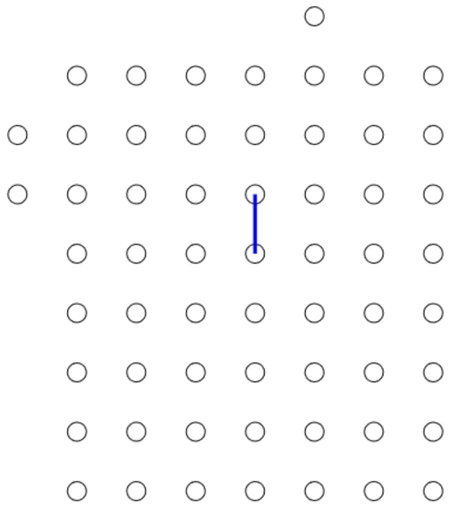


Phase 4 (n=85)

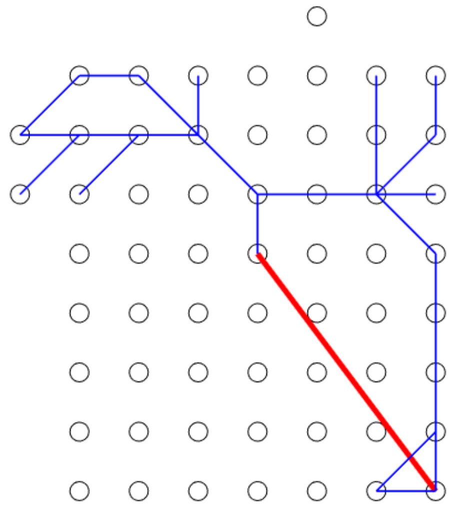


TUNM

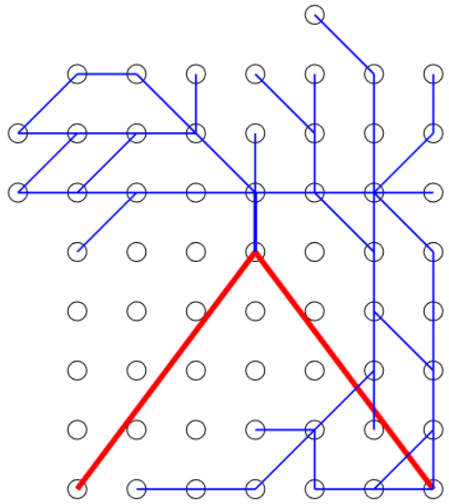
Phase 1 (n=1)



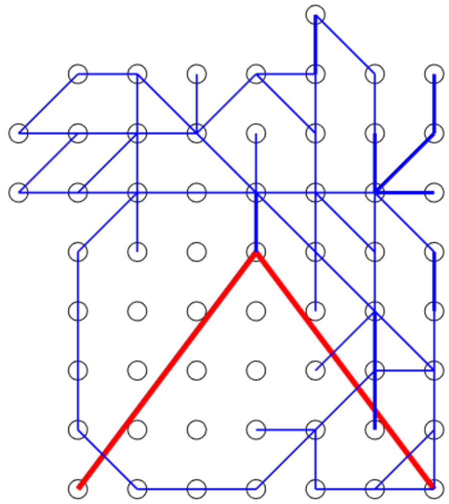
Phase 2 (n=26)



Phase 3 (n=51)

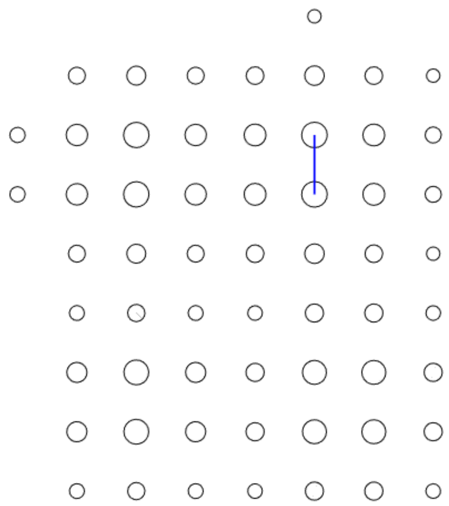


Phase 4 (n=74)

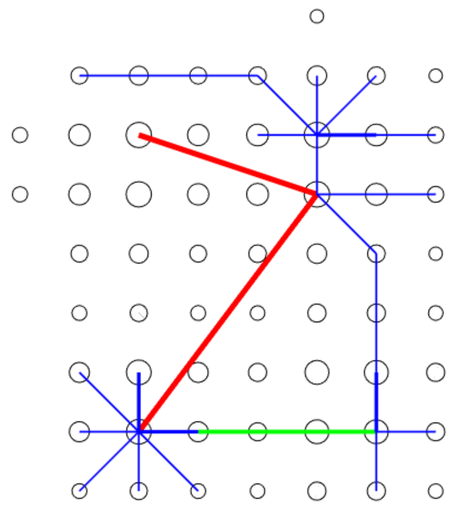


TLNM

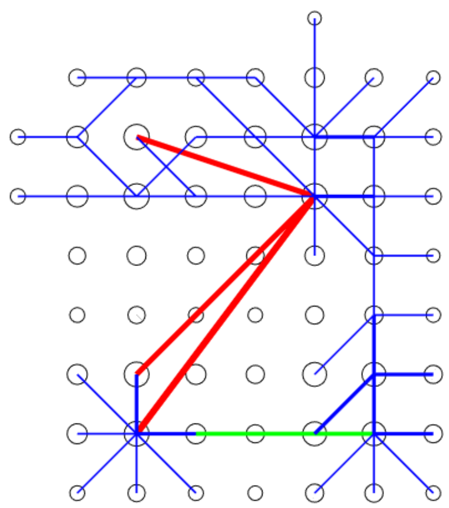
Phase 1 (n=1)



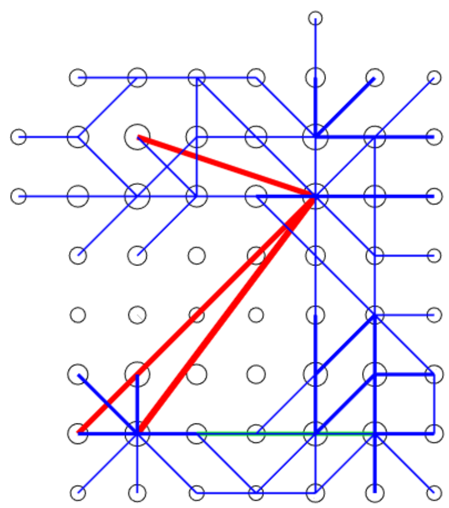
Phase 2 (n=30)



Phase 3 (n=65)

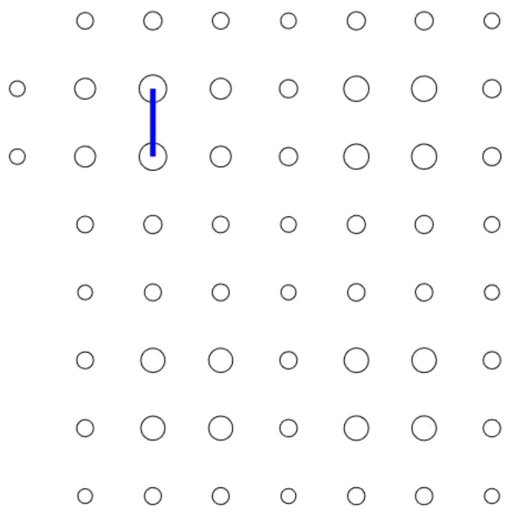


Phase 4 (n=96)

