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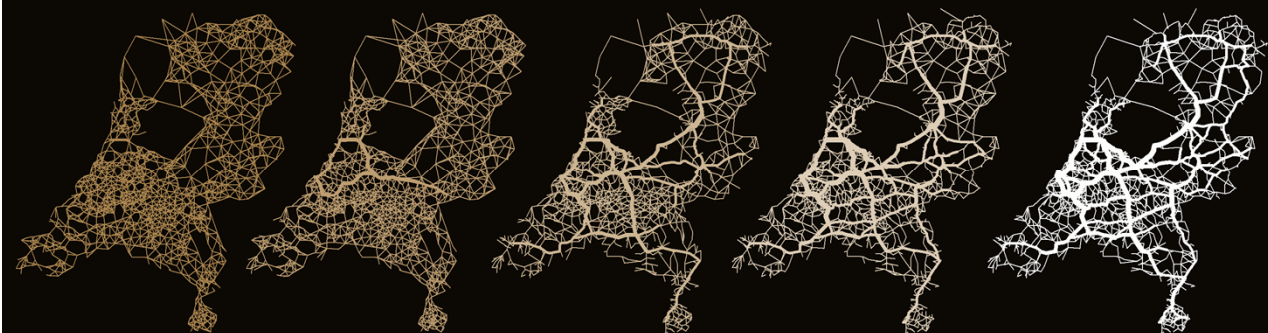
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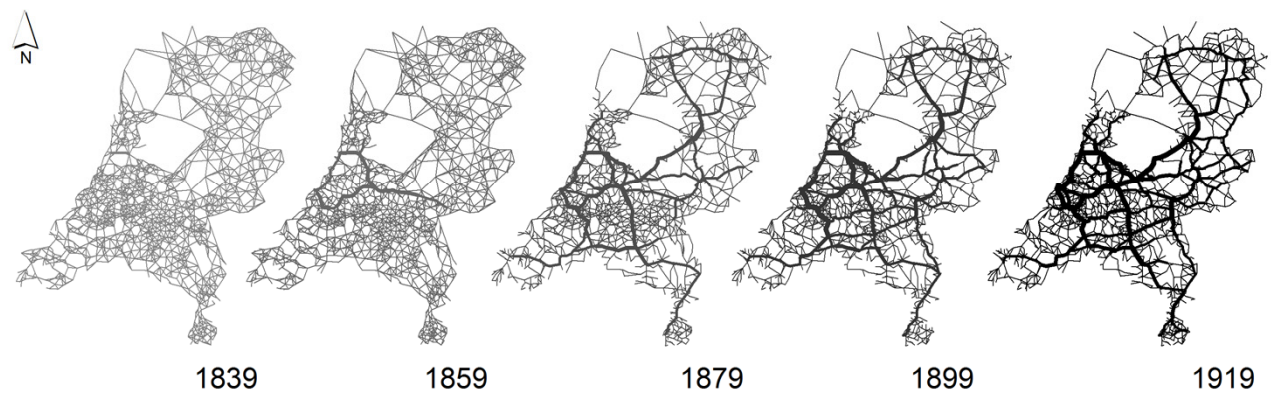
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SPATIAL DATA ANALYSES OF URBAN LAND USE AND ACCESSIBILITY



CHRIS JACOBS-CRISIONI



SPATIAL DATA ANALYSES OF URBAN LAND USE AND ACCESSIBILITY

Cover illustrations by Chris Jacobs-Crisioni. Front: estimated passenger flows in the Netherlands indicated by line thickness for (from left to right) 1839, 1859, 1879, 1899 and 1919. Back: the abandoned railway station of Santadi, Sardinia, Italy, in 2016.

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VRIJE UNIVERSITEIT

Spatial data analyses of urban land use and accessibility

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. V. Subramaniam,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Economische Wetenschappen en Bedrijfskunde
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De Boelelaan 1105

door

Christiaan Govert Willebrordus Jacobs - Crisioni

geboren te Breda

promotoren: prof.dr. P. Rietveld (†)
 prof.dr. H.J. Scholten
copromotor: dr. E. Koomen

Dedication

*For my mother, who learned me to reflect; and
for my father, who learned me to love what you do.*

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Preface

Having an ample amount of selfish motivation is very useful when pursuing a Ph.D. As a case in point, this dissertation documents the results of my ongoing attempts to answer the questions I began to ask myself while studying spatial planning. If fast transport and communications technology is indeed transforming the way our society deals with space, what does that mean for future urban forms? What will be the effect on life in public space? And can we use transport network forms as a way to control urbanization and vitality? After obtaining my master's degree, my studies had still left me wanting for the knowledge and tools that I felt were necessary to satisfy my curiosity. In order to become better equipped at dealing with my questions, I quit a comfortable permanent job in transport consultancy and, in December 2007, started working as a researcher at VU University's SPINlab. Looking back nine years later, I believe that decision helped me improve on myself in many different ways. However, I could not have made those improvements without the help of many others. I will therefore use the rest of this preface to thank all those that contributed to this dissertation.

Special thanks must go to the three people from VU University that contributed the most to my learning and the finalization of this dissertation. I first have to acknowledge the invaluable help offered by Piet Rietveld, who introduced me to the field of econometrics and remained supportive of my work when even the most patient supervisor could have honorably given up. That Piet cannot see this final result saddens me deeply. Henk Scholten has, in a way, been more distant to the finalization of this dissertation. His support of my search for answers has nevertheless been a great help. Although the thought scared me at first, Henk's philosophy that scientists should profit from their freedom and carve out their own paths in academia has become an important inspiration for me to this very day. Eric Koomen was bestowed with the no doubt difficult task of supervising my work on a daily basis. Eric not only added constructive criticism to this work but also tried to prepare me for all the hurdles a PhD candidate must take, and instilled in me the wisdom that even the best idea is no good if it is not expressed properly. And that it probably needs to be planned. Eric, thank you for your collaboration, and I hope we will continue working together now that you are relieved from the duty of being my supervisor.

Although I do claim sentimental ownership of the analyses and writing collected in this dissertation, and naturally take full responsibility for any errors and omissions,

I owe much to the authors that helped write the articles that shape this dissertation. Piet Rietveld and Eric Koomen have already been mentioned. I am thankful for Carl Koopmans' contributions to the two chapters on railway network development. Carl contributed in particular by confronting my often technologically oriented solutions with his economic reasoning. The ensuing discussions and the intellectual challenges that Carl raised made the final results all the better. Emmanouil Tranos has helped a lot in Chapter 6, when we both tried to make sense of the mobile phone data that are used in that chapter, and I am thankful for his contributions. Chapter 8 is based on data generated together with Ana Barbosa and my colleague LUISA modellers: Carlo Lavalle, Filipe Batista e Silva, Claudia Baranzelli and Carolina Perpiña Castillo. Ana, I enjoyed our collaboration and wish you all the best in Malaga. Carolina, Carlo, Claudia and Filipe, it is a great pleasure to be part of our team, and I am looking forward to address all the challenges that will come our way! Most of the analyses in this dissertation are published or soon to be published as journal articles. Although the cycle of submission, revisions and resubmission can seem tedious, I am grateful for the anonymous peer reviewers that have provided invaluable comments and have surely helped improve the quality of the analyses in this dissertation. I would also like to express my gratitude to the members of the thesis committee (Michael Batty, Karst Geurs, Jan Ritsema van Eck, Erik Verhoef, Michael Wegener and Jasper van Vliet), who have also provided constructive comments that helped improve the quality of this dissertation.

Two institutions have given important support to the creation of this thesis. I started my research in the LUMOSpro project funded by what was then called the *Milieu- en Natuurplanbureau*, but soon became the *Planbureau voor de Leefomgeving*. The projects I worked on in that time, and the discussions I had in that period in particular with Bart Rijken, helped shape many of the ideas that are now part of this dissertation, and I am grateful for the support I received. The work for Chapter 6 of this dissertation has been financed by the research programme Urban Regions in the Delta, part of the 'Verbindend Duurzame Steden' programme of the Netherlands Organisation for Scientific Research, which I most gratefully acknowledge.

A word of thanks is also necessary for others that helped shape this dissertation. Most of all, I feel indebted to Maarten Hilferink and Martin van der Beek from ObjectVision, who helped me on my way in using their GeoDMS software. The capacities of that software have enabled analyses that, because of their

computational complexity, would have been impossible with run-of-the-mill GIS software. Their help and patient explanations, have meant a great deal for this book, and I am very grateful for their help. Two chapters in this dissertation cover the expansion of the Dutch railway network in the 19th century. For those chapters I needed to rely on reports stored in the Dutch railway museum. The library of that museum kindly provided the necessary hospitality to me, for which I am grateful. It goes without saying that the task of writing a dissertation has been made much more bearable by my friends, family and colleagues at the VU's department of spatial economics, at the SPINlab and at the JRC. Thank you!

Last but certainly not least, I must concede that the time spent on my studies has been at the expense of time share with those I hold dearest. Concetta and Saira, thank you for your patience whenever I locked myself up behind my computer. I hope you are proud of this final result, and look forward to celebrating its completion together!

Chris Jacobs-Crisioni

Castello Cabiaglio, October 2016

Part I: Introduction

Chapter 1. Introduction

1 Motivation

The spatial distribution of human activity has impacts on topics ranging from the Earth's climate (Meyer & Turner 2007; Kalnay & Cai 2003), ecological systems and land resources (Lambin et al. 2001; Foley et al. 2005), health (Dannenberg et al. 2003), transport (Wegener et al. 1999; Cervero 1996) to quality of life (Frank 2000). The spatial patterns of human activity are commonly described by means of land-use patterns. The term land use is notoriously ambiguous (Dickinson & Shaw 1977). In this dissertation I use the definition also used by Jansen (2006): *the type of human activity taking place at or near the surface*. Land use must be separated from similar terms such as land cover, which deals with the physical manifestation of ecological environments or human activities, and land function, which deals with land's provision of benefits and goods that have a utility for society. For a detailed discussion of the land use, land cover and land function concepts I refer to Verburg et al. (2009).

The impact that land use may have on various environmental and societal issues ought to make the strategic management of human activity patterns a key concern of policy makers, which is tackled in the various disciplines involved in spatial planning. According to Hopkins (2001: p. 5) spatial plans deal with interdependent, indivisible and irreversible decisions that face imperfect foresight; in all cases, spatial plans are decisions that affect the future. There is a societal component as well: spatial planning should improve the outcomes of 'natural' systems in favour of society. An extreme case of natural system failure that needs mending by policies and/or planning is the so-called tragedy of the commons, where rational individual behaviours yield an outcome that is suboptimal for the whole group (Hardin 1968). Faludi (2002) defines spatial planning as 'the systematic preparation of spatial policies' and emphasises the integrative role that spatial planning entails. In fact, an important task of spatial planning is the coordination between various sectors and various scales of administration. Naturally, varied interests are at stake in the spatial planning process, and thus spatial planning requires a thorough understanding of, amongst others, 'the dynamic behaviour of systems' (Hopkins 2001: p. 6). In fact, to facilitate such a thorough understanding, a broad range of scientific disciplines have made contributions to the field of spatial planning (Couclelis 2005).

Despite the fact that many sectors have a vested interest in spatial planning, and despite the fact that spatial policies often have multi-sector implications, the conception of spatially relevant policies is usually arranged along sector lines (Priemus et al. 2001; Bertolini et al. 2005). Thus, criteria for plan evaluation regularly focus on sector-specific aims such as reducing congestion, increasing mobility or limiting urban sprawl. Unfortunately, such an approach to policy evaluation misses overarching societal goals. In the last years, policy making communities are increasingly aware of the necessity of integrated policy making (Geerlings & Stead 2003). Examples are OECD's promotion of a more comprehensive evaluation framework in order to understand policy impacts on sustainability (OECD 2010) and the European Commission's guidelines for the assessment of economic, social and environmental impacts of policies (EC 2013; EC 2002).

One aspect of the slow shift to integrated policy assessment is the developing insight that transport systems and human activity patterns are intrinsically linked, as has been reiterated in a variety of recent papers (Bertolini et al. 2005; Bertolini & Le Clercq 2003; Cervero & Landis 1997; Wegener et al. 1999). This intrinsic link implies that those involved in either land-use or transport planning should in all cases consider their counterparts, and that comprehensive insights into the linkages between transport systems and land use are needed. Thus the level of knowledge required to evaluate the usefulness of plans is increasing. Multi-sector policy evaluations are especially difficult because various sector policies might interact directly or indirectly and negate or propagate policy impacts, thus leading to end results that cannot be predicted in a straightforward way. The complexity of multi-sector policy evaluation has therefore led to the increasing acceptance in the policy making domain of land-use models, which aim to forecast future land-use changes and support multi-sector policy evaluations.

Examples of land-use models that are being used in integrated policy preparation and policy evaluation are the Image, UrbanSim, Land Use Scanner, Tigris XL and EUClueScanner models (Koomen, Hilferink, et al. 2011; Hilferink & Rietveld 1999; Lavalle, Baranzelli, Batista e Silva, et al. 2011; Zondag & De Jong 2005; Waddell 2002; Alberti & P.Waddell 2000; Alcamo et al. 1998). Recently, such land-use modelling tools have been used to assess the economic and environmental impacts of climate change (Koomen, Koekoek, et al. 2011; Hartje et al. 2008; Verburg et al. 2012; Koomen et al. 2012; Koomen, Loonen, et al. 2008) and government actions such as the instalment of a regional and national spatial strategy (Koomen &

Dekkers 2013; Jacobs et al. 2011; Zondag & Geurs 2011), agricultural policies (Lavalley, Baranzelli, Mubareka, et al. 2011), transport network investments (Geurs et al. 2012) and regional investments (Batista e Silva et al. 2013). On a side note, the attentive reader will note that, while economic and environmental impacts of policies have received considerable interest, social impacts are rather disregarded in the presented policy evaluations; this is at least partly because relevant indicators are difficult to estimate and therefore often unavailable (Geurs & van Wee 2004). Linked to this is that social impact assessments are chiefly executed as interactive processes involving stakeholders, which aim at achieving local project development success (Esteves et al. 2012). Clearly, such processes are not compatible with the more technically oriented practice of land-use modelling, where stakeholders are normally not consulted. Nevertheless, a more inclusive approach to social impacts in modelling-oriented planning policy evaluation is called for; furthermore, although stakeholder participation is normally not included in such method-driven evaluations, such projects could presumably benefit from the inclusion of stakeholders as advocated in the newly coined Geodesign concept (Lee et al. 2014).

The growing necessity for land-use models in the policy-making domain presses the need for a sound empirical validation of some of the assumptions made in those models, and this dissertation aims to do so with regard to certain aspects of land-use modelling. Land-use models in policy evaluation practice are still largely derived from Von Thünen's (1826) and Christaller's (1934) conceptual models of land-use organisation. Von Thünen's model describes likely agricultural land use patterns given a featureless plain with one central market and other limitations. According to Von Thünen, land uses that depend more critically on transport are located closer to the city, causing that distance to the central market becomes the principle on which land uses are sorted. Christaller's model describes levels of service of various market places in a limited and again featureless plain. According to this model a hierarchy of market places exists, in which more central places have higher levels of service than more peripheral market places. An economic explanation why land uses are organized according to distance to a central market has been given by Alonso (1964), who proposed bid-rent functions of different land-use types according to distance from city centres, and in a decentralised form by Anas (1982), who modelled residence choice based on a limited amount of amenities including distance to the city centre.