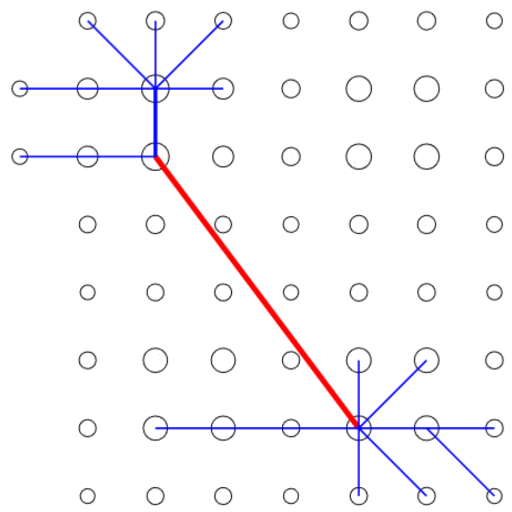


TENM

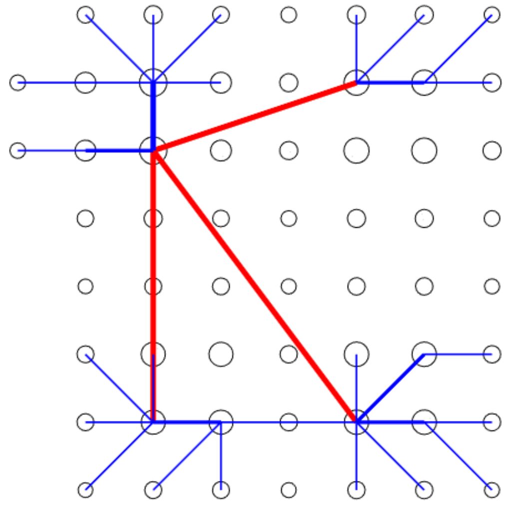
Phase 1 (n=1)



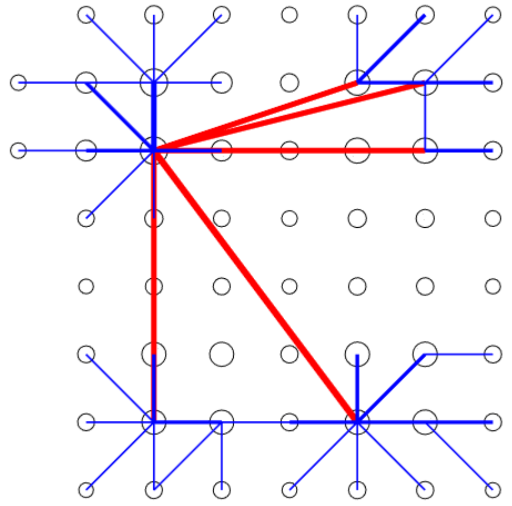
Phase 2 (n=20)



Phase 3 (n=39)

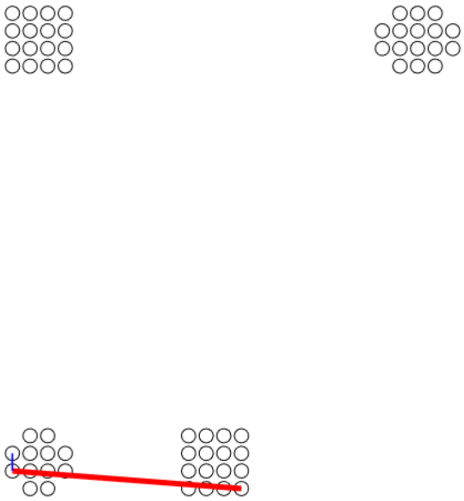


Phase 4 (n=60)

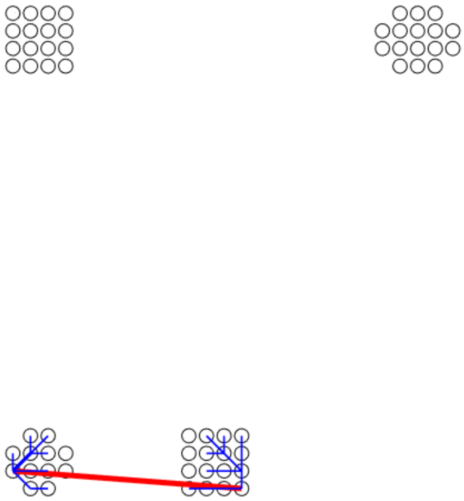


FUNM

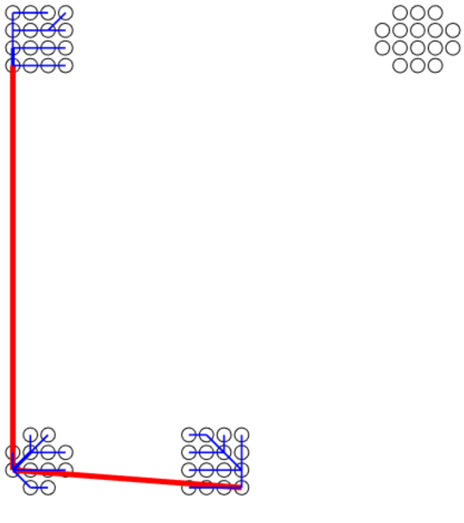
Phase 1 (n=2)



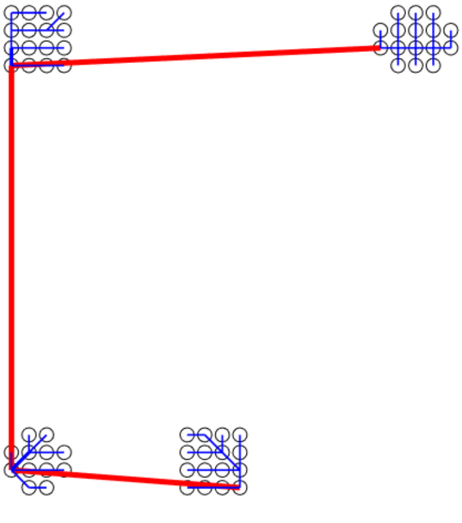
Phase 2 (n=22)



Phase 3 (n=44)

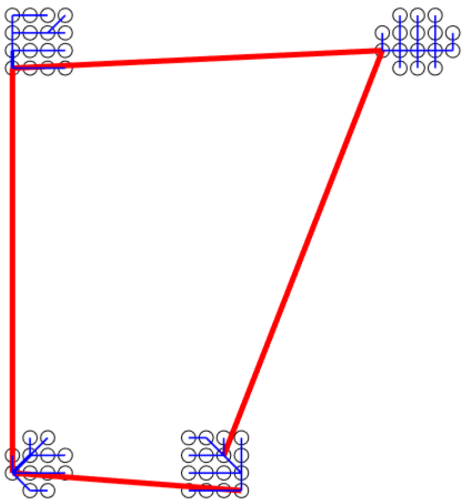


Phase 4 (n=61)

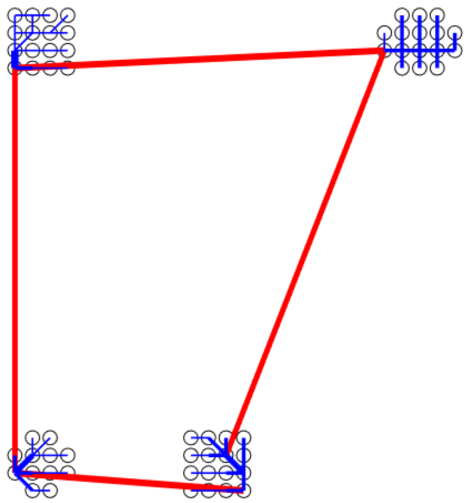


FUNM (continuation)

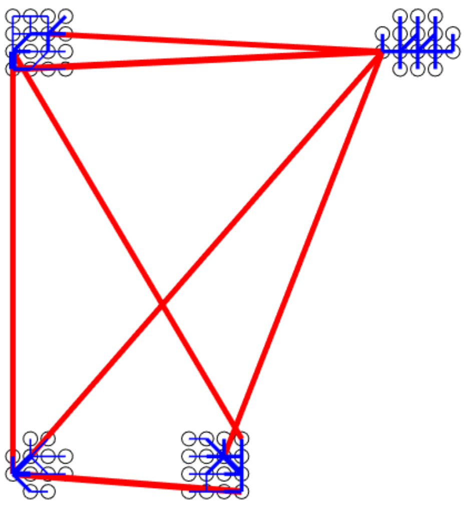
Phase 5 (n=62)



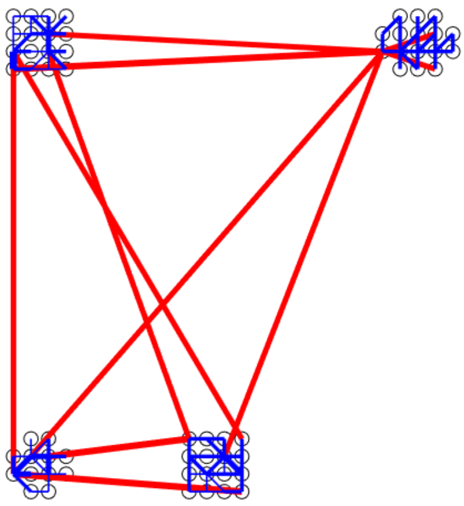
Phase 6 (n=97)



Phase 7 (n=120)

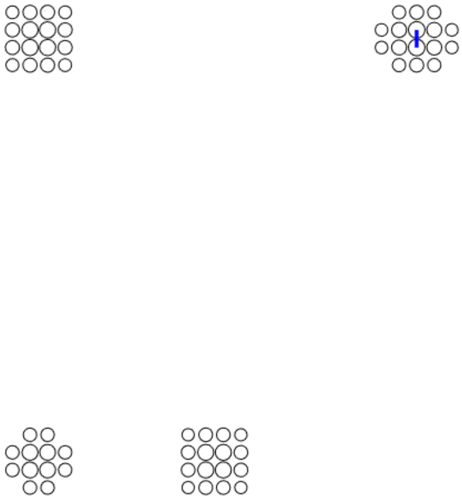


Phase 8 (n=166)

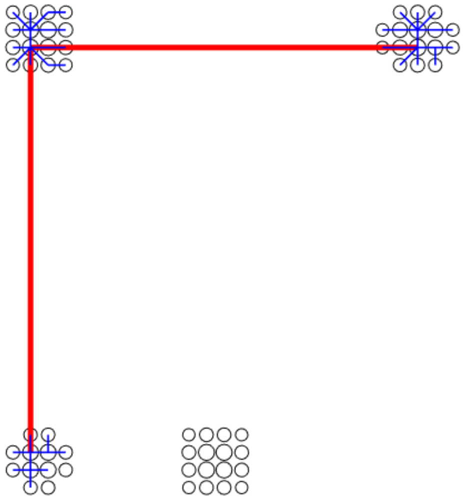


FLNM

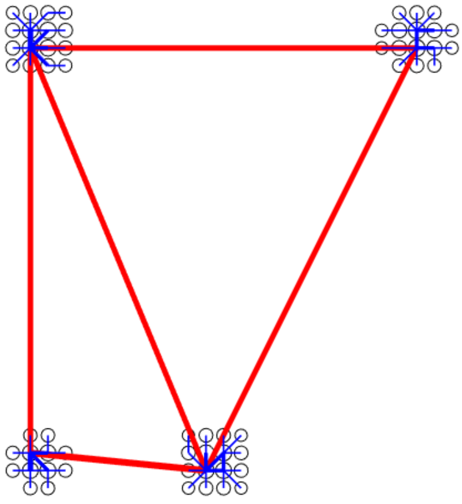
Phase 1 (n=1)



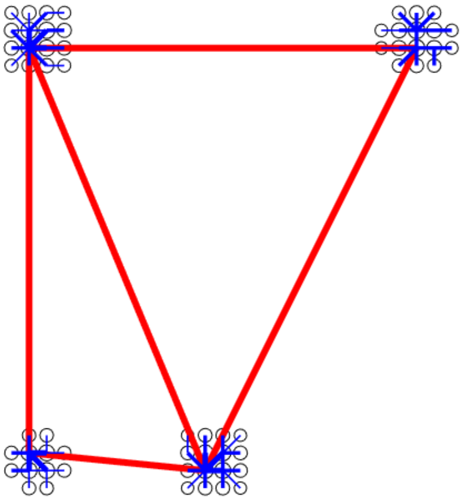
Phase 2 (n=58)



Phase 3 (n=80)

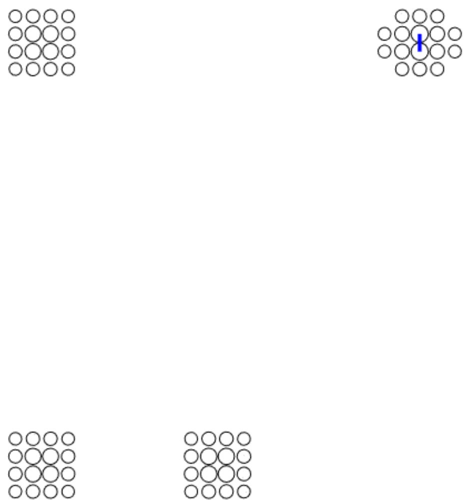


Phase 4 (n=119)

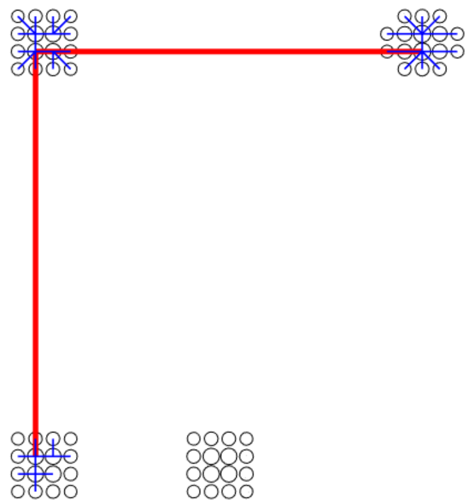


FENM

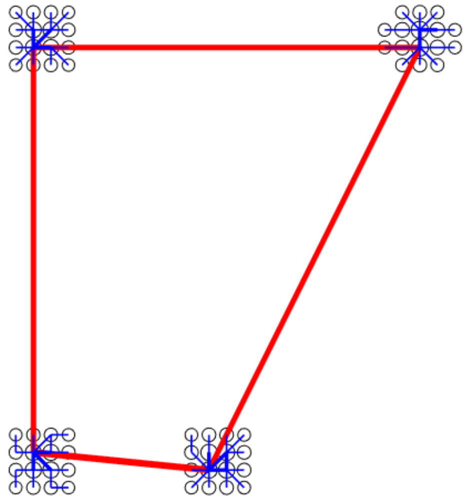
Phase 1 (n=1)