The general conclusion to be drawn from the abovementioned models is that the opportunity to interact, expressed as a function of distance to a central hypothetical market with clearly defined boundaries, is a strong organizing element in human activity patterns. However, new developments cause that geographers will need to reconsider how these models are interpreted for use in practical analyses. One development is the historical diffusion and current ubiquity of fast overland transport in many societies, which has caused that the surface of the world has both shrunk and shrivelled, as Waldo Tobler noted during a conference in 1999 (Miller 2004). Some have even proposed that distance is, or will no longer be an important factor for human activity patterns (Cairncross 1997); although empirical findings suggest that geographical distance continues to matter despite the fact that people continue to move ever greater distances on a daily basis (Rietveld & Vickerman 2004).

A consequence of overland transport becoming faster is that cities and societies are increasingly defined by social relations that are sustained over much larger distances than has been witnessed ever before; a change already observed by Webber (1964). In this context Castells (1996) describes that economic and social flows are increasing between highly specialized nodes over much larger distances; thus enabling increased specialization and agglomeration opportunities. The reciprocities between market access and agglomeration benefits are being formalized in theories of new economic geography, which offers means to simultaneously model the impacts of market access and agglomeration forces on spatial economies (Krugman 1998; Fujita & Krugman 2004). All in all, one result of faster overland transport may be that Euclidean distance to a centre is becoming less and less useful as a basis for defining interaction opportunities for the sake of understanding and modelling land-use patterns. Another revision to models of centrality may be retrieved from the insight that, despite ever increasing mobility, neighbourhood interactions and unobserved local factors remain to be important additional factors to explain the geography of human activities. Patterns of human activity may be substantially affected by agglomeration benefits as described by Castells (1996) in combination with the need for face-to-face contact (Storper & Venables 2004), as well as access to local services and a range of local factors. Thus, any effort to understand and model human activity patterns at the local level should include local dependencies, next to the interaction opportunities that are enabled by modern transport networks. One last revision to models of centrality may be that the costs of overland transport is not a constant or exogenous force: in fact, transport supply may change as a result of changes in transport demand, and

thus offset interaction opportunities and finally human activity patterns (Levinson 2008; Xie & Levinson 2010; Koopmans et al. 2012).

2 Research question and dissertation structure

In this dissertation I attempt to uncover aspects of the relation between interaction opportunities over long distances, local interactions and human activity patterns. The main question of this dissertation is:

“How do long-distance interaction opportunity and local interactions affect land-use patterns and the management of those patterns?”

I recognize that any separation of long-distance and local can be contended, as close and far are intrinsically subjective concepts. For the sake of simplicity, local will be defined here as an area easily travelled on foot – typically, one’s immediate neighbourhood or municipality; while long-distance will be defined here as any destination in the world not easily reached on foot, so that most, if possible, would use motorized transport to reach that particular destination. I have to acknowledge that this is a decidedly marred definition of local and long distance, that ignores more refined definitions of neighbourhood and reachability, such as are tackled in for example the rich literature on mental maps (Gould, 1999) and activity spaces (Dijst, 1995). Given the aggregate nature of the studies in this dissertation, I believe my marred definition suffices for a rough separation between what is local and what is not.

A number of aspects pertaining to this question will be investigated using empirical analyses of spatial data. The following three themes will be addressed in the parts that comprise this thesis:

- A. Methodological aspects of the relationship between long-distance interaction opportunities, local interactions and urban land-use patterns.
- B. The driving forces and rationale behind the geographic expansion of overland transport networks.
- C. The role that land-use patterns, local and/or long-distance interaction opportunities play in current spatial planning dilemmas.

As a proxy of interaction opportunity I will use a potential accessibility measure. Potential accessibility has often been used as a proxy of interaction opportunities by researchers interested in the interaction between land use and transport (Geurs

et al. 2001). The measure combines three dimensions relevant to a population's experience of interaction opportunity: the amount of potential activities at one destination; the costs of reaching that destination from the point of origin, given available transport methods; and the person's response to transport costs, often described in terms of a distance decay function for the aggregate population. Potential accessibility, to some degree depending on distance decay functions, commonly describe the opportunity to interact; with emphasis on intra-regional and extra-regional interactions. It is, for explanatory analysis, by all means inferior to individual level time-geography based spatial constraints (Dijst 1995) or accessibility measures. It has first been described by Hansen (1959) as a factor that discerns whether a city block is developed sooner, or later, or not at all. Wegener and Fürst (1999) stress that it is an important factor to understand the location of residential or industrial developments. This measure is, all in all, a useful alternative for the distance to the city centre measures often seen in land-use pattern analyses.

Potential accessibility is directly linked to spatial interaction modelling: in fact, the measure used repeatedly in this dissertation is computed as the total number of flows that could reach a location if competition from other destinations and the provision of activities at the destination are not taken into account. As such, it is a measure of relative opportunity for the spatial location of human activity and, I expect, an indication of the probability of the location of that activity if the societal, environmental and economic context allows some degree of freedom in the geographical location of that activity. It is important to stress here that potential accessibility measures are meant to describe opportunity devoid of individual traveller's characteristics. Accessibility measures of individual time-geographies as proposed by Hägerstrand (1970) are surely much more informative, but can only be used when personal characteristics and constraints are available to the modeller (see for example Dijst 1995 and Kwan and Weber 2008). At best, the used potential accessibility measures function as a proxy of the summed interaction opportunities of such individual measures.

2.1 Analysing relationships between interaction opportunities and urban land use

Some questions related to using potential accessibility measures in the analysis of urban land-use developments still require an answer. Part II of this thesis will therefore focus on particular methodological aspects that deal with the definition

of areal units when analysing the relationship between interaction opportunities, local interactions and land-use patterns. The following questions will be addressed in Chapters 2 and 3 of this dissertation:

1. Can potential accessibility measures be computed on a spatially continuous plane using interpolation methods without substantial loss in accuracy?
2. Does the captured impact of potential accessibility on urban development levels depend on the selection of areal units in which data are analysed? And to which extent does the impact of local interactions depend on those areal units?

2.2 Understanding overland transport network expansion

The studied accessibility values themselves are driven by steadily lowering transport costs. Those transport costs are mainly lowered because of decisions to invest in specific forms and stretches of transport infrastructure. Those decisions are presumably largely driven by an economic logic, but other factors may matter as well. Because the choices for transport infrastructure may have a considerable societal impact, this brings forth the question what factors come into play here? Is it possible to reveal why certain network expansion paths are followed? And if so, can past investments be reproduced and can the effect of policy preferences on future network outcomes be predicted? Those questions will be addressed in Chapters 4 and 5:

1. Which factors drive the decisions to invest in overland transport, which in turn lead to accessibility improvements?
2. Is it possible to reproduce the decisions to invest in overland transport, and possibly evaluate the impact of policy decisions on future investments?

2.3 Assessing spatial planning related impacts of the interactions between land-use patterns, local and long-distance interaction opportunities

The reciprocities between land-use patterns, local and long-distance interactions are playing an important role in current spatial planning dilemmas. One of those dilemmas is that the ever increasing mobility of people enables, on the one hand, increasing potential for agglomeration economies in retail and consumer-oriented

service industries, causing ever larger and ever more specialized land-use blocks such as shopping malls and peripheral entertainment districts; and on the other hand, the increasing mobility of people fosters spread-out, low-density residential development for people that are economically tied to an urban centre that is ever further away; a development often referred to as urban sprawl (Koomen, Dekkers, et al. 2008; Irwin et al. 2006; Halleux et al. 2012). A number of concerns related to the resulting monofunctional land-use blocks and low-density urban expansion have repeatedly been voiced. One important concern is that such developments do not facilitate vibrant urban streets or the persistence of interaction in public space, which have been deemed an important asset of successful cities in Jane Jacobs's seminal work (1962). According to some, because of the impending loss of high-quality urban areas spatial planners should strive to preserve high-density, mixed-use, urban land-use patterns.

Another dilemma considers the role that national borders play in urban growth. National borders may reduce the impact that interaction opportunities have on urban growth, if those interaction opportunities are on the other side of a national border; but the real impact is unclear. It has repeatedly been shown that border regions tend to lag behind economically, but the causes for that lagging behind are uncertain. Costs of crossing borders, differences in culture, language and legislation, and increased risks in contract enforcement may all contribute to border effects (Rodrik, 2000). Furthermore, relatively poor cross-border transport supply has repeatedly been singled out as an important factor in the lagging development of border regions (Rietveld, 2001; Brühlhart, 2011). On the other hand, ongoing processes of international economic integration may be presumed to remove many of the limitations that national borders impose on cross-border development. All in all, there is considerable uncertainty about the causes as well as the current and future role of border effects in urban growth, which may be relevant when considering policies to uplift often struggling border regions.

One final dilemma is that policy makers are trying to decrease territorial inequalities, such as levels of accessibility, by investing in transport network infrastructure improvements. However, accessibility has its own impact on population distributions, and inequality measures given current population distributions and certain transport investments might not fully capture the net effect on territorial inequalities if adequate land-use planning measures are not set in place. This requires rethinking of territorial inequality policy aims or spatial planning adjustments to ensure the continued effectiveness of transport

infrastructure investments. All in all, the following questions will be further investigated in part III of this dissertation:

1. Do dense and mixed land-use patterns have social benefits by instigating more people to remain in an area for a longer part of the day?
2. Do national borders affect the impact of interaction potential on urbanization? And does increasing international economic integration have any impact on the impact of borders?
3. What are the impacts of road network investments in terms of territorial equality when people are expected to move?

In a later section a number of key methodological components of this dissertation will be discussed. First, however, the layout of the dissertation will be tackled.

3 Dissertation structure

In the following chapters a number of spatial data analyses are presented and discussed that contribute to answering the questions posed before. The various chapters differ in temporal scope and in the breadth of tackled thematic issues. A schematic representation of this is given in Figure 1-1. Almost all chapters that form the main part of this dissertation are either published or are expected to be published in peer-reviewed journals. The publication details of those chapters are indicated in Table 1-1.

The following three chapters comprise the first section of this dissertation and discuss a number of spatial data analyses that serve as cases for more general questions concerned with accessibility and urban land use. Chapter 2 introduces the method to compute accessibility at a very fine spatial resolution that is used in Chapters 3 and 8. In Chapter 3, structural impacts of changing the shape or scale of areal units on explanatory analyses of urban land-use shares in the Netherlands are investigated. This chapter shows that there is a structural and a stochastic element to the effects of scale and shape on analyses; and that there are strong reciprocities between the degree of variance that a fixed set of explanatory variables can explain, and the degree of variance caused by presumably highly local values as captured by models with a spatial econometric specification.

Part III of the dissertation contains two chapters that focus on investments in the construction of overland transport network infrastructure. Chapter 4 uses

estimated construction costs and passenger flow changes to examine the factors involved in the historical expansion of the Dutch railway network. It investigates the choices involved in the geographic development of the Dutch railway network. This analysis shows that all actors involved in railway construction, including the Dutch state, chose railway network expansion projects with the primary aim to increase passenger mileage on the railway network. It further shows that, if investors indeed aim to increase passenger mileage, there is a clear point of saturation after which further expansion options are no more available for the transport network. Lastly this chapter discusses the effectiveness of the ambiguous role that the Dutch state took in railway expansion as a direct competitor to private enterprises.

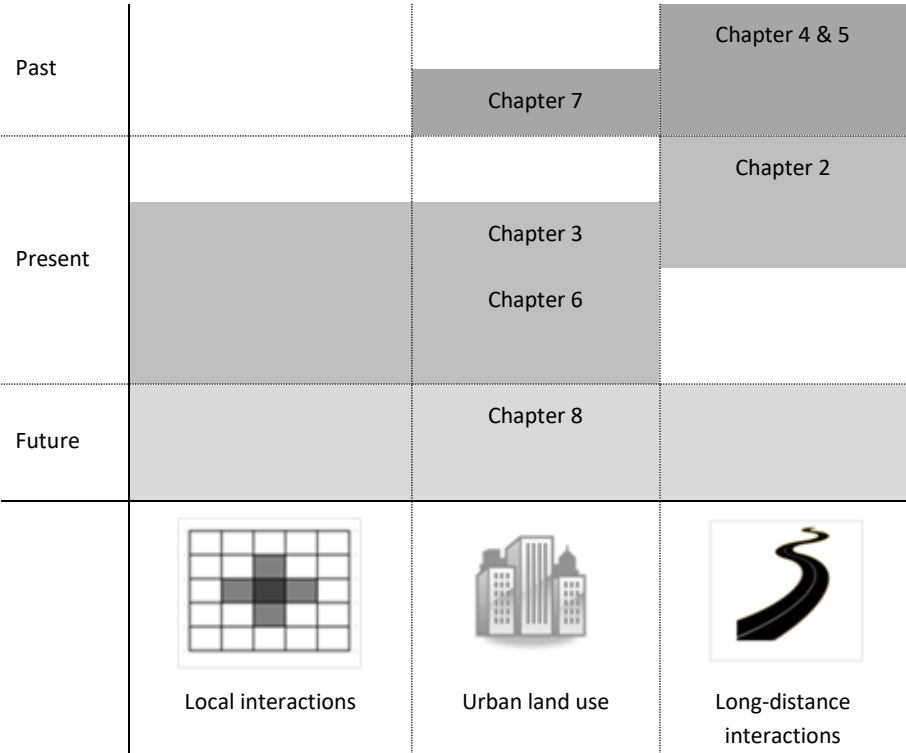


Fig. 1-1. schematic display of the prevailing temporal and thematic scope of the main chapters in this dissertation.

Chapter 5 documents a model that is setup to reproduce the historical expansion of that network and includes a short exploration of the effects of a number of different institutional settings on final network outcomes.

Table 1-1. Publication details of the main chapters in this dissertation.

Part I	Introduction
Chapter 1	Unpublished.
Part II	Analysing relationships between interaction opportunities and spatial organization
Chapter 2	Jacobs, C. (2011) <i>Integrating spatially explicit potential accessibility measures in Land Use Scanner</i> . SPINlab Research Memorandum SL-10, VU University, Amsterdam.
Chapter 3	Jacobs-Crisioni, C., Rietveld, P., Koomen, E. (2014) The impact of spatial aggregation on urban development analyses, <i>Applied Geography</i> , 47: 46-56.
Part III	Understanding overland transport network expansion
Chapter 4	Unpublished.
Chapter 5	Jacobs-Crisioni, C., Koopmans, C.C. (2016) Transport Link Scanner: Simulating geographic transport network expansion through individual investments. <i>Journal of Geographical Systems</i> , 18(3): 265-301.
Part IV	Assessing spatial planning related impacts of the interactions between land-use patterns, local and long-distance interaction opportunities
Chapter 6	Jacobs-Crisioni, C., Rietveld, P., Koomen, E., Tranos, E. (2014) Evaluating the impact of land-use density and mix on spatiotemporal urban activity patterns: An exploratory study using mobile phone data <i>Environment and Planning A</i> 46(11): 2769-2785.
Chapter 7	Jacobs-Crisioni, C., Koomen, E. International accessibility spillovers and persistent borders: Historical growth in West-European municipalities (submitted to <i>Journal of Transport Geography</i>).
Chapter 8	Jacobs-Crisioni, C., Batista e Silva, F., Lavalle, C., Baranzelli, C., Barbosa, A., Perpiña, C. (2016) Accessibility and cohesion in a case of infrastructure improvements with changing population distributions <i>European Transport Research Review</i> 8(1): 1-16.
Part V	Conclusions and summary
Chapter 9	Unpublished.