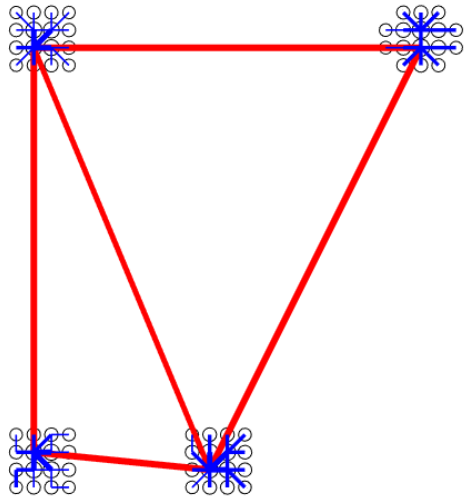
Phase 2 (n=46)



Phase 3 (n=85)

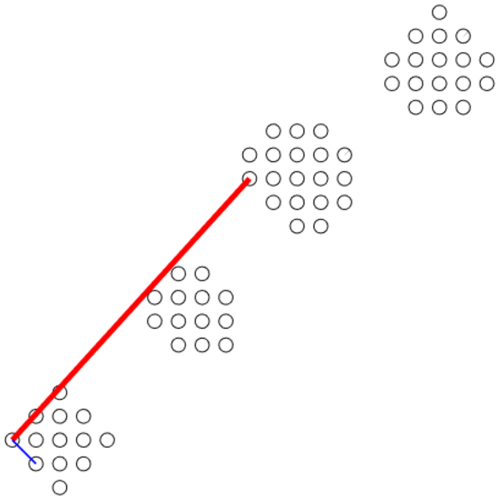


Phase 4 (n=121)

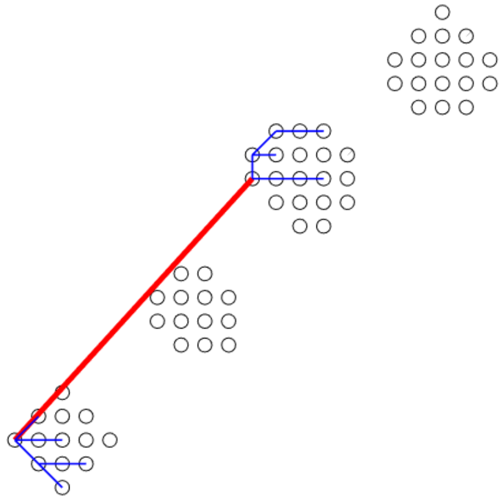


RUNM

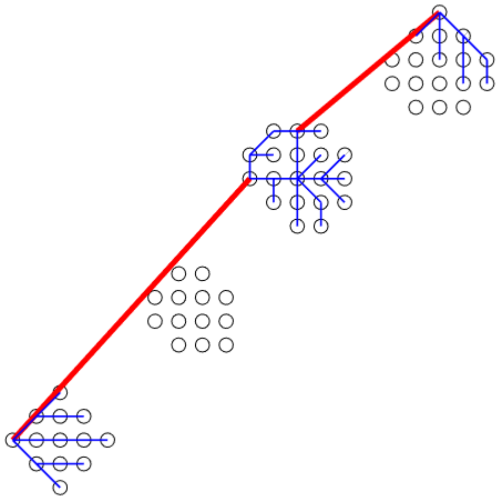
Phase 1 (n=2)



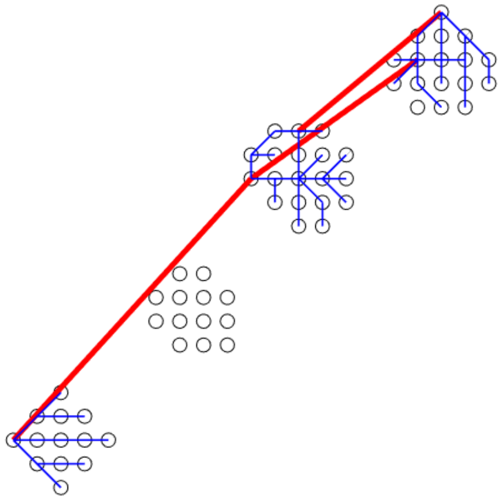
Phase 2 (n=16)



Phase 3 (n=42)

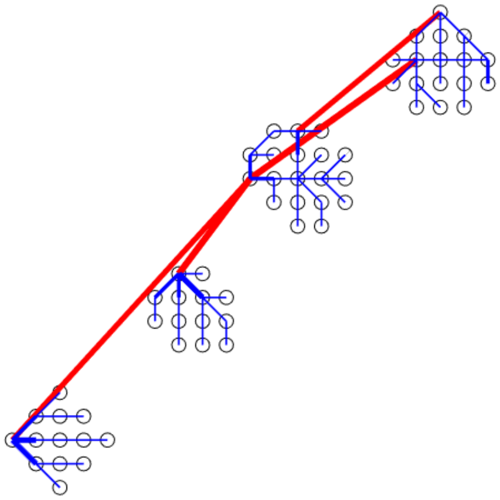


Phase 4 (n=52)

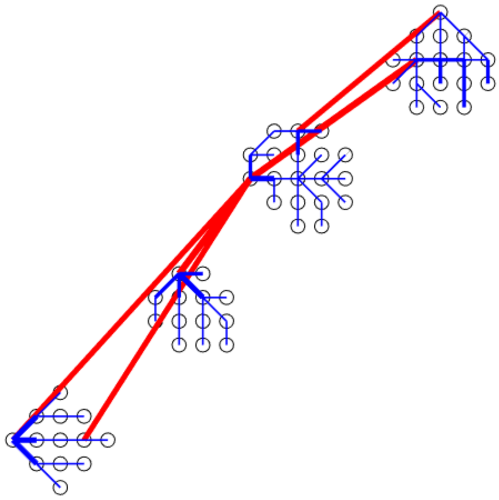


RUNM (continuation)

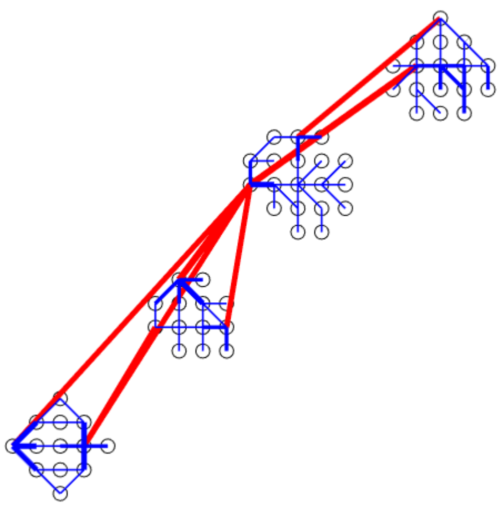
Phase 5 (n=75)