Finally, Chapters 6 to 8 in Part IV demonstrate how the reciprocity between land-use patterns, local and long-distance interaction affects two important spatial planning dilemmas. Chapter 6 evaluates the long expected benefits of dense and mixed land-use patterns on human presence in urban areas. Through intensifying and lengthening human presence in urban areas those areas are expected to become safer and more attractive (Jacobs 1962). Using mobile phone data in Amsterdam, the Netherlands, the analyses in this chapter demonstrate that dense and mixed land-use patterns indeed are associated with more intense and longer

lasting human presence in urban areas; furthermore it is shown that urban areas with higher urban densities and a more balanced mix of land uses correspond with urban areas that are deemed attractive by experts.

Drawing much from Chapter 3, I investigate the importance of cross-border accessibility compared with the importance of accessibility to domestic destinations in Chapter 7. This analysis uses urban land-use shares in the border areas of five countries in Western Europe as a case. This analysis shows that, although cross-border accessibility does matter, its impact is much smaller than that of domestic accessibility. This leads to the conclusion that accessibility analyses should take foreign accessibility into account; but that improving cross-border accessibility will not have a drastic impact on urban land-use patterns in a country.

Chapter 8 reports on a study done for the European Commission's Directorate-general Regio that estimated the effects of substantial network investments on accessibility and land-use patterns in four countries in Central Europe, given two urbanisation scenarios. It shows that the final distribution of accessibility levels depends considerably on the degree in which supply of land for urban expansion is available around major urban areas, and that policies that aim at improving accessibility in the periphery should take reciprocities with land-use change and spatial policies into account. Lastly, Chapter 9 synthesizes the major conclusions of this dissertation and discusses topics for further study.

4 Spatial data analysis methods

Chapters 2 to 8 are all based on the application of so-called spatial data analyses. I define spatial data analyses here as the investigation of, in most cases, pre-recorded classes, quantities and geographic characteristics of spatially distributed phenomena by means of systematic deduction, in order to obtain evidence in favour or against any predefined hypothesis. This means of analysis is similar to any other data analysis using tried-and-tested analysis methods, however, space and geographical relations are explicitly taken into account. Thus, spatial data analysis methods observe the two core characteristics of geography, namely: spatial heterogeneity, which is the fact that contexts are decidedly different depending on where on earth a phenomenon is observed; and spatial dependency, which is the fact that any two things are probably more similar when located closer to each other, as immortalized in Tobler's well-known first law of geography (Tobler 1970; Miller 2004). Explicitly taking into account the geography of studied

phenomena requires specialized tools in order to display, organize, edit and relate spatially explicit data; and it requires specialized methods to take the idiosyncracies of geographic patterns into account. The last decades have seen a notable rise in the development and use of tools and methods to analyse spatial data, and currently a wide range of tools and methods is available; for a recent overview of available methods I refer to Fischer and Getis (2010). A number of developments started in the second half of the 20th century have been instrumental to execute the analyses presented in this chapter: these are the advancement of Geographical Information Systems (GIS) and the development of spatial econometric and spatial interaction modelling methods. In the following paragraphs those developments will be introduced briefly.

4.1 Geographical Information Systems and spatial data

Although their intended use and users, application, architecture and functionality can differ substantially, GIS are essentially computer programs tasked with, amongst others, capturing, making, displaying, managing, editing and/or analysing spatial data. For a full review of what GIS entail and their path to development from the 1950s to now I refer to Longley et al. (2005). In the last decade GIS software has become increasingly specialised, with some applications specifically designed for exploration (for example 'Google Earth'), navigation (for example the many in-car navigation devices that are currently available on consumer markets), exploratory data analysis (for example OpenGeoda), and data modelling.

Nearly all of the data management and modelling for this dissertation has been executed in the Geo Data and Model Server (GeoDMS) software package (ObjectVision 2014), which is an open source platform specialized in the modelling of sizeable data sets. This software essentially provides a platform that interprets scripts into a transparent sequence of operations, and subsequently acts to execute these operations on dynamically defined C++ arrays. Just like geospatial semantic array programming tools such as the Mastrave library (de Rigo et al. 2013), GeoDMS adheres to large-scale modelling and assessment tasks. It has been under development since the inception of Land Use Scanner in the late 1990s (Hilferink & Rietveld 1999). The major advantages of using GeoDMS for the work presented in this dissertation are considerable gains in computation speed, reproducibility of modelling steps, flexibility and control over data operations, and straightforward links between various data types such raster and vector type spatial data. GeoDMS itself is arguably best known as the platform that supports land-use models such as Land-Use Scanner and EUClueScanner (Koomen, Hilferink,

et al. 2011; Lavalle, Baranzelli, Batista e Silva, et al. 2011; Hoymann 2010), but it has also been used to analyse opportunities to heat dwellings by means of renewable energy sources in the Netherlands (van den Wijngaart et al. 2012) and for local-scale social impact assessments (ObjectVision 2010). This dissertation's Chapter 4 proves it is also capable of bridging the gap between GIS and transport models, providing a fast environment for transport flow modelling and alternative transport link generation combined with common GIS functionalities. Building on the software's transport modelling capabilities, a GeoDMS-based model to simulate the expansion of transport networks is introduced in Chapter 5.

The increasing development and use of GIS is paired with an enormous growth of available spatial data (Kwan 2000). Technical and societal developments have been very important for this rising supply of data. One important technical development is the increasing use of satellites to capture land-related processes occurring on Earth. Such data offer structurally obtained and categorized descriptions of often large geographical extents on often reasonably low resolutions. Remotely sensed data, generated from satellite imagery, are used in this dissertation in Chapters 3 and 6. Another data source that recently has become available is crowd-sourced data where citizens are acting as sensors (Goodchild 2007). Such data come into existence when the public, either consciously or unconsciously, generates data on topics such as individual behaviour or the built environment. In one chapter of this dissertation, Chapter 6, a type of crowd-sourced data is used as a proxy for human activity patterns.

According to Koomen (2008), the use of GIS for data analysis has become a mainstay in geographic analysis literature since the 1990s, and this increased use of GIS in geographical analysis has blurred the previously clear distinction between the fields of GIS and geographical analysis. Also in this dissertation the data management capacities of GIS are used next to geographical analysis methods such as spatial interaction and land-use modelling. GIS offers many spatial data analysis methods. A number of those are particularly relevant for this dissertation, and often used without explicit mention. Those methods will be discussed below.

Spatial data aggregation

Spatial data aggregation is the task of generalizing fine-resolution spatial data to either areal units of a coarser resolution (Arbia 1989) or to a zero-dimensional statistic. Commonly, summing or averaging are applied to compute aggregated values. Spatial data aggregation can be useful for a number of purposes: 1) to

generate a set of variables with consistent areal representations; 2) to reduce the size of data for computation considerations; 3) to obscure individual data for the purpose of privacy-related concerns; and 4) to filter local patterns out of spatial patterns and thus generate more informative maps. Aggregation methods have been used in one form or another in Chapters 3 to 8 of this dissertation. With the use of spatial aggregation methods comes the hazard that choice of areal units biases statistical findings; this problem has been named the Modifiable Areal Unit Problem (Openshaw 1984). Chapter 3 is devoted to exploring practical consequences of areal unit aggregation when analysing spatial patterns of urbanization.

Data combination by location

Regular data management software allows data to be linked based on a shared attribute (the process of 'joining'). GIS enable the combination of various data sources by geographical relation; just as in regular joining, this can be done with various rules of cardinality between those sources. Thus, a spatial join can lever the data attributes of a set of points to data records observed in an areal unit that contains those points. It must be clear to the reader that methods of spatial joining vary between types of spatial data involved (i.e., continuous or discrete spatial representations), between shapes of spatial representations (i.e., lines, points or polygons) and between rules of spatial association that are applied (e.g., elements that are contained by an areal unit or elements that are within a certain range of a given point). Thus, the method of spatially joining data does change with various combinations of spatial representation between the data sources. Spatially joining data has been used as a method to generate a part of the data that are analysed in Chapters 2 to 8.

Network analysis

GIS offer analytical tools to obtain degrees of geographical separation when interaction is assumed to be restricted by a predefined network. Degrees of separation are often expressed in distance, travel time or generalized travel cost. A number of preparatory data-editing steps are usually necessary to make a set of lines, for example describing roads, ready for such an analysis. The connectivity of all lines to neighbouring lines will need to be encoded. Furthermore, the location of origin and destination locations relative to network links will have to be made known. Subsequently, algorithms such as Dijkstra's shortest path finding algorithm are employed to find shortest paths. Network analysis methods such as these are

commonly applied to observe more accurate measures of geographical separation when transport networks are likely used. In this dissertation, network analysis methods to find shortest paths over road or rail networks have been applied in all main chapters except Chapter 6, which analyses the relationships between local-scale urban land-use density mix and spatiotemporal urban activity patterns .

4.2 Spatial econometrics

Shortly after the advent of geographical research using quantitative methods, roughly in the second half of the 20th century, the realization came that geographical phenomena tend to cluster; a fact formalized in Tobler's first law of geography (Tobler 1970). This clustering tendency signals spatial autocorrelation; essentially the fact that observed values are more correlated when the geographic distance between the observations decreases. Spatial autocorrelation implies that observations in a spatial system to some degree depend on each other. That can be considered a source of additional information (Gould 1970), or as a problematic violation of the assumption that one observed value of a dependent variable does not depend on other observed values in the data, which is a necessary assumption for unbiased results from ordinary least squares (OLS) regressions. The existence of spatial autocorrelation requires that methods more elaborate than OLS are needed to analyse geographic patterns in an explanatory framework. After contributions from in particular Cliff and Ord (1981), so-called spatial econometric methods have been developed that deal with spatially auto-correlated data (Griffith 2000; Anselin 2001; Anselin 2003; LeSage 1997). In these methods the correlation between geographically proximate observations is captured as an additional estimated effect of spatially lagged dependent variables and/or as a spatially dependent error term that is separated from a white-noise error term. In this dissertation spatial econometric methods have been applied in Chapters 3, 6, 7 and 8.

4.3 Spatial interaction modelling

Interactions between geographical units, for example flows of money, commuters or goods, are for a long time at the forefront of geographical analysis methods. Spatial interaction models are the common tool to describe such interactions. Those models commonly assume a pool of generation at the origin of flows (e.g., population at the origin zone); a pool of attraction at the destination of flows (e.g., number of jobs at the destination zone); and a function of the degree of geographical separation as a force that decreases the level of flows commonly more than linear. An entropy-based theoretical explanation of spatial interaction

models is offered by Wilson (1967). Many applications of spatial interaction modelling have followed; important for this study are discussions on the statistical estimation of spatial interaction models (Fotheringham & O’Kelly 1989; Sen & Sööt 1981), Alonso’s general spatial interaction modelling theory that captures various formulations of spatial interaction models as special cases (Alonso 1978; De Vries et al. 2001), the link between spatial interaction models, potential accessibility and economic growth (Rietveld 1989) and the debate on how crossing national borders affects levels of spatial interaction (Anderson & Van Wincoop 2003; Feenstra 2003). The implications of reduced spatial interaction when crossing borders are investigated in Chapter 4; spatial interaction models have been empirically estimated for Chapter 4 and 5.

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Part II: Analysing relationships between interaction opportunities and spatial organization

Chapter 2. Developing local-scale potential accessibility measures

Abstract: *Measures of interaction opportunity such as potential accessibility measures should play an important role in land-use models. The fine spatial resolution of many land-use models currently makes it computationally infeasible to obtain separate potential accessibility results for each modelled unit. This chapter introduces a method to obtain potential accessibility results for the local scale. The introduced method uses asymmetric origins and destinations to overcome computational barriers, and spatial interpolation methods to infer the value of accessibility levels between origins. A short comparison of spatial interpolation results with zone-based results demonstrates that spatial interpolation is a more accurate method of spatial inference.*

Key words: Potential accessibility, spatial interpolation, land-use modelling.

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1 Introduction

From the work of Alonso (1964) follows that economic opportunities play an important role in location decisions and that such economic opportunities vary across space; due to differences in costs of access to the economic centre. We can expand Alonso's theory to take into account the complex spatial patterns of employment in modern polycentric urban landscapes, and state that *access to job-markets* is an important location factor for households. Let us expand Alonso's theory even further and state that not just job-market access, but *the opportunity to interact* is central in location decisions of economically driven actors, and thus, in economically motivated land use changes. In this light an indication of the amount of interaction opportunities ought to be central in explaining and predicting land-use change.

There is overwhelming empirical evidence for such a central role of interaction potential in location decisions. In his seminal work Hansen (1959) demonstrates that places with better access to jobs, people or shops are more likely to be developed into residential areas. Others underpin the importance of changes in accessibility levels as a factor in urbanization and population changes (Levinson 2008; Xie & Levinson 2010; Koopmans et al. 2012). Wegener and Fürst (1999) add that accessibility is an essential factor for retail, office and residential land uses. Recent evidence from the Netherlands confirms the role of accessibility in

urbanization processes. Priemus and Hoekstra (2009) have stressed the influence of interaction opportunities on location decisions of households and companies. Others highlight the role of easy access: proximity of transport-system entry points such as highway exits, train stations and airports (Atzema et al. 2009; De Graaff et al. 2007). Evidence that both interaction potential and infrastructure proximity are important for urbanization processes has recently been demonstrated for a number of cities (Borzacchiello et al. 2009; Borzacchiello et al. 2010).

All in all, there clearly is a use for measures of interaction opportunity to either study the drivers of urbanization or model urbanization at a very fine spatial resolution. Unfortunately, measures that accurately identify interaction opportunity need to be obtained from spatial interaction methods, and typically have an $n \times n$ algorithm complexity because they require the solving of a full origin-destination matrix, regardless of which measure of physical separation is applied. This leads to inherent computation limitations when downscaling interaction opportunity measures, as the number of observations n increases fourfold with each halving of areal unit size, thus leading to a 16 times larger origin-destination matrix each time the areal unit size is halved. It is clear that this is not feasible for modelling applications such as Land-Use Scanner (Hilferink & Rietveld 1999) or EUClueScanner (Lavalle et al. 2011), with n in the millions or even billions. Thus, heuristics are needed to compute measures of interaction opportunity at a very fine spatial resolution. This chapter discusses one such heuristic approach that centres on the spatial interpolation of a spatially asymmetric potential accessibility measure. It outlines the used potential accessibility measure and the method to downscale this measure to a fine resolution grid. In subsequent sections this accessibility measure is demonstrated in a case study for the Netherlands, together with a short comparison of the accuracy of spatially interpolating rather than applying accessibility levels per zone. The chapter finishes with some general conclusions of using this method for analysis and land-use modelling. The method introduced here is subsequently used in chapters 3 and 8 of this dissertation.

2 Methods

In this section, the used potential accessibility measure between a limited number of origins and destinations is discussed first. This is followed by a discussion of the spatial interpolation of accessibility values at the origin to a much finer spatial resolution.