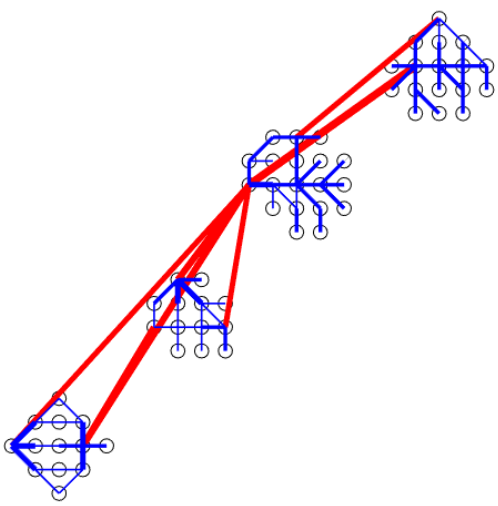
Phase 6 (n=90)



Phase 7 (n=103)

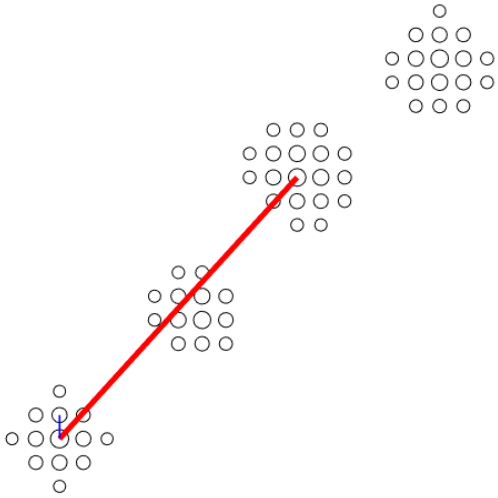


Phase 8 (n=136)

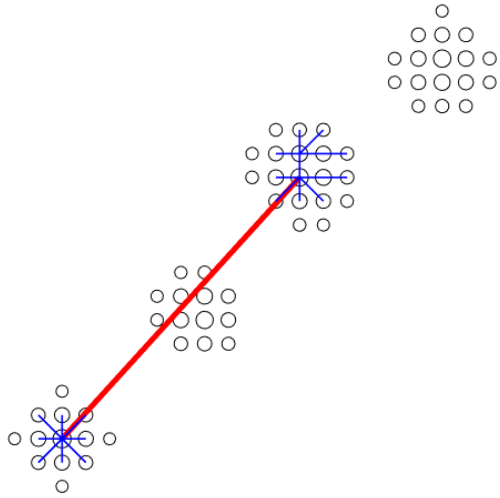


RLNM

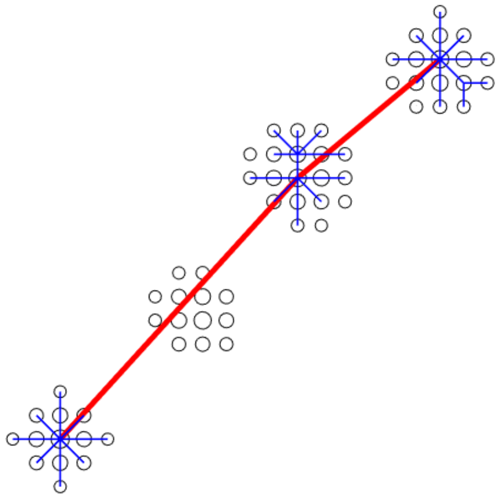
Phase 1 (n=2)



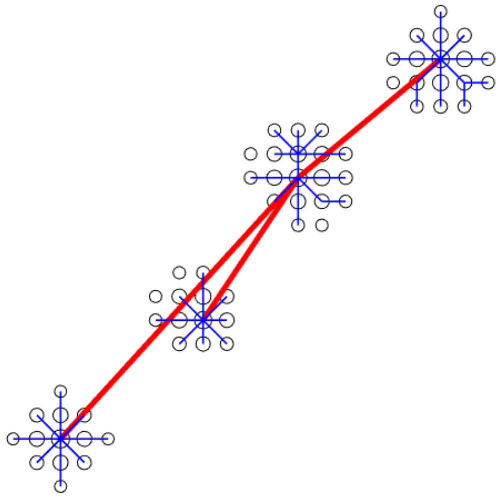
Phase 2 (n=21)



Phase 3 (n=44)

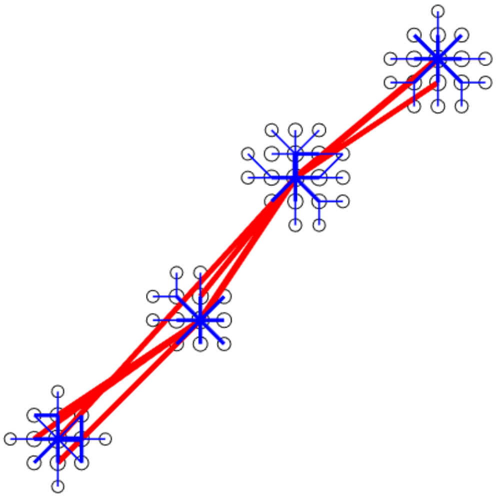


Phase 4 (n=57)

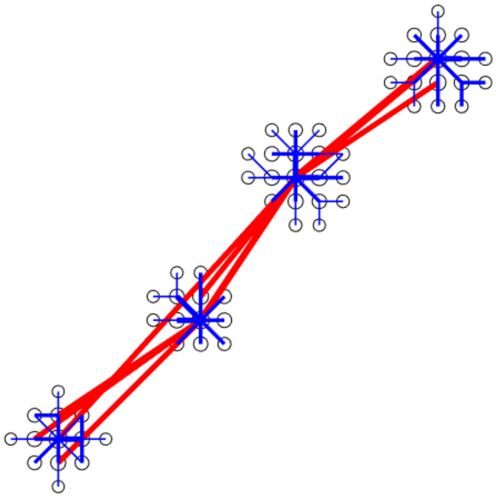


RLNM (continuation)

Phase 5 (n=101)

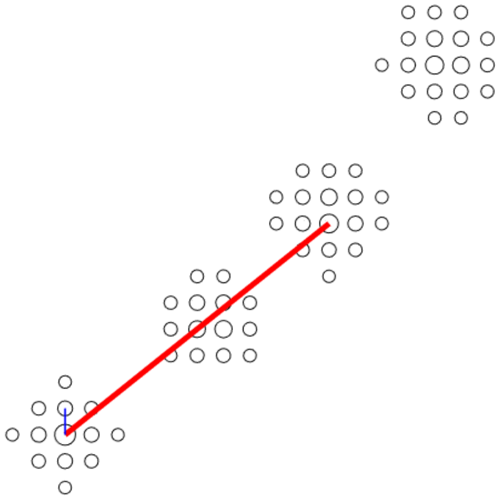


Phase 6 (n=118)

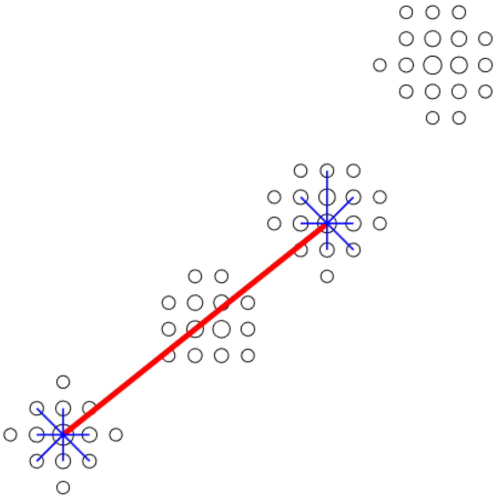


RENM

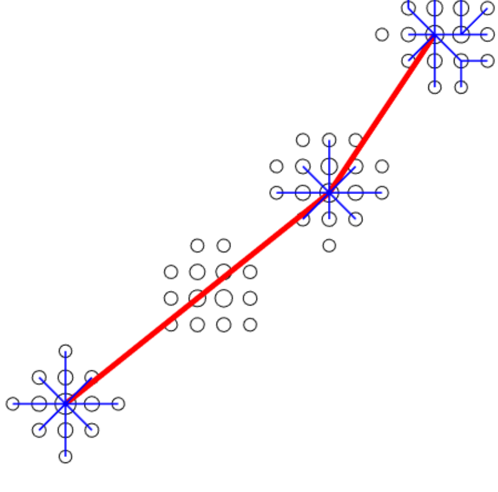
Phase 1 (n=2)



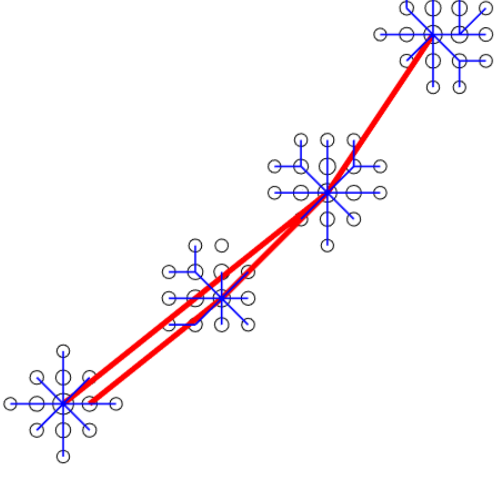
Phase 2 (n=16)



Phase 3 (n=39)

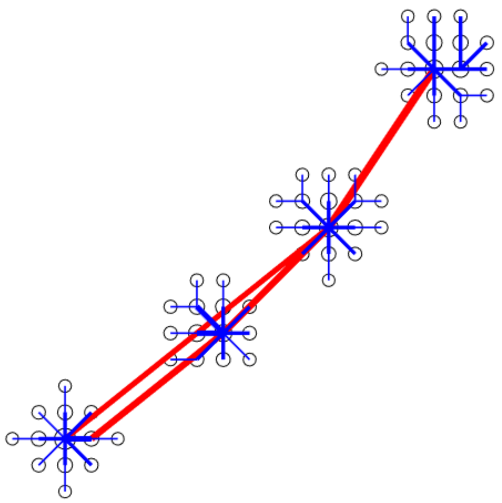


Phase 4 (n=59)

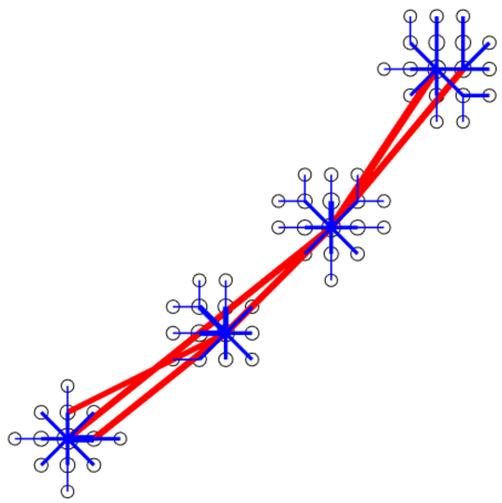


RENM (continuation)

Phase 5 (n=101)

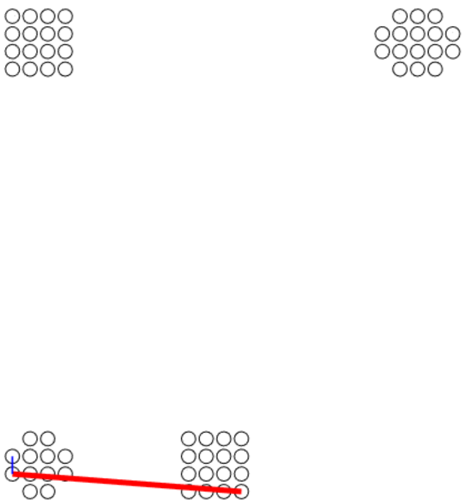


Phase 6 (n=113)

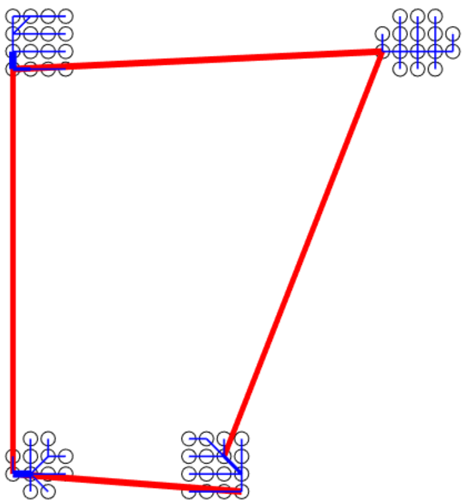


FUAM

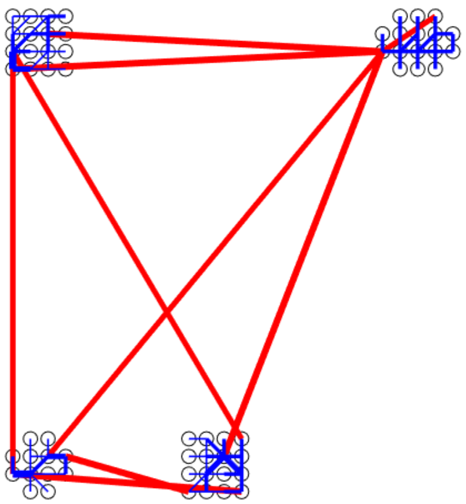
Phase 1 (n=2)



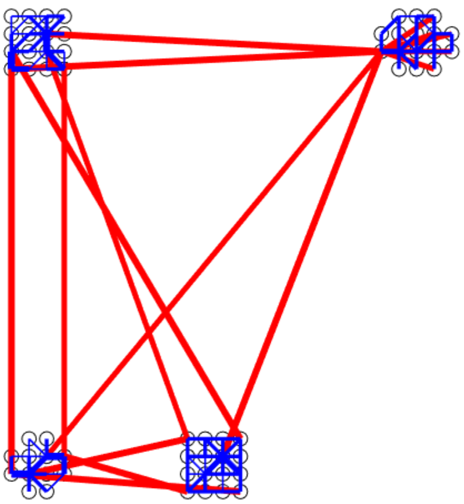
Phase 2 (n=66)



Phase 3 (n=155)

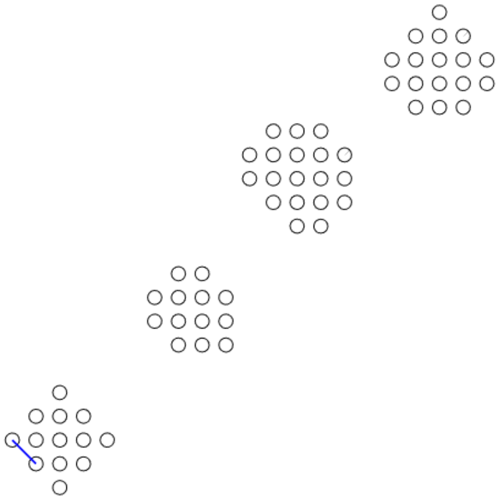


Phase 4 (n=208)