2.1 Potential accessibility

Several accessibility measures have been described in publications (see for example Geurs & Van Wee 2004; Rietveld 1989). In this work I focus on measures that describe the spatial distribution of social and economic opportunities for specific land uses; i.e. how access to jobs, services or other people vary over space. Potential accessibility measures are adequate to indicate such spatial variance for the purpose of analyzing and modelling land-use change. Interaction opportunities are therefore calculated as potential accessibility measures as expressed in equation (1):

$$A(P)_{i,m,t} = \sum_{j=1}^n \frac{P_{j,t}}{f(c_{ij,m,t} + c_{jj,m})} \quad (1)$$

in which $A(P)_{i,m,t}$ is calculated for origins i at time t , given connectedness by transport mode m with all destinations j and opportunities P . This measure indicates the amount of opportunities P at destinations j that can be reached from i . The boundary between *can reach* and *cannot reach* is fuzzy: it is based on a distance decay function $f(c_{ij,m,t})$, which in turn is based on travel costs c between origin i and destination j at time t , given travel mode m . In the presented case these travel costs are derived as travel times from a shortest path algorithm that is applied on the database representation of a passenger car road network. Travel times or other travel costs are commonly computed to the geographic centres of destination zones. However, not all opportunities in a destination zone are situated at the same location and additional travel within the zone is needed to reach all destinations. Furthermore, the dispersion of opportunities throughout zones depends at least partially on the geographical size of zones. Thus, simply taking travel costs to a destination zone's geographic centre into account likely causes an underestimation of travel costs, in particular in larger zones. To take the dispersion of opportunities within zones into account an additional destination-specific travel cost penalty is added to each origin-destination pair. In the presented case this penalty is based on a common solution to obtain travel times from estimated intrazonal distances, as in Horner and Murray (2002) and is expressed in (2):

$$c_{jj,m} = \frac{\sqrt{\frac{A_j/\pi}{2}}}{s_m}, \quad (2)$$

in which the internal impedance $c_{jj,m,t}$ for zone j , with area A , for mode m is defined, given an estimated friction s_m . As a rough estimate of the average speed on local streets a constant intra-zonal travel speed (s_m) of 40 km/h is used. When comparing results with or without penalties, the addition of penalties seems to cancel out biases that may exist due to differences in zone size; but this finding needs more robust empirical validation (Stępniaak & Jacobs-Crisioni 2015).

The presented potential accessibility measure does not take into account that the opportunities at potential destinations might be non-replenishable, so that the actors that utilize these opportunities compete with each other. In multi-scale land-use modelling frameworks this non-competitive method is usually consistent with the land use modeling framework, because the effect of competition for opportunities on regional growth is already accounted for in the overarching models that provide regional land demands. In explanatory analyses of urban development, it can be expected that land-uses are more intense in areas with higher accessibility levels.

2.2 Downscaling method

Commonly, accessibility is computed for a set of areal units that represent both the origins and destinations in the measure. This is a convention, not a conceptual necessity: it is possible to compute accessibility levels for each point in space while taking into account each individual social or economic interaction opportunity as a destination. It can easily be verified that equation (1) should have the same result for one origin i regardless of the number of data points observed in j . Thus, in all cases the locations i in a potential accessibility measure represent sample points that are distributed over space for which interaction opportunities are computed; and j represent an available spatial database in which opportunities are observed. On a side note, measures of accessibility are usually not invariant to the level of aggregation in j , and computing A with opportunities P summed to different zoning systems in j may yield rather different results (Stępniaak & Rosik 2014; Stępniaak & Jacobs-Crisioni 2015). This is presumably because the centroids and implicit averaged transport costs to a zone are not an accurate representation of the underlying distribution of opportunities; however, tackling this is outside of the scope of this chapter.

Due to computational and data availability limitations, both i and j are usually observed at relatively coarse spatial resolutions (for example the roughly 4,000 areal units in the four-digit postcode system in the Netherlands), and subsequently

all geographic space that is part of one areal unit is assumed to have the same level of accessibility. However, when an analysis uses very fine resolution spatial data, for example 100 meter rasters, another method will have to be applied because imposing zonal levels on finer resolution areal units will cause inexplicable zone border effects and inaccuracies in the measure in particular at the edge of larger zones. Taking all individual grid cells as origins and destinations is at the time of writing computationally infeasible. Furthermore, very fine resolution data on the distribution of interaction opportunities is generally not available, although efforts to downscale demographic and economic data (see for example Batista e Silva et al. 2013) may yield fine-resolution data on opportunities at destinations in the foreseeable future.

To overcome the presumed inaccuracy of zonal representations of accessibility and limited data availability, I propose a method in which accessibility values are computed for a set of sampling points i with interaction opportunities observed in administrative units j . Those accessibility values are subsequently spatially interpolated using an Inverse Distance Weighting (IDW) method. To optimize the effectiveness of the spatial interpolation operation, the generated sampling points i are regularly distributed as the centroids of hexagonally shaped zones, thus ensuring that distances with neighbouring points are similar in horizontal, vertical and diagonal directions. Thus, the accessibility values that result from equation (1) are interpolated to a regularly latticed grid by solving equation (3):

$$A(P)_{g,m,t} = \frac{\sum_{i=1, d_{gi} < \max_d} \left(\frac{A(P)_{i,m,t}}{(d_{ig})^2} \right)}{\sum_{i=1, d_{gi} < \max_d} \left(\frac{1}{(d_{ig})^2} \right)} \quad (3)$$

in which the accessibility value $A(P)$ for grid cell g is based on the Euclidean distance d_{ig} between sampling point i and grid cell g . It is implausible that accessibility levels from farther away are more related to the accessibility of zone i than the accessibility levels of direct neighbours. Thus the parameter \max_d is invoked to control that values of A are only obtained from the closest neighbouring sample points. In the presented case the centroids of zone i are approximately 6,500 meters apart. The influence of i on g is calculated with $\max_d = 5,250$ meters.

3 Results

3.1 Accessibility measure

By way of example two versions of the accessibility measure are presented for the Netherlands. For this case, opportunities are taken as population (access to people in Figure 2-1) and employment (access to jobs in Figure 2-2) in a set of destinations j consisting of the Dutch four-digit postcode areas. In both cases only origins and destinations in the Netherlands are taken into account. The results of the accessibility calculations depend on the formulation of the distance decay function $f(c_{ij,m,t})$. This is a function that relates the likelihood of an interaction to a measure of spatial separation. For this case a log-logistic distance decay function is implemented, with a limited distance decay on short travel times followed by substantial distance decay at mid-range travel times. Using such a function reduces the systematic overestimation that exponential and power specifications risk with short distances. The implemented function is expressed in equation (4):

$$f(c_{ij,m,t}) = [1 + \exp(a + b \ln c_{ij,m,t})]^{-1} \quad (4)$$

in which the likelihood of an interaction $f(c_{ij,m,t})$ between locations i and j is based on travel cost c (given travel mode m at moment t) and opportunity and motive specific parameters a and b . In this case, exemplary social opportunity and employment opportunity indicators are presented. These are both estimated on the chance of an interaction occurring *from the home* by Hilbers (1993). For social opportunities their parameters for trips with social motives are applied, with $a = -5.336$ and $b = 2.426$. For employment opportunities their parameters for commuting are applied, with $a = -5.691$ and $b = 2.463$. As can be expected, both figures emphasize the abundance of opportunities in the most urbanized western part of the Netherlands (the 'Randstad'). The spatial interpolation yields reasonably fluently varying patterns of accessibility levels.

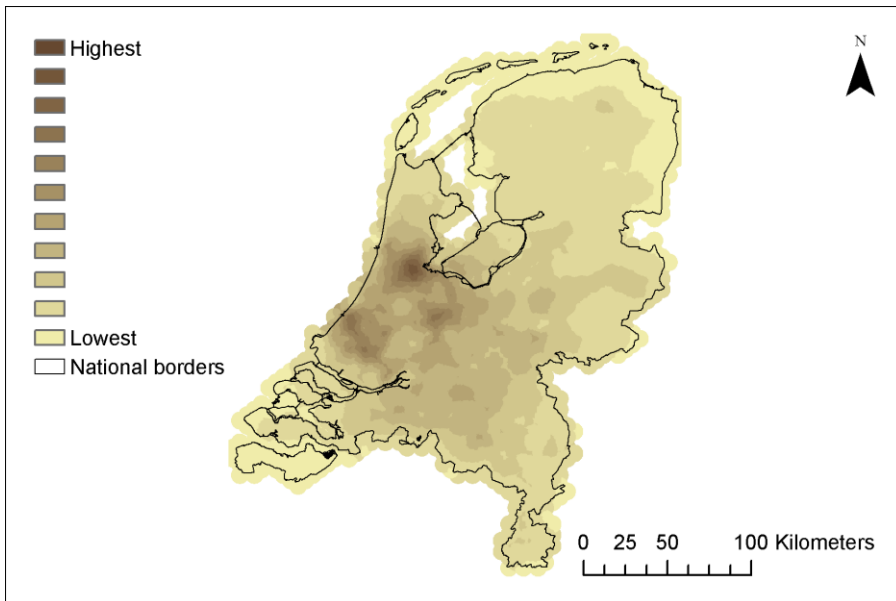


Fig. 2-1. Access to people in 2006 in the Netherlands as calculated with the presented method.

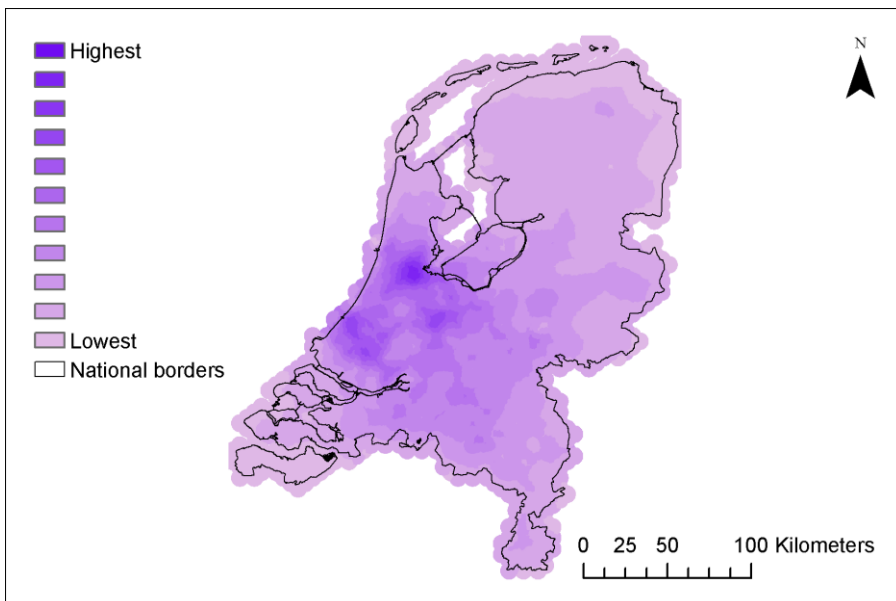


Fig. 2-2. Access to employment in 2006 in the Netherlands as calculated with the presented method.

3.2 Comparison of spatial inference methods

The spatial interpolation method shown in this study is assumed to yield more accurate approximations of accessibility at a particular point in space than zonal accessibility estimates. To verify this, the following hypotheses have been tested: 1) a larger degree of the variance in real accessibility (an estimate calculated for an exact location) can be explained with interpolated accessibility estimates; and 2) when comparing the performance of the interpolated and the zonal spatial inference methods, there is less systematic influence of the distance between the source of the accessibility estimate and the point of interest in the error component of the interpolated estimates.

To test these hypotheses 1,500 random sample points s have been generated. Subsequently, directly calculated accessibility values as well as accessibility levels derived from the interpolation and zone-based spatial inference methods (M) are attributed to these points. First, the direct level of accessibility (the 'real' accessibility levels $RealAccess_s$) has been computed for each of the points s . Subsequently, accessibility values $InferredAccess(M)_s$ as derived from the two spatial inference methods were assigned to the points s . The spatially interpolated values were directly derived from the accessibility maps in the previous section. The zonal inference values were derived from the hexagonally shaped zones from which the centroids i have been obtained. All accessibility values have been derived from the same network and the same spatial distribution of opportunities.

Errors for both zonal and interpolated inference methods have subsequently been calculated as expressed in equation (5):

$$\begin{aligned} & InferenceError(M)_s \\ &= \left(\sqrt{(InferredAccess(M)_s - RealAccess_s)^2} \right) / RealAccess_s \end{aligned} \quad (5)$$

The performance of inference methods is compared with a t-test. The deviation of values of $InferenceError(M)_s$ is tested (see Table 2-1). The conducted test shows that with 95% certainty the errors of the interpolation method are smaller than the errors of the zonal method. Conclusively, for the presented application the interpolation method (0.044 on average) is slightly more reliable than zone-based spatial inference (0.057).

To find if the interpolation method is systematically more reliable, more tests on the compared inference methods are necessary. Presumably, any method of

spatial inference is increasingly erroneous when the distance from the source of the inference increases. However, it can be expected that spatial interpolation performs better at larger distances from the sources of inference than a zonal inference method, and in particular at the edge of zones one may expect large inaccuracies with such a zonal inference method. To test these assumptions the performance of inference methods over distance is compared. To do so, Euclidean distances d_{is} between sample point s and the nearest source of inference i have been calculated and classified into 15 classes with equal amounts of observations.

Table 2-1. t-test results of spatial inference methods; test value = 0; n = 1500

Method	Mean error	Significance (2-tailed)	95% confidence interval (lower, upper bound)	
Interpolation method	0.044	0.000	0.042	0.046
Zonal method	0.057	0.000	0.054	0.059

Figure 2-3 presents the standard deviations of errors of the two inference methods at average distance values of the 15 classes of d_{is} . At increasing distances d_{is} no systematic under- or overestimation of accessibility occurs. However, as the trend lines in Figure 2-3 suggest, the errors of the estimations deviate more when d_{is} increases. With Pearson correlation coefficients of respectively 0.880 and 0.924, deviations in the errors of the interpolation and zonal inference methods are both highly correlated with distance to the source of inference. It can be concluded that indeed, regardless of the method of inference, the error of spatial inference increases when the distance to the source of inference increases.

However, the trend line that indicates the standard deviation of errors of the zonal inference method increases more when d_{is} increases than the trend line of the interpolation method. This suggests that the interpolation method is better at reducing systematic errors of spatial inference that are conjoined with distance to the source of inference. It can thus be concluded that, for the application at hand, the interpolation method is systematically more reliable than the zonal inference method.

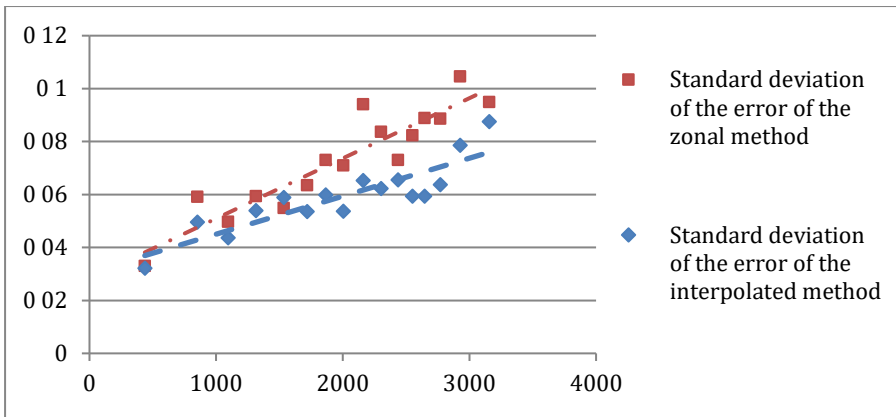


Fig. 2-3. Standard deviations of the errors in accessibility estimates by the distance between a random point and the nearest source of spatial inference. The classes are obtained by an equal-n classification method.

4 Conclusions

This chapter presents a method to compute potential accessibility at a very fine spatial resolution by means of spatial interpolation of accessibility levels between sample points. This is a necessary heuristics in cases where it is not possible to compute accessibility directly at the desired resolution because of technical or data limitations. Using this method enables the inclusion of potential accessibility measures in fine resolution spatial analyses and land-use modelling efforts. The interpolation method yields more accurate accessibility estimates than when imposing a zone's accessibility level to all space that is part of that zone; the zonal method is shown to be particularly less accurate away from the centroid of a zone, for which point accessibility levels are computed.

Some issues still pertain to the definition of accessibility measures. Some long-lasting questions considering the 'right' distance function will remain to be unanswered as long as the data needed to estimate a function for any application is unavailable. Some have endeavoured to find a satisfactory general solution (De Vries et al. 2009; Nijkamp & Pepping 1998); others apply their analyses with various distance decay functions to assess the sensitivity of their findings (Stępnia & Rosik 2013). However, I would like to make the case here that currently the chief problem with potential accessibility measures is the fact that, although accessibility measures should not depend on the shape or spatial resolution of the areal units in which opportunities are observed, they often do so. This problem may well be a

more general issue that also plagues MAUP issues in spatial interaction models (Batty & Sikdar 1982b; Batty & Sikdar 1982a). In this chapter a zone-size based penalty is taken into account in the presented method to overcome problems posed by variation in the size of those zones, but a rigorous analytical approach such as proposed by Sępniak and Jacobs-Crisioni (2015), will have to be adopted to solve these problems.

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Chapter 3. The impacts of spatial aggregation on urban development analyses

Abstract: *This paper illustrates the impacts of spatial data aggregation on the analysis of urban development. Spatial econometric methods are used to control for spatial autocorrelation in the data and existing weighting methods are used to overcome aggregation dependencies that are due to uneven portions of consumable land in observed areal units. The analyses show that shape dependencies can be partially removed by the used weighting methods, and that even regularly latticed areal units need such weighting in practice. Aggregating to coarser resolutions does not affect the order of magnitude of coefficients estimated for variables that are aggregated by averaging, if the aggregation process maintains sufficient variance within variables. We argue that small-sized areal units approximating the true characteristics of the studied process are to be preferred in urban development analyses, because such micro-data allows the exploration of highly local factors alongside higher scale linkages. We demonstrate that spatial autocorrelation and scale dependencies interact and that spatial econometric methods can ease the difficulties with the worryingly low levels of explained variance that are characteristic of analyses of small-grained land-use data.*

Key words: MAUP, spatial aggregation, spatial econometrics, urban development, land use.

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1 Introduction

Recent studies into the geographical determinants of urban land consumption and urban sprawl (Borzacchiello et al. 2010; Irwin & Bockstael 2002; Irwin et al. 2006; Loonen et al. 2009; Verburg, Ritsema van Eck, et al. 2004) or the reciprocities between urbanization and infrastructure development (Koopmans et al. 2012; Levinson 2008) rely on multivariate statistical analyses of fine grained spatial data. Such high resolution data bring the promise of more accurate results because the observed variables lie closer to the individual parcel level where individual choices affect the urban development process (Irwin et al. 2003). However, a number of studies have given rise to concerns related to relying solely on such data; the main concerns being that 1) urban growth, as any other type of land-use change, is a multi-scale process, with variables that can have unpredictably different impacts on different resolutions (Aguayo et al. 2007; Verburg & Chen 2000); furthermore, 2) urban growth and other land-use change models perform poorly in terms of

explained variance when using fine-grained spatial data (Irwin et al. 2006; Kok et al. 2001; Jantz & Goetz 2005; Aguayo et al. 2007); and 3) built-up land, as any other type of land use, often exhibits substantial positive spatial autocorrelation (Chakir & Parent 2009; Hsieh et al. 2000; Irwin & Bockstael 2002; Verburg, De Nijs, et al. 2004; Verburg, Ritsema van Eck, et al. 2004), of which the levels generally increase with finer resolution data (Arbia 1989; Hong Chou 1991; Overmars et al. 2003; Qi & Wu 1996). All in all, the results of urban development analysis results are tied to areal unit selection, and this emphasizes the importance of understanding the implications of using a particular set of areal units for the conclusions drawn from urban development analyses.

All concerns about the implications of areal unit selection come into existence when the spatial representation of variables differs from their true spatial characteristics; Gotway and Young (2002) describe these cases as change of support problems. One case of such problems has been named the Modifiable Areal Unit Problem or MAUP, which is first demonstrated by Gehlke and Biehl (1934), and named by Openshaw (1984). This problem describes the fact that statistical analysis outcomes depend on the areal units in which the analysed data are aggregated. The MAUP is commonly associated with irregularly sized areal units such as census tracts or postcode areas, but it is just as persistent in regularly latticed data, in which the arbitrary and modifiable aspects of unit delineation commonly follow from technical specifications (e.g. sensor resolution, satellite trajectory) instead of zone design principles. Outcomes depend on spatial aggregation through the scale (or resolution; a result of the minimum grain or size of units) and the shape (a result of decisions to amalgamate particular units in the aggregation process) of the applied spatial units. Many authors described the MAUP and methods to mitigate its impact, most notably: Robinson (1950), Openshaw (1984), Arbia (1989), Fotheringham and Wong (1991), Amrhein (1995) and Briant et al. (2010). From these studies no clear-cut solution arises for the MAUP. Concerning the impact on multivariate analyses, the severity of the MAUP is still debated: Fotheringham and Wong (1991; p. 1042) warn that this impact is “essentially unpredictable”. Amrhein (1995) and Briant et al. (2010) nuance this and demonstrate that model specification has a more crucial impact on the results of multivariate analyses. Briant et al. (2010) emphasize that shape dependencies are of little concern in their results and that scale dependencies can be mitigated when models are well-specified, are based on data aggregated by averaging, and incorporate higher scale variables (i.e. variables that have little heterogeneity within units). A number of questions particularly relevant to urban development

analyses have been left unanswered in the MAUP literature. First, the effect of areal unit selection on essentially multi-scale processes such as urban development is unclear. Scale dependencies are mitigated when higher scale linkages are included, but previous analyses using small-grained land-use data have nevertheless yielded unsatisfying results. In particular the explained variance of such analyses is disappointing, which is troublesome when researchers attempt to replicate or predict urban growth patterns. In contrast, it is unclear whether the lack of locally important explanatory factors does not distort results obtained from coarser resolution data.

The land-use change literature has not provided definitive answers to scale and shape dependencies in land-use patterns either (Obeysekera & Rutchev 1997). Notable suggestions to tackle scale dependencies are to explicitly model land-use changes as multi-scale processes (Kok et al. 2001; Verburg & Chen 2000) or to identify the scales on which particular variables affect land-use changes (Aguayo et al. 2007; Jantz & Goetz 2005). Unfortunately, those methods are all based on deduction from model results; an explanation of why particular variables affect land-use patterns on particular scales and why models perform poorly with fine resolution data is missing; furthermore, the methods to limit the impact of scale dependencies available in the MAUP literature have been left unexplored. Another problem is that built-up land uses usually exhibit spatial autocorrelation, of which the levels are also impacted by scale dependencies. Where scale dependencies are studied in the land-use change literature, spatial autocorrelation is usually controlled for by taking a sample of spatially spread observations; thus ignoring the causal impact that spatial autocorrelation may have on urban land-use patterns. It is however well-known that levels of spatial autocorrelation are tied to the impact of scale and shape dependencies (Arbia 1989), and this link deserves more attention. Lastly, shape dependencies are hardly mentioned in the land-use change literature, although those dependencies likely exist even in raster data.

Aims and study design

The overall aim of this article is to shed light on the influence of data aggregation on spatially-explicit urban development analyses, and to provide recommendations on choosing aggregation levels for such studies. With regard to scale dependencies, emphasis is put on the interplay between estimated impacts, spatial autocorrelation and explained variance. Further emphasis is put on weighting methods that are suggested in the MAUP literature to limit shape dependencies. We use fine resolution data of residential land-use shares in the Netherlands that,

for the purpose of this study, are averaged into various spatial data configurations with a fixed extent, but ever coarser resolutions. The impacts of this repeated aggregation are explored for basic (univariate) data properties and more extensive multivariate explanatory analyses. Statistical results in terms of averages, variances, levels of spatial autocorrelation, estimated coefficients and explained variance will be compared between spatial data configurations in order to assess scale and shape dependencies. The essential question to be answered here is whether those may affect qualitative conclusions drawn from the results of the computed statistics. Although our study focuses on one particular country we believe that many characteristics of the analysed urban patterns are representative for urban land-use patterns worldwide. These characteristics are the multi-scale nature of the factors that affect urban land-use patterns, the tie of urbanization with interaction opportunities that are explicitly modelled, and the ubiquitous presence of spatial autocorrelation in urban land use. We therefore assume that the results of this article are to some extent valid for urban development elsewhere, and possibly also for other processes with similar characteristics.

2 Methods and data

We aggregate all variables from a 100m raster into various areal units. Because variables aggregated by averaging are believed to be less susceptible to spatial aggregation dependencies (Arbia 1989; Briant et al. 2010) the dependent and some other variables are averaged. To explore particular aspects of the impacts of scale and shape dependencies we apply three methods: weighting to account for differences in observation unit size, econometric methods to address spatial autocorrelation and the inclusion of a multi-level set of explanatory variables. Those methods are discussed after we present the dependent variable and the target areal units in the next section.

2.1 Urban land-use data and areal units

We analyse residential land-use shares that are derived from discretely valued land-use data in the Netherlands in 2000 in a 25 meter resolution, provided by CBS (2002). Residential land shares are calculated as aggregate amount of residential land per *suitable* land area in an areal unit i so that $Y_i = RESIDENTIAL_i / SUITABLE_i$. All the surface captured by an areal unit is considered suitable for residential land uses, except water bodies and land covered by large transport infrastructure or mining operations. The latter categories are considered not suitable. The land-use shares are averaged in various spatial data

configurations; see Table 3-1. To resemble varying scales all data are aggregated to differently sized areal units, and to resemble varying shapes all data are regrouped into zone units (or zones) and three sets of regular lattices (or rasters). The selected zone units are administrative zones that are commonly applied in spatial analysis. The different sets of regular lattices only differ in their origins that (compared to the one original lattice) are moved north-westerly 25 and 50 percent of the cell width. The resolutions of these lattices resemble either resolutions (the 100m and 1km resolutions) that are common in land-use models (Agarwal et al. 2002; Pontius Jr. et al. 2008), or the average areas of used zone units (the coarser resolutions).

The aggregations performed in this study cause that the studied observations are no longer linked with individual processes that act on individual residential parcels. Those parcels are 820 m² on average in the Netherlands¹ (Kadaster & Netherlands 2008). This implies that even fine resolution data such as a 1 km raster can group more than 1,000 individual processes.

Table 3-1. Applied spatial data configurations. With raster units, ranges of N are given because N varies with origin choice.

Raster units	N	Zone units	N
100 m. ^a	3,438,279		
1 km. ^b	36,534 – 36,585		
2 km.	9,519 - 9,548	Neighbourhoods	11,473
4 km.	2,524 - 2,550	Urban districts	2,530
10 km.	465 – 474	Municipalities	484
20 km.	137 – 138		
30 km.	65 – 70	Corop+ regions	52

Note: All data configurations are examined in all analyses except: ^a not in multivariate analyses; ^b explanatory model is based on sample of 9,766 observations with smaller geographic extent

2.2 Methods

Weighting for area size

Weighting methods are used to overcome scale and in particular shape dependencies that exist because of unevenly sized areal units and consequential inequalities between areal units in aggregated number of cases (Arbia 1989).

¹ This includes the parcels of apartment blocks and rental corporations, which commonly have multiple dwellings on one parcel.

Weighting is based on the comparative amount of suitable land in an areal unit, which is $S_i = \text{SUITABLE}_i / \frac{1}{n} \sum_i \text{SUITABLE}_i$. Let X_i denote the value of a variable in areal unit i . Then, weighted averages are computed as $\overline{XS} = \sum_i S_i X_i / \sum_i S_i$ and standard deviations as $\sigma XS = \sqrt{\sum_i S_i (X_i - \overline{X})^2 / \sum_i S_i}$. Similar weighting methods have been introduced by Robinson (1950; 1956). Thomas and Anderson (1965) have shown that such weighting methods surely do not remove all impacts of spatial data aggregation. However, Arbia (1989) demonstrates that, in particular when data are aggregated by averaging, weighting schemes almost completely negate scale and shape dependencies in univariate properties such as means and variances, and reduce scale and shape dependencies in bivariate and multivariate statistical tests. To assess the usefulness of weighting in this study, we compare our results with unweighted alternatives.

We weigh both zone units and raster units for the amount of suitable land in the unit. In applications that do not focus on areal densities, weighting should presumably be based on aggregate number of cases; we argue that the selected area weighting method is more fitting for analyses that aim to explain areal density measures because, with such measures, every equal portion of land should serve as an equal case. Despite their even sizes, raster units are weighted because the edges of the study area are quite capricious, which causes differences in the average shares of relevant area covered by rasters. Larger raster units in particular can entail large portions of sea or exterior lands, which makes these units sensitive to shape dependencies.

Addressing spatial autocorrelation

When studying the impacts of spatial aggregation it is important to account for its relationship with spatial autocorrelation. According to Arbia (1989), spatial autocorrelation between individual entities is increasingly dampened when aggregating to coarser resolutions (see Figure 3-1 for a schematic representation). In the case of regularly latticed data, the share of individual entities on the fringe of areal units is expected to decline monotonically under aggregation - and levels of spatial autocorrelation with them. In the case of irregular areal units scale dependencies in spatial autocorrelation are less predictable, because those are less regular in numbers of neighbouring units and in the share of individual entities on the fringe. The potentially sizeable effect of the number of neighbouring units on the results of spatial autocorrelation tests has been demonstrated by Wall (2002).

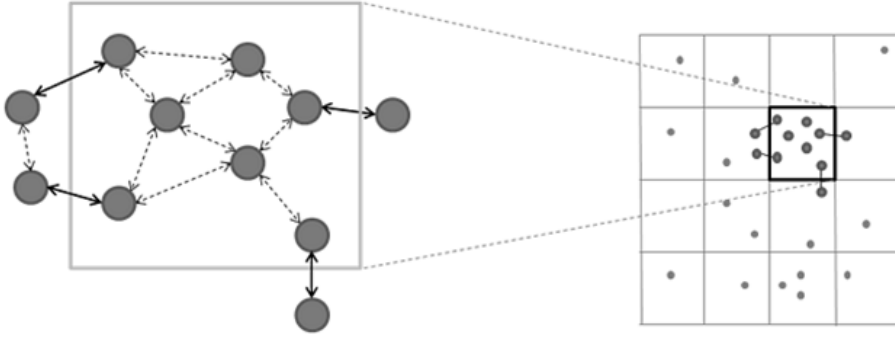


Fig. 3-1. Aggregation of positively spatially autocorrelated individual phenomena. Circles indicate spatial processes, arrows indicate spatial interdependencies between neighbouring processes, and gridlines indicate an aggregation scheme. The dashed arrows indicate interdependencies between individual processes that are unobservable after aggregation (based on Arbia, 1989).