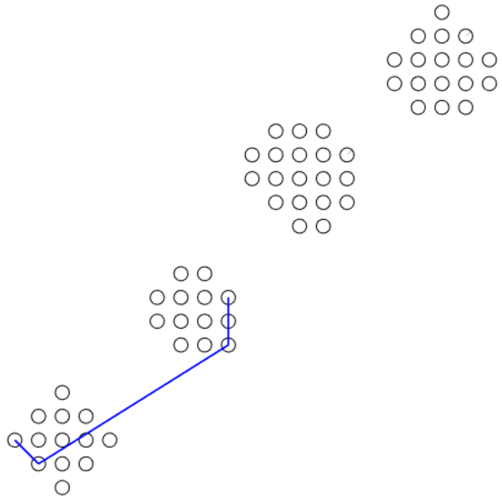


RUNU

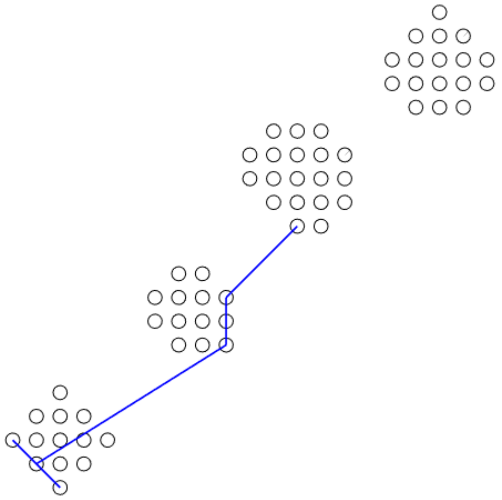
Phase 1 (n=1)



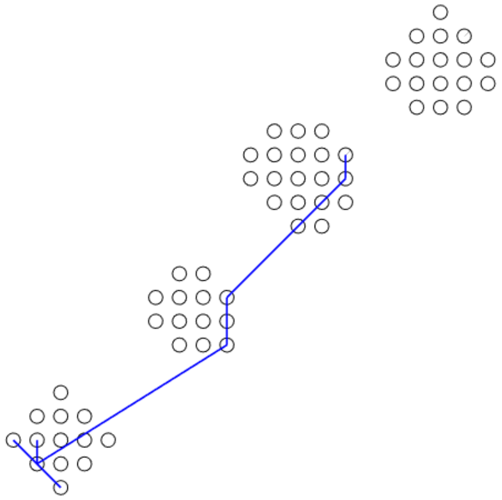
Phase 2 (n=3)



Phase 3 (n=5)

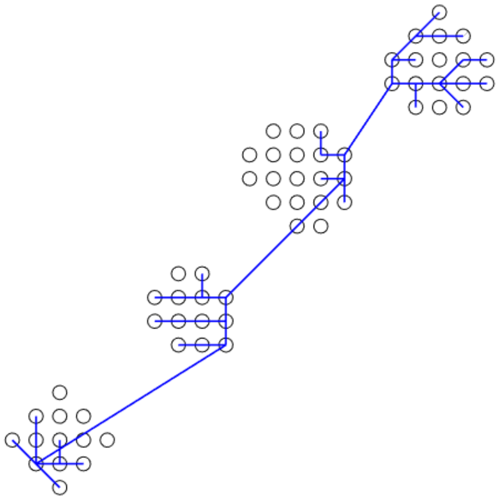


Phase 4 (n=8)

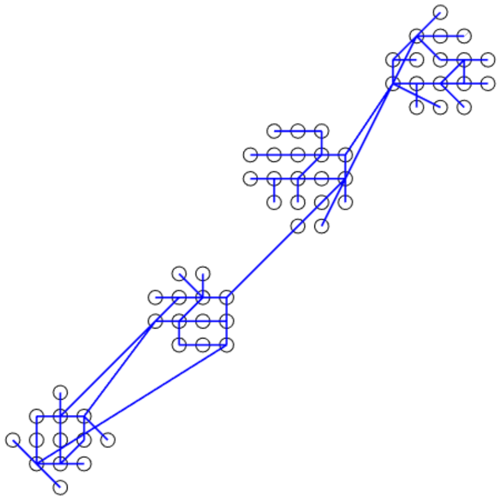


RUNU (continuation)

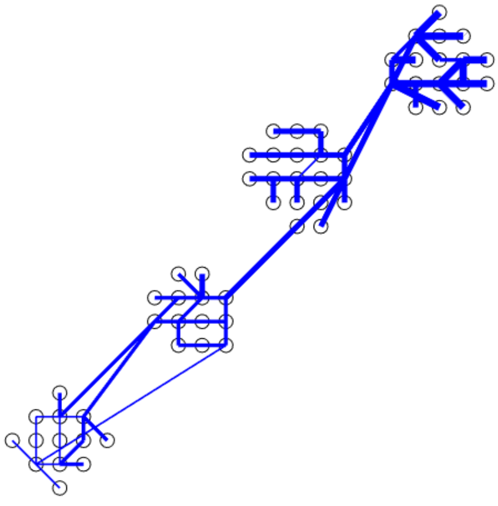
Phase 5 (n=40)



Phase 6 (n=70)

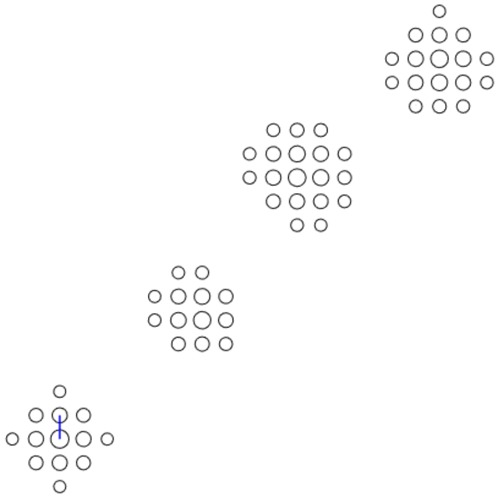


Phase 7 (n=179)

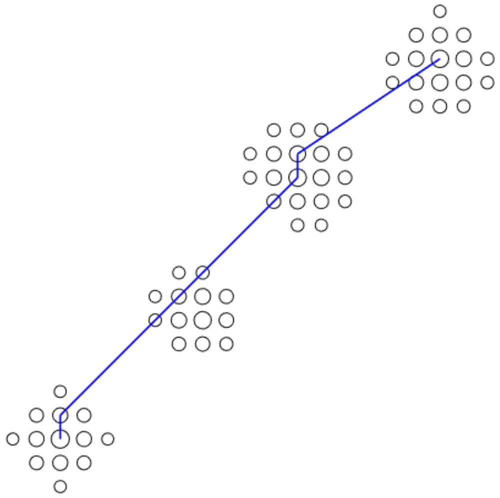


RLNU

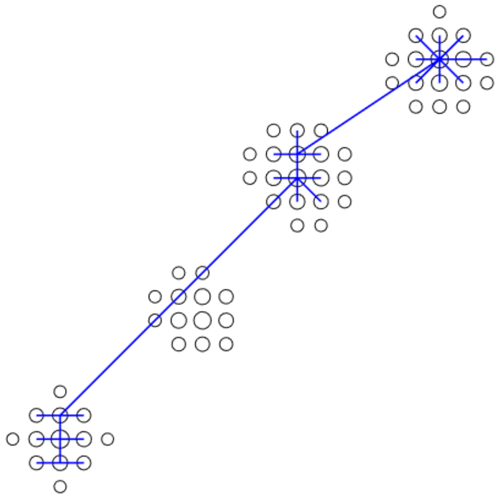
Phase 1 (n=1)