To describe the spatial autocorrelation behaviour in our dependent variable in relation to spatial aggregation we apply Moran's I (1950). We weight Moran's I so that: 1) neighbours j with a larger suitable surface have more weight in defining the level of spatial association between an observation i and its neighbours j ; and 2) observations i with a larger suitable surface have more weight in defining the global measure of spatial autocorrelation. The weighted Moran's I (MIS) is computed as in equation (1).

$$MIS = \frac{n \sum_i S_i^2}{\sum_i \sum_j S_i S_j W_{ij}} \frac{\sum_i \sum_j S_i S_j W_{ij} (X_i - \bar{XS})(X_j - \bar{XS})}{\sum_i S_i^2 (X_i - \bar{XS})^2} \quad (1)$$

Where $W_{ij} = 1$ when i and j are neighbours, $W_{ij} = 0$, otherwise.

Multivariate explanatory analyses are employed to explore the influence of spatial aggregation on explanatory analyses. In order to explore possible interactions between spatially autocorrelation and regression results we employ spatial econometric methods; for an overview of such methods we refer to Anselin (2001), Anselin (2003) and LeSage and Fischer (2008). We compare the outcomes of an Ordinary Least Squares model (OLS) and a spatial error model (SEM). A SEM model is applied because Lagrange multipliers diagnostical tests such as documented in Anselin (2005) demonstrated that such a model is more suited for our particular

data than a spatial lag model². The models explaining the distribution of residential land use densities Y in spatial units i take the form of equations (2.1 – 2.2).

$$OLS: Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki} + \varepsilon_i \quad (2.1)$$

$$SEM: Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki} + \varepsilon_i; \quad (2.2)$$

$$\text{and in the SEM model } \varepsilon_i = \lambda W_{ij} \varepsilon_j + \mu$$

In the SEM model the error term ε of observation i consists of an independent and identically distributed (i.i.d.) disturbance term μ and the impact of spatially adjacent residuals in j . Following Anselin (2001), (2.2) can be rewritten to:

$$Y_i = \lambda W_{ij} Y_j + \beta_k X_{ki} - \lambda W_{ij} \beta_k X_{kj} + \mu. \quad (2.3)$$

We will use the latter form to compute predicted values Y after the model has been estimated, in order to uncover scale dependencies in SEM explained variances. We do so using a pseudo-R² measure based on the squared correlation between observed and predicted values. We are aware that caution has to be exercised when computing that indicator from spatial model results (Anselin & Lozano-Gracia 2008) and therefore refrain from direct comparisons between variances explained by the OLS and SEM models. To obtain weighted estimates in the OLS and SEM models, we apply an exogenous constant with values $S_i^{1/2}$ and multiply all exogenous inputs with the same values. This weighting method is thus equal to estimating by means of weighted least squares, in which $\sum S_i (Y_i - Y'_i)^2$ is minimized³.

In the SEM model, spatial autocorrelation is located in the error term that affects the outcomes of OLS estimations (Anselin 2001; p. 11). We interpret ε as the representation of unobserved variables that are subject to spatial dependence. The spatial dependency between error terms is defined by spatial weight matrix W_{ij} , which in this exercise is based on the queen's model of contiguity (Cliff & Ord 1981; p. 247). We limit this matrix to first order neighbours because, in reverence of Tobler's first law of geography (Tobler 1970; p. 236), we expect that the most proximate observations in Y_j correlate most with Y_i . The SEM models are

² Results of the diagnostical tests are available upon request.

³ Weighting was not an available option in the spatial econometrics module of the used software (STATA), and we therefore resort to these prior computations.

estimated in STATA 11.2, using the estimator developed by Kelejian and Prucha (2010) that controls for heteroskedasticity.

Including a multi-level set of explanatory variables

In our explanatory analysis we apply a set of spatially explicit independent variables, which aims to capture the most important driving forces acting at different scale levels. All variables are originally obtained in detailed 100 metre resolution rasters that allow aggregation to higher scale levels. Continuous variables are aggregated by averaging, dichotomous values by predominance. Table 3-2 lists the most important characteristics of the variables. It includes the standard deviations of the values of explanatory variables when aggregated into a coarser raster unit, which indicates the amount of local variance of that data. Variables with, relative to their average values, higher internal standard deviations have higher local variance, indicating that these variables represent phenomena with smaller individual geographic extents. The given internal standard deviations have been instrumental to characterise the expected scale of variable effects, which are given in the last column.

As indicators of ease of access we apply the natural logs of distances to nearest *railway stations* and *motorway exits*. Previous work demonstrates that the likelihood of built up land first increases and then decreases with distance to such transport system terminals (Borzacchiello et al. 2010), but such subtleties only hold on spatial resolutions finer than those applied in this study. More straightforward relations between the dependent and natural logs of distances are therefore imposed.

As an indicator of economic opportunity a potential accessibility indicator, *job access*, is applied. It can be interpreted as the number of jobs one can reach, with a *fuzzy* definition of what is *reachable* (Geurs et al. 2001). In a seminal paper potential accessibility is found to positively affect the intensity of urban development (Hansen 1959). Our measure is calculated with dissimilar origin and destination units and the results are subsequently spatially interpolated (for more information, see Jacobs 2011). The accessibility measure A is described in equation (3):

$$A_i = \sum_{j=1}^n \frac{P_j}{(C_{ij} + C_j)^2}, \quad (3)$$

where i consists of points that are regularly distributed with 8 km. intervals, P_j is the number of job opportunities in municipalities j . C_{ij} is the road travel time between municipalities j and locations i obtained from a complete road network dataset. C_j is a municipality specific additional travel cost to observe the intrazonal distribution of job opportunities. Ceteris paribus, the applied distance decay function (the inverse of squared traveltime) explained the most variance in residential land use shares when fitting it in the later presented regression analyses. For the sake of interpretation, the accessibility levels in this study have been rescaled in such a manner that the maximum accessibility is 1 in any spatial data configuration.

Table 3-2. Variable characteristics and characterization of their spatial scales in the scale char. column.

Variable	Computed as	Aggregated by	Min	Average	Max	Internal st. dev.	Scale char.
Station distance	log(km)	Averaging	-2.996	1.761	3.600	0.300	Meso
Motorway exit	log(km)	Averaging	-2.996	1.561	3.729	0.298	Meso
Job access	Eq. (3)	Averaging	0.028	0.320	1.000	0.003	Macro
Exterior proximity	0/1	predominance	0	0.207	1	0.006	Meso
Airport noise	0/1	predominance	0	0.013	1	0.004	Micro
Buffer zone	0/1	predominance	0	0.019	1	0.007	Micro
Green heart	0/1	predominance	0	0.066	1	0.003	Meso
New town	0/1	predominance	0	0.021	1	0.005	Meso

Note: presented statistics are for the 100m raster resolution. Internal standard deviation is computed as the standard deviation of values at the 100m resolution within 1000m zones, averaged in all 1000m zones.

Exterior proximity indicates whether areal units are predominantly within 10 kilometres of an overland national border and so proxies the barrier effect that national borders have on economic interaction (Cheshire & Magrini 2009; Rietveld 2001). We emphasize that proximity to the sea is not measured in this variable.

A number of spatial policy indicators are applied that, except airport noise contours, are all based on administrative units. The *airport noise contours* indicate if an observation is in an area where airport noise is present and urban development is restricted. The *buffer zone* and *green heart* policy variables indicate

whether areal units are predominantly in areas with severe restrictions on residential land-use development. The related policies have been considerably successful in the preservation of open space (Koomen et al. 2008). Lastly, the *new town* policy variable indicates if an areal unit is predominantly within municipalities that have been assigned residential development incentives by national planning authorities. These new town policies have positively affected Dutch urban development (Verburg, Ritsema van Eck, et al. 2004).

3 Results

This section starts by exploring how univariate properties of residential land-use shares are affected by spatial aggregation. Subsequently we discuss how spatial aggregation affects the results of multivariate explanatory analyses.

3.1 Data properties

Table 3-3 shows that the weighted average residential land use-shares (\overline{XS}) are unaffected by scale dependencies, as expected by Arbia (1989). Note that not-weighted averages from the same data (Table B.1) vary from 0.06 to 0.30, which underpins the usefulness of weighting here. The weighted standard deviations decrease monotonically under aggregation, showing that local variation is dampened by spatial aggregation. However, shape dependencies are apparent in that zone units have consistently higher weighted standard deviations than their equivalent raster scales. This indicates that these zone units have a higher internal homogeneity. Apparently, the underlying design principle of the used zonal units is to achieve relatively homogenous units (e.g., cities or towns), which causes an additional shape effect next to the influence of uneven sizes. This impact of the deliberate shaping of the zonal units is also apparent in the decidedly fatter tails of residential land-use share histograms for zone units; see Figure A.1.

The impact of spatial aggregation on Moran's I can be seen in Table 3-3 and Figure 3-2. Moran's I decreases monotonically under aggregation up to regional levels, but increases again at coarser resolutions. Such an increase of Moran's I contradicts Arbia's expectations (1989) and previous empirical results (Hong Chou 1991; Qi & Wu 1996) and is not easily explicable. For a better understanding we visualize clustering patterns with the local indicators of spatial associations (LISA) method (Anselin 1995). The results in Figure 3-3 demonstrate sporadic spatial associations at the municipality level, while at the coarser Corop+ level the main urban areas in the west and the peripheral northeast become identifiable as

related regions (in terms of habitation). This unexpected increase in spatial autocorrelation might be due to the specific regional urbanization patterns in the Netherlands. The western part of the country is characterised by a concentration of cities at relatively short distances from each other that upon aggregation reveal the relatively densely populated urban agglomeration known as the 'Randstad', while the northeast consists of fewer cities that upon aggregation become dominated by the relatively large low-density areas surrounding them.

Table 3-3. Properties of residential land-use shares aggregated to raster and zone data. For raster units ranges of results are produced because counts of units vary with origin choice.

Raster units (n)	Weighted avg (sd)	Weighted Moran's I	Zone units (n)	Weighted avg (sd)	Weighted Moran's I
100 m. (~3,5M)	0.07 (0.24)	0.82			
1 km. (~36,500)	0.07 (0.17)	0.45			
2 km. (~9,500)	0.07 (0.13)	0.38 to 0.39	Neighb. (11,467)	0.07 (0.18)	0.55
4 km. (~2,500)	0.07 (0.10)	0.36	Districts (2,529)	0.07 (0.12)	0.42
10 km. (~470)	0.07 (0.06)	0.37 to 0.41	Municip. (483)	0.07 (0.07)	0.35
20 km. (~140)	0.07 (0.05)	0.42 to 0.47			
30 km. (~70)	0.07 (0.04)	0.41 to 0.52	Corop+ reg. (52)	0.07 (0.05)	0.46

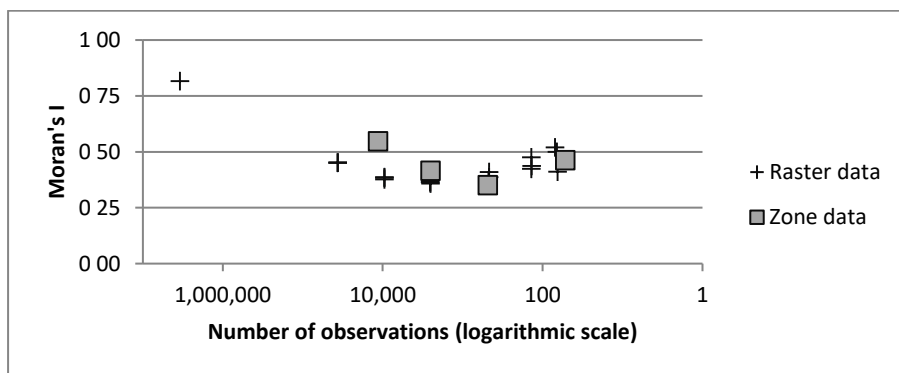


Fig. 3-2. Moran's I coefficient of residential land-use shares under aggregation.

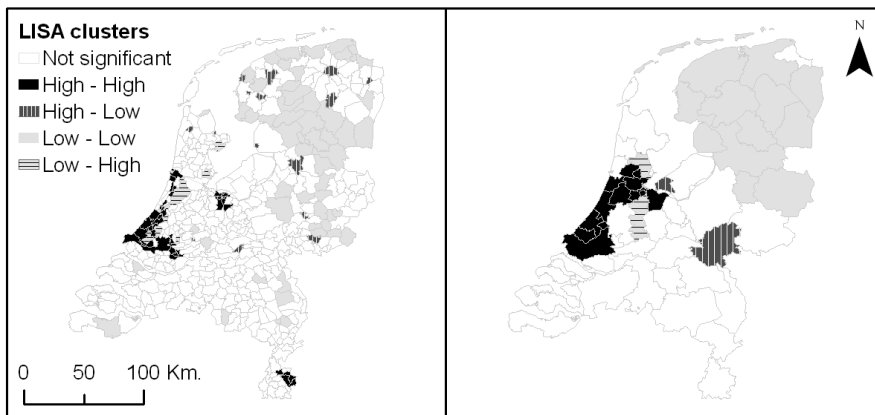


Fig. 3-3. Significant clustering of residential land-use shares in the Netherlands according to a LISA analysis at municipality (left) and Corop+ level (right).

Other notable results are that with fine resolution data, levels of Moran's I are higher in the case of zone units. We assume that here there is a coincidence between: 1) units with higher internal homogeneity, and 2) a higher density of areal units in urban areas, which causes that zonal inner-city units more often border units with similar values, and thus causes inflated levels of Moran's I. Lastly, we find that, with fewer observations, the values of Moran's I from rasters with differing origins deviate more. We interpret the effect of changing origins on values of Moran's I as the result of a chance effect of aggregation that has a higher uncertainty with smaller sample sizes.

3.2 Multivariate analyses

In this section scale and shape dependencies on multivariate analysis results are assessed. We first assess how areal unit choice impacts spatial autocorrelation in the error term and its consequences for model results. We subsequently assess impacts on estimated coefficients. To keep the computational tasks manageable the 100m scale is excluded and the 1km scale model is only fitted to a sample of the data.

Spatial aggregation impacts on spatial autocorrelation in the error term and on explained variances

Table 3-4 shows how spatial autocorrelation (expressed in the spatial lag coefficient λ) increases with increasing resolution. Figure 3-4 shows the same relationship

graphically. Just as is the case with levels of Moran's I this behaviour becomes unpredictable when relatively few observations are available. This shape effect is illustrated by the impact of applying three different origins per resolution.

Table 3-4. Explained variance and levels of spatial autocorrelation in model residuals (λ) estimated on residential land-use shares. For raster units, ranges of results are given because counts of units vary with origin choice.

Areal units (n)	R ² OLS	Pseudo-R ² SEM	λ
1 km. (9,766) ^a	0.32-0.33	0.98-0.99	0.786** - 0.795**
2 km. (9,548)	0.37-0.38	0.94	0.636** - 0.651**
4 km. (2,550)	0.52-0.53	0.91-0.93	0.590** - 0.629**
10 km. (465)	0.71-0.73	0.87-0.89	0.533** - 0.550**
20 km. (137)	0.82-0.84	0.82-0.97	0.458** - 0.741**
30 km. (65)	0.84-0.88	0.65-0.93	0.249** - 0.643**
Neighb. (11,467)	0.25	0.97	0.678**
Districts (2,529)	0.43	0.92	0.575**
Municip. (483)	0.69	0.66	0.382**
Corop+ reg. (52)	0.86	0.31	0.205

Notes: * significant at the 0.05 level. ** significant at the 0.01 level. ^a for the 1km. unit set a sample of the observations is taken.

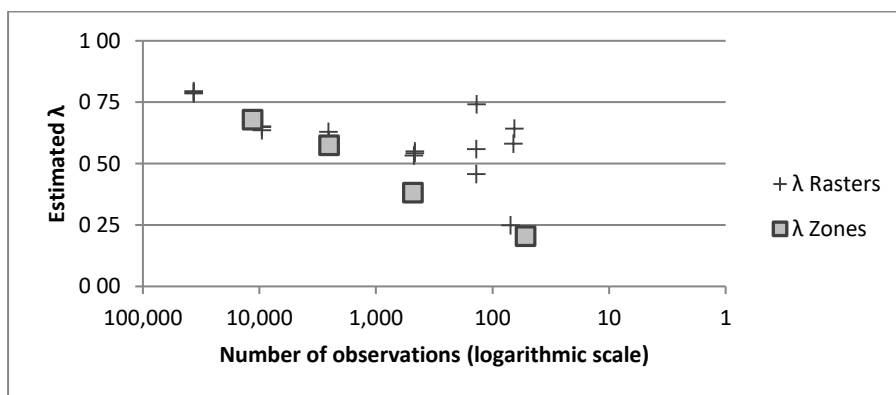


Fig. 3-4. Values of λ of the SEM model under aggregation. Raster results with similar counts are from rasters with different origins.

In most cases, scale dependencies cause lambda to increase with finer resolutions. In parallel with scale dependencies in lambda, explained variances of the OLS

models appear much more affected than those of the SEM models. These results hint at a trade-off between data resolution, the explanatory power of exogenous variables and the explanatory power of a spatial auto-correlative term. A line profile of job access and residential land-use shares on the neighbourhood and Corop+ levels (see Figure 3-5) illustrates this further. At the Corop+ level the averaged land-use shares are smoothed and gradually increasing when job access increases, but at the neighbourhood level this smoothed pattern is replaced by spikes.

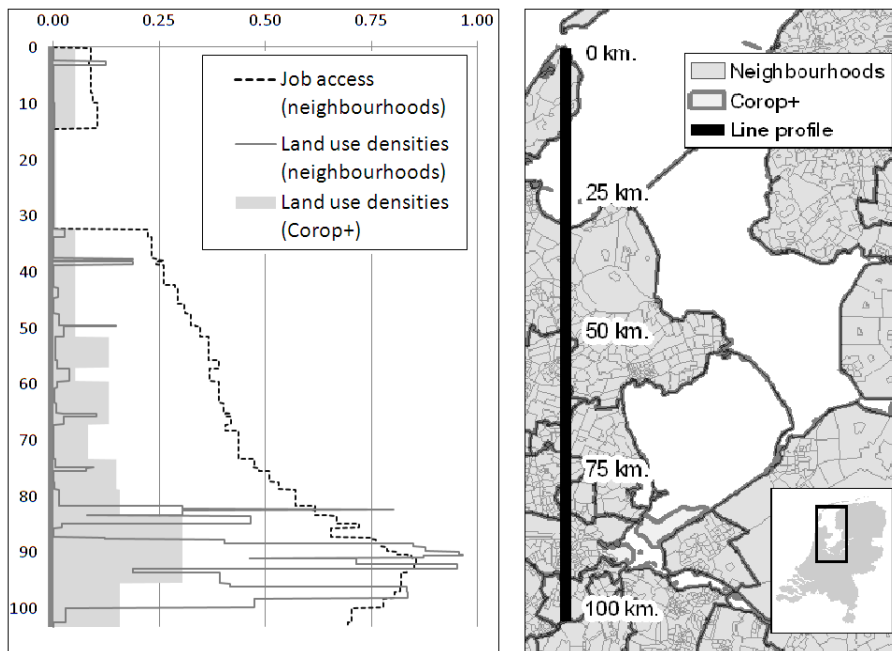


Fig. 3-5. Line profile of residential land-use densities and job access aggregated to neighbourhoods and Corop+ regions. In the chart (left) the Y axis indicates distance from the origin of the profile line, and the X axis indicates values of both residential land-use densities and job access. The map (right) indicates the position of the line profile in the Netherlands.

It is immediately clear that job access is far less associated with residential land-use share at the neighbourhood level. In contrast, we have seen that the impact of spatial autocorrelation in the error term is higher at the finer resolution of neighbourhood zones. To invoke the analogy of spectral densities (Curry 1966) the spiked pattern at low resolutions represents 'short wavelength processes' that are

filtered out by large areal units; where many variables in the analysis lack sufficient local variation, the spatial autocorrelation term picks up the 'short wavelength'.

Table 3-5. Unstandardized coefficients of the SEM models estimated on residential land-use shares. The last row expresses the correlation of the estimated coefficients with the number of observations.

	Const.	Station distance	M'way exit	Job access	Ext. Prox.
1 km.^a	0.124**	-0.128**	0.027**	0.314**	0.012
2 km.	0.179**	-0.093**	0.006	0.144**	0.011
4 km.	0.154**	-0.076**	0.000	0.152**	0.011
10 km.	0.069**	-0.043**	-0.002	0.209**	0.024**
20 km.	0.061*	-0.031**	0.000	0.151**	0.024*
30 km.	0.052	-0.025	0.005	0.113**	0.026*
Neighb.	0.082**	-0.062**	0.000	0.111**	0.007
Districts	0.133**	-0.063**	-0.006	0.122**	0.007
Muncp.	0.097**	-0.046**	-0.007	0.184**	0.018*
Corop+	0.114*	-0.046**	-0.007	0.126**	0.027*
Correl. with N	0.57	-0.88	0.58	0.43	-0.89
	Buff. zone	Green Heart	Airport noise	New town	
1 km.^a	-0.196**	-0.048**	-0.011	0.053*	
2 km.	-0.125**	-0.041**	-0.050**	0.061**	
4 km.	-0.075**	-0.045*	-0.049	0.053*	
10 km.	-0.015	-0.084**	-0.057	-0.012	
20 km.		-0.053**	0.044**		
30 km.		0.003			
Neighb.	-0.099**	-0.033**	-0.035*	0.031*	
Districts	-0.083**	-0.050**	0.004	0.025	
Muncp.	-0.074**	-0.056**	-0.018	0.079*	
Corop+	0.028	-0.041	-0.009	0.060*	
Correl. with N	-0.95	-0.14	-0.42	0.34	

Note 1: * significant at the 0.05 level. ** significant at the 0.01 level. Blank spaces indicate coefficients that could not be estimated due to insufficient variation of the variable. ^a for the 1km. unit set a sample of the observations is taken. The correlations are computed with the log of number of observations, with the 1km resolution set to 36,534 observations.

Note 2: because of space limitations, for each scale the results of only one set of rasters are presented. Varying origins generally does not affect the order of magnitude of estimated coefficients; results are available upon request.

The result of aggregating to larger units is that the data are smoothed into representing only the results of higher wavelength processes, with which the applied variables are more accurately associated. It is immediately clear that multivariate analyses in which spatial autocorrelation is modelled are more likely to mitigate scale dependencies such as the poor explained variance of OLS regressions at fine resolutions; essentially, the spatial autocorrelation factor serves as a proxy for otherwise unobserved variables at the local level.

Spatial aggregation impacts on estimated coefficients

Table 3-5 presents estimated constant terms and coefficients of the SEM model. To preserve space, OLS coefficients are not included⁴. Job access and distance to stations have the expected effects. Motorway exit proximity wavers between insignificant positive and negative effects. Its estimated effect apparently suffers from ambiguity: although the environs of highways are unattractive for housing, the ease of access provided by motorway exit proximity increases attraction. The effects of airport noise contours on residential land-use densities are mostly insignificant as well. Exterior proximity has a significant positive effect, presumably because other variables underestimate cross-border interaction opportunities that may impact Dutch cities close to borders. This analysis confirms that land-use policies have been successful (Verburg, Ritsema van Eck, et al. 2004); the restrictive green heart and buffer zone policies have significant negative, and new town incentives significant positive effects on residential land-use shares.

In the bottom row of Table 3-5, correlations between coefficient size and the natural log of number of observations demonstrate that estimation results for some variables (e.g. station distance, buffer zone policies) are strongly associated with resolution. Thus, with many variables, scale has a rather monotonous effect on coefficient size. Where coefficients vary unexpectedly, the absolute differences in coefficient size are relatively small. Changes in coefficient sign (possibly the most troublesome impacts of areal unit choice reported in the MAUP literature) are rare and occur mostly if estimated effects vary around zero (e.g. motorway exit proximity) or in the case of micro-scale variables, have almost insufficient variance due to the aggregation process (e.g. airport noise, new town and buffer zone policies). Shape dependencies still are visible in the results, but much larger in the not-weighted results (see Table B.2). One interesting result here is that the estimated impacts of spatial policies are decidedly larger when their effects are

⁴ OLS coefficients are available upon request.

estimated at the level in which those policies are formulated; compare for example the effect of municipalities that are appointed as new towns. Here the homogeneity of the policy effect within the areal unit is picked up by an estimator that is inflated when regarded as an effect on spatial rather than municipal distributions.

4 Conclusions

This paper demonstrates to what extent statistically analysing spatial urban patterns is impacted by the scales and shapes of aggregated areal units. To do so, residential land-use shares are averaged into regularly and irregularly shaped areal units of various sizes. In all our statistical computations, the observations are weighted to remove the biases that originate from variations in the amount of consumable land that the areal unit represents. *Scale dependencies* are subsequently quantified by comparing results from different resolutions and *shape dependencies* by comparing results obtained from zone units and raster units with varying origins.

4.1 Scale dependencies

Contrary to previous empirical results, we do not find that particular variables affect urban development only on particular scales. Coefficients from variables at the meso and macro levels, in particular those that are aggregated by averaging, are hardly affected by scale dependencies; while micro level variables that are aggregated on basis of predominance do suffer from such dependencies. On the one hand this confirms Arbia (1989), Amrhein (1995) and Briant et al. (2010) that aggregating by averaging is a sound strategy for limiting scale dependencies; on the other hand this demonstrates, perhaps trifle, that data in very coarse resolutions are not fit for assessing the impacts of factors that are important on the micro level. From our findings it follows that for multivariate analyses, resolutions the closest to the (usually fine-grained) true spatial characteristics of the studied process are to be preferred, because the data in such units are able to inform of linkages on the widest range of 'wavelengths'. There presumably is substantial residual spatial autocorrelation in such fine resolution data, and this makes spatial econometric methods particularly useful here. Our findings further suggest that such methods may solve the poor explained variance that is a common concern amongst analysts of fine resolution data. Notwithstanding the promising results obtained with fine resolution data, our findings are not drastically affected when derived from more sizeable areal units; thus, if the research question deals solely

with regional level variables, data on coarser resolutions can be used. One last noteworthy finding is that, contrasting Arbia's (1989) expectations, levels of spatial autocorrelation do not necessarily follow a monotone decrease when resolutions become coarser. In our view, this shows foremost that there is a stochastic element in the results of spatial data aggregation; there is a chance element in shape and scale dependencies, and its impact seems to increase with coarser resolutions.

4.2 Shape dependencies

Our findings concerning shape dependencies suggest that we need to discern two shape dependencies: a first shape effect exists because areal units vary in geographical size, or observed relevant area. Such varied sizes cause that equal amounts of space, and the entities that relate to that space, are not treated with equivalent weight in statistical tests (see Arbia, 1989). Weighting methods such as applied in this paper can greatly reduce this bias. The second shape effect exists because the delineations of irregular areal unit schemes (such as postcode areas or administrative units) may be related to the studied individual entities, which causes that such data may have a structurally higher internal homogeneity than their regularly latticed counterparts. In regular lattices, the event that the delineations of areal units separate homogenous entities is less probable, and regular lattices are therefore to be preferred as a basis for urban development analysis. We discovered a feature of rasters that nevertheless is unattractive and that did not yet receive systematic attention in the discussion of this issue. The choice of a reference point for a raster will strongly affect the outcome of the analysis. In the case of small spatial units this effect will be negligible, but as shown in Table 3-2 and Figure 3-2, it may affect outcomes of analyses to some extent when raster resolution is coarse. This holds true in particular in irregularly shaped study areas, since these irregular shapes will strongly affect the weight of spatial units near borders.

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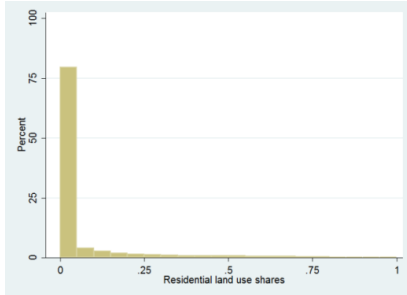
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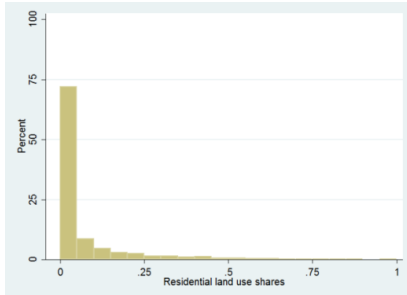
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Appendix A: distribution of residential land uses in areal units

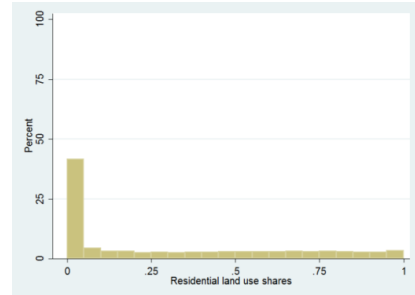
1x1km raster (9,766)



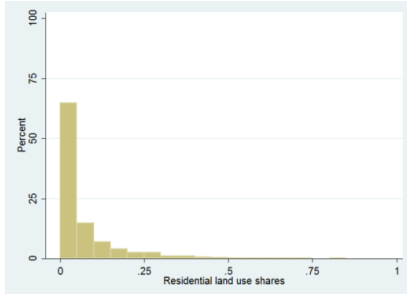
2x2km raster (9,548)



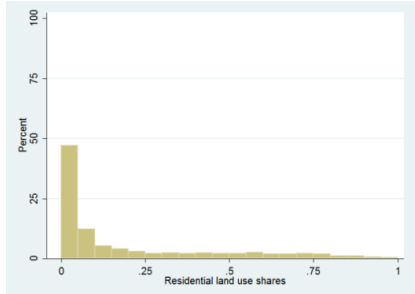
Neighbourhoods (11,467)



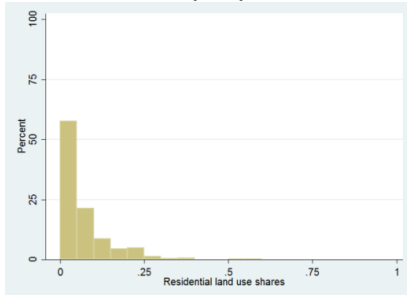
4x4km raster (2,550)



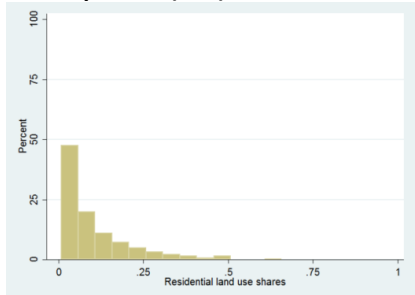
Districts (2,529)



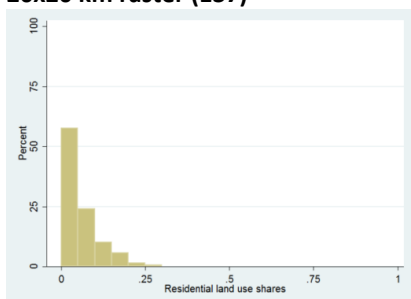
10x10 km raster (465)



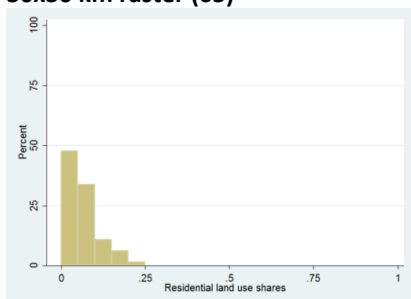
Municipalities (483)



20x20 km raster (137)



30x30 km raster (65)



Corop+ regions (52)

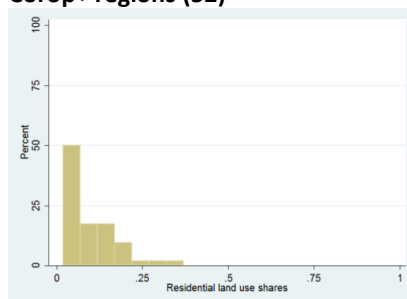


Fig. A.1. Distribution of residential land-use share values in the spatial data configurations used in the explanatory analysis.