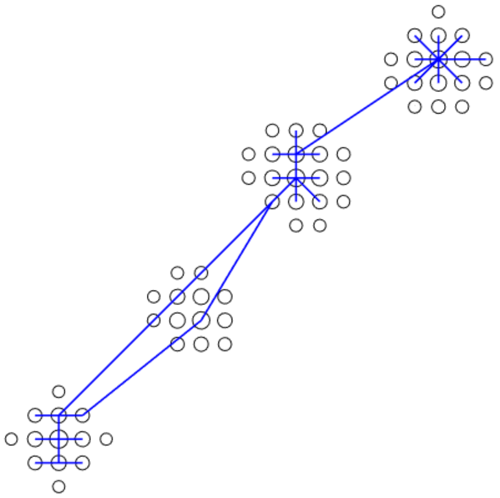
Phase 2 (n=4)



Phase 3 (n=26)

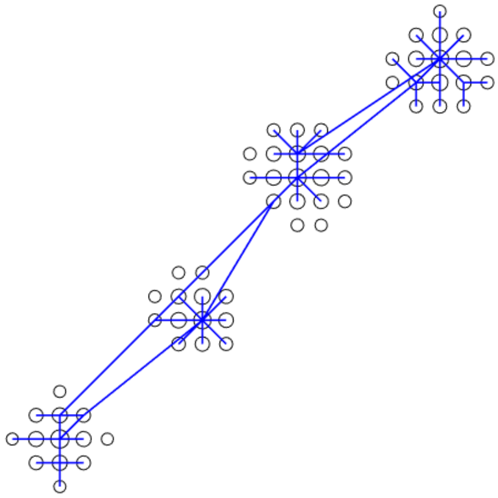


Phase 4 (n=28)

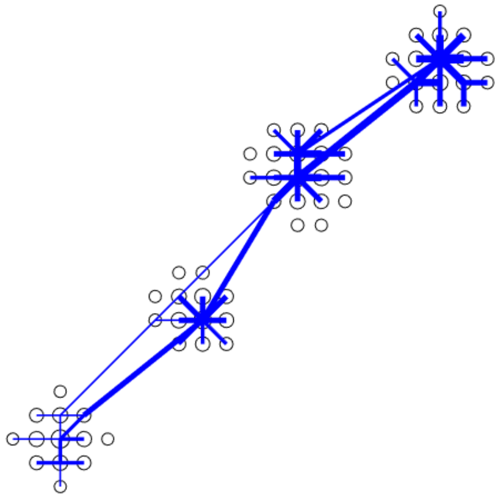


RLNU (continuation)

Phase 5 (n=54)



Phase 6 (n=147)



Appendix D: List of stops included in Randstad PT network

Randstad PT network stops		
Heemstede-Aerdenhout	Utrecht Overvecht	Utrecht Lunetten
Dordrecht	Den Haag Centraal	Amsterdam Amstel
Rotterdam, Marconiplein	Amsterdam RAI	Overveen
Rotterdam, Kralingse Zoom	Voorschoten	Haarlem
Rotterdam, Capelsebrug	Capelle Schollevaar	Voorhout
Rotterdam, Schenkel	Leiden Centraal	Weesp
Rotterdam, Prinsenlaan	Houten	Breukelen
Rotterdam, Graskruid	Rotterdam Centraal	Lage Zwaluwe
Rotterdam, Binnenhof	Den Haag Laan van NOI	Culemborg
Rotterdam, Coolhaven	Vlaardingen Centrum	Leerdam
Rotterdam, Dijkzigt	Houten Castellum	Den Haag Moerwijk
Rotterdam, Eendrachtsplein	Maassluis West	Geldermalsen
Rotterdam, Voorschoterlaan	Barendrecht	Baarn
Rotterdam, Nieuw Verlaat	Voorburg	De Vink
Rotterdam, De Tochten	Waddinxveen	Amsterdam Zuid
Rotterdam, Nesselande	Amsterdam Centraal	Maarssen
Capelle ad IJssel, De Terp	Sliedrecht	Den Haag HS
Capelle ad IJssel, Capelle Centrum	Bunnik	Boskoop
Capelle ad IJssel, Slotlaan	Rijswijk	Bodegraven
Schiedam, Troelstralaan	Dordrecht Stadspolders	Zaandam
Pernis, Pernis	Amersfoort	Schiphol Airport
Hoogvliet Rotterdam, Hoogvliet	Delft Zuid	Woerden
Spijkenisse, Spijkenisse Centrum	Arkel	Sassenheim
Spijkenisse, De Akkers	Gouda	Rotterdam Zuid
Rotterdam, Stadhuis	Utrecht Centraal	Amsterdam Holendrecht
Rhoon, Rhoon	Amsterdam Sloterdijk	Amsterdam Science Park
Poortugaal, Poortugaal	Alphen aan den Rijn	Den Haag Ypenburg
Rotterdam, Leuvehaven	Den Haag Mariahoeve	Zoetermeer
Rotterdam, Rijnhaven	Rotterdam Lombardijen	Zoetermeer Oost
Rotterdam, Maashaven	Naarden-Bussum	Vleuten
Rotterdam, Zuidplein	Hoek van Holland Strand	Utrecht Terwijde
Rotterdam, Slinge	Hilversum	Bilthoven
Rotterdam, Blijdorp	Leiden Lammenschans	Halfweg-Zwanenburg
Rotterdam, Meijersplein	Zandvoort aan Zee	Beesd
Nootdorp, Nootdorp	Nieuw Vennep	Lansingerland-Zoetermeer
Pijnacker, Pijnacker Centrum	Diemen Zuid	Rotterdam, Oosterflank
Pijnacker, Pijnacker Zuid	Amsterdam Lelylaan	Amsterdam, Vijzelgracht
Berkel en Rodenrijs, Berkel Westpolder	Abcoude	Amsterdam Noord
Berkel en Rodenrijs, Rodenrijs	Rotterdam Alexander	Amstelveen, De Boelelaan/A.J. Ernststraat
Rotterdam, Melanchthonweg	Dordrecht Zuid	Amstelveen, Oranjebaan
Rotterdam, Delfshaven	Gorinchem	Amstelveen, Westwijk
Rotterdam, Oostplein	Amsterdam Muiderpoort	Breda
Rotterdam, Beurs	Hoofddorp	Eindhoven
Rotterdam, Wilhelminaplein	Rotterdam Blaak	Arnhem Centraal

Amsterdam Bijlmer ArenA	**Haarlem Spaarnwoude**	**Zwolle**
Bussum Zuid	**Hardinxveld-Giessendam**	**Den Haag, Kurhaus**
Delft	**Rotterdam Noord**	**Den Haag, Spui**
Soest Zuid	**Diemen**	**Den Haag, Leyenburg**
Schiedam Centrum	**Nieuwerkerk aan den IJssel**	**Wateringen**
Schiedam Nieuwland	**Hollandsche Rading**	**Almere Centrum**
Duivendrecht	**Gouda Goverwelle**	**Uithoorn**
Hillegom	**Zwijndrecht**	**s-Hertogenbosch**