Appendix B: results of statistics in paper when data are not weighted

Table B.1. Properties of unweighted residential land-use shares aggregated to raster and zone data. For raster units ranges of results are produced because counts of units vary with origin choice.

Raster	Mean (sd)	Moran's I	Zonal	Mean (sd)	Moran's I
100 m.	0.07 (0.24)	0.91			
1 km.	0.07 (0.16 to 0.17)	0.69			
2 km.	0.07 (0.13)	0.63 to 0.64	Neighb.	0.30 (0.33)	0.69
4 km.	0.06 (0.10)	0.60 to 0.62	Districts	0.20 (0.26)	0.71
10 km.	0.06 to 0.07 (0.07)	0.62 to 0.63	Muncp.	0.10 (0.10)	0.49
20 km.	0.06 to 0.07 (0.05 to 0.08)	0.42 to 0.68			
30 km.	0.06 (0.05 to 0.06)	0.40 to 0.61	Corop+	0.10 (0.07)	0.60

Table B.2. Unstandardized coefficients of the unweighted SEM models estimated on residential land-use shares. The last row expresses the correlation of the estimated coefficients with the number of observations.

	Const.	Station distance	M'way exit	Job access	Ext. Prox.
1 km. ^a	0.131**	-0.132**	0.030**	0.257**	0.013
2 km.	0.184**	-0.095**	0.007	0.133**	0.009
4 km.	0.157**	-0.077**	0.002	0.144**	0.012
10 km.	0.080**	-0.042**	0.000	0.180**	0.023**
20 km.	-0.070	-0.014	0.039*	0.241*	0.021
30 km.	0.030	-0.028*	0.018	0.121**	0.029
Neighb.	0.414**	-0.126**	0.012	0.300**	0.006
Districts	0.313**	-0.155**	0.019	0.282**	0.029
Muncp.	0.137**	-0.064**	-0.006	0.207**	0.011
Corop+	0.132**	-0.062**	-0.006	0.158**	0.037*
Correl. with N	0.61	-0.80	0.18	0.44	-0.72
	Buff. zone	Green Heart	Airport noise	New town	
1 km. ^a	-0.188**	-0.028	-0.007	0.037	
2 km.	-0.116**	-0.034*	-0.051**	0.057**	
4 km.	-0.069**	-0.043*	-0.057	0.052*	
10 km.	-0.019	-0.075**	-0.053	0.010	
20 km.		-0.076**	0.049		
30 km.		0.007			
Neighb.	-0.296**	-0.068**	-0.048	0.038	
Districts	-0.175**	-0.093**	-0.013	0.129**	
Muncp.	-0.089**	-0.047*	-0.025	0.136**	
Corop+	0.012	-0.040	-0.030	0.054	
Correl. with N	-0.84	-0.12	-0.37	0.21	

Note 1: * significant at the 0.05 level. ** significant at the 0.01 level. Blank spaces indicate coefficients that could not be estimated due to insufficient variation of the variable. ^a for the 1km. unit set a sample of the observations is taken. The correlations are computed with the log of number of observations, with the 1km resolution set to 36,534 observations.

Note 2: because of space limitations, for each scale the results of only one set of rasters are presented. Varying origins generally does not affect the order of magnitude of estimated coefficients; results are available upon request.

Part III: Understanding overland transport network expansion

Chapter 4. Railway network evolution in a mixed private and public playing field

Abstract: *This chapter analyses the formation of the Dutch railway network by econometrically assessing individual construction choices of railway investors. This network is of particular interest because of strong competition between private and public investors. Our results demonstrate that economic considerations were key in the decisions of all investors. We further find that strong competition between investors resulted in a higher density network, compared with the situation without competitors. Further, our analysis demonstrates that a similar network structure would have emerged with less active involvement by the Dutch state.*

Key words: Network evolution, transport investment, diffusion, railways.

1 Introduction

The development of railways, and their capacity to shrink and ‘shrive’⁵ the surface of our world, has in part determined the spatial distribution of economic growth and urbanization (Fogel 1964; Krugman 1996; Vickerman et al. 1999; Voigt 1973). Recent contributions particularly emphasize the reciprocity between railway network development and urbanization (Koopmans et al. 2012; Levinson 2008; Xie & Levinson 2010). But, if railway networks are indeed linked to the spatial patterns of urbanization, why did those networks assume their particular forms, and what influence did market conditions and state involvement have on their final shape? The evolution of railway networks is often seen as a technology diffusion process, consisting of birth, growth, maturity, and decline stages (Grübler 1990; Levinson 2005; Nakicenovic 1995). The pace of railway network development is related to market conditions and state involvement. The degree of competition in an oligopoly has been found to speed up railway network expansion (Knick Harley 1982). Antitrust policies reduced the vitality of competitors, and increased the number of failures (Dobbin & Dowd 1997). Empirical evidence further suggests that the nationalization of railway networks has decreased the pace of network expansion (Bogart 2009).

⁵ As Waldo Tobler once characterized the increasing spatial disparities in transport and communication costs (Miller, 2004).

The aforementioned macroscopic approaches do not explain what factors contribute to the individual, self-organizing link construction choices that shape a network. Considerable attention has been dedicated to network formation in air transport (Burghouwt & Hakfoort 2001; Huber 2009), but many airline strategies are not available to railway investors because of the fixed nature of railway investments. Taaffe et al. (1963) argue that railway network expansion is influenced by many economic, social and political forces. Rietveld and Bruinsma (1998) confirm that railway link formation is to some degree driven by return on investment considerations. Xie and Levinson (2008) show that, in the declining stage of an overland transport technology, the links that are the least profitable are removed first.

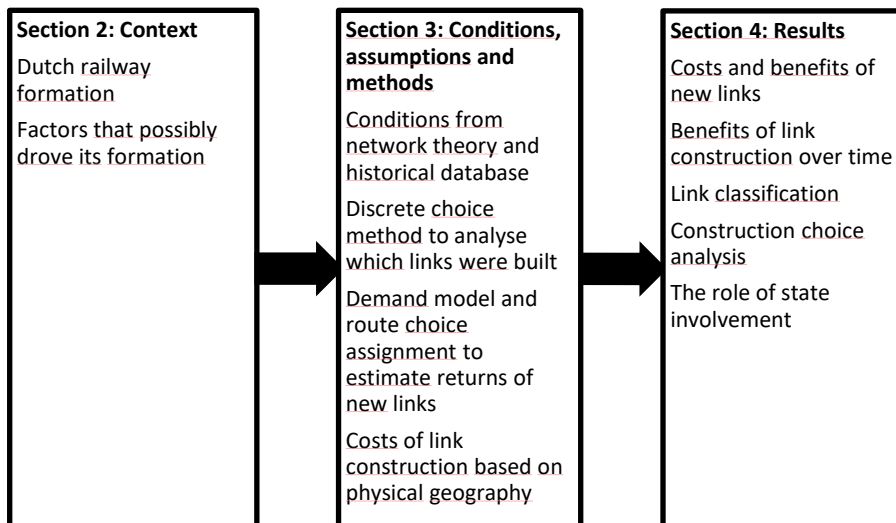


Fig. 4-1. Structure of this paper

In the remainder of this paper we econometrically assess the factors that drove investors to build links in the Dutch railway network between 1839 and 1929. This case is of particular interest because it was subject to strong competition between private and public investors. The course of Dutch railway network development is outlined in Section 2. Section 3 is devoted to the model and data, the applied discrete choice analysis methods and choice sets, and the various methods to estimate returns and costs. Finally, the results of assessing line construction

choices are presented in Section 4 from which conclusions are drawn in Section 5. Figure 4-1 summarizes the structure of this paper.

2 The formation of railway networks in the Netherlands

The first railway in the Netherlands opened in 1839 (Veenendaal 2008). It was operated by the 'Holland Iron Railway Company' (HSM), and linked Amsterdam to Haarlem. It was soon extended towards Rotterdam. Subsequently, competing companies built their own lines in the Netherlands. The Dutch government began participating actively by defining state lines in the Railway Acts of 1860 and 1875. Such public interventions in private railway network formation occurred in many countries: examples are the United States (Fogel 1964) and Canada (Carlos & Lewis 1992). In the Netherlands, most state lines were run by the 'State Railways' (SR), a private company that leased lines owned by the state. In 1878 a third Act followed that allowed for the cheaper construction of railways, if operated with slow light trains. This incited the construction of 'local tracks', which often connected rural areas (Veenendaal 2008).

In the Netherlands, policy makers shaped network formation with strict pro-competition policies, in which the state itself acted as a matter-of-fact competitor (Veenendaal 1995). Many operators struggled for survival, and by 1879, the number of private operators gradually began to decline. In 1890 the infrastructure of the third largest railway company, the 'National Rhenish Railways' (NRS), was nationalized. Dutch policy makers, however, remained vigorously pro-competition, and even went as far as to ensure that the existing infrastructure was divided in such a way that the two remaining large railway companies (HSM and SR) both served all bigger cities (Fremdling 2000). In 1917, decreasing revenues forced HSM and SR to cooperate within an institutional framework, in which Dutch policies regarding railroad operations shifted from pro-competition to pro-cartel. Finally, in 1936 all railway infrastructure was nationalized, and operations were continued by the state.

The length of the Dutch railway network increased in line with technology diffusion processes (see Figure 4-2). It finally materialized as a patchy system that at its peak was 3,278 kilometres long and, with 81 metres of railway per km² of land, currently has the seventh highest network density in the EU (UIC, 2010). We apply the network diameter (the longest network distance between two stations within the Netherlands) to indicate the geographic extent of the Dutch railway network

(Rodrigue et al. 2006), and find that it reached its maximum extent by 1880, after which a slight decline indicates increasing efficiency because of smaller detours.

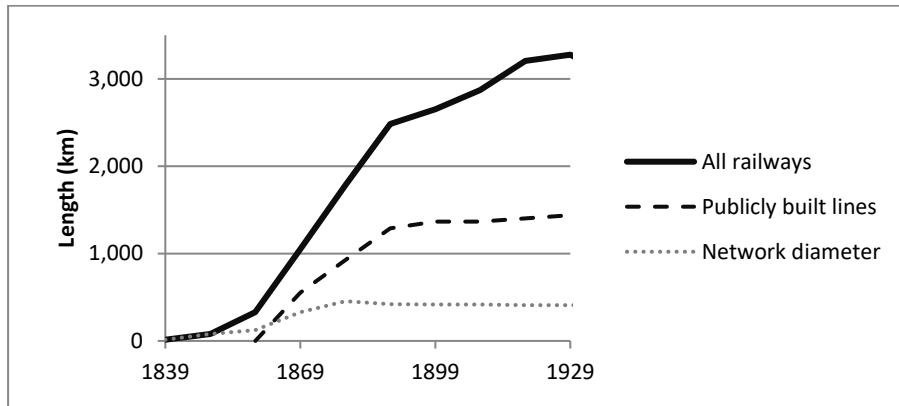


Fig. 4-2. Length of railway lines and network diameter in kilometres.

Over the years many economic factors have influenced the development of the Dutch railway network (see Table 4-1). Because inland water transport provided the Dutch freight sector a cheap substitute for rail, passenger transport was a particularly important service for Dutch railway operators (Filarski & Mom 2008, p. 380). Furthermore, railways have been considered to possess unifying qualities (Veenendaal 2008), which were presumably sought after by the Dutch administration in the 19th century. After all, although the ‘United Provinces’ created in the 17th century had become a centrally-led monarchy by 1806, the country was only starting to form a cultural and political union when the railways began to develop (Kossmann 1986).

Table 4-1. Demand and cost factors in the formation of the Dutch railway network

Demand	Costs
Connecting seaports with industrial hinterlands	Spanning waterbodies
Connecting large cities with each other	Traversing weak soil types
International passenger and mail transport	
Commuting	

Source: Rietveld and Bruinsma (1998), Veenendaal (2008)

3 Conditions, assumptions and methods

Economides (1996) outlines several economic aspects of networks that are important conditions for understanding network formation. They are: the role of (to some degree) individually-operating investors; the notion that link construction serves a strategic purpose for decision makers; the necessity for complementarity *between*, and compatibility *of*, network components; and, finally, the existence of positive network externalities. Furthermore, Bala and Goyal (2000) show that any combination of decision-maker strategies, costs, and pay-offs can lead to a stable state of the network. We assume that Dutch railway networks were formed by profit-maximizing decision makers who individually incurred the costs of building links; a condition that is characteristic of non-cooperative network formation (Bala & Goyal 2000). We find the necessary complementarity of nodes in the spatial distribution of economic activity. De facto technical compatibility of the Dutch railway network was achieved when HSM adopted a standard rail gauge in 1864 (Filarski & Mom 2008).

Given the aforementioned conditions of Dutch railway network formation, we assume the following. Link construction is *incremental*. The potentially-connected nodes are municipalities, which vary in some relevant attributes. These nodes are already part of a road- and water-based, pedestrian-oriented transport network. Transport demand depends on generalized travel costs (proxied by travel time). Railway links reduce generalized travel cost, although there is a cost of building them. Investors make informed decisions. These investors benefit from link construction through flows over their network, and maximize the return on investment in links, which is computed as the ratio of marginal costs and returns. Costs are estimated as the relative costs associated with different soil types and spanning rivers. Returns are proxied by passenger mileage on the investor's network after the addition of an alternative, minus passenger mileage on that network at the start of the decade in which the link is built. Note that, both in the reference situation *and* after an addition, returns are computed with the same population sizes. To compute returns, passenger transport demand is estimated by a spatial interaction model, and subsequently assigned over multiple paths. We compare a demand model in which total demand is elastic to travel cost with a model in which changing travel cost only causes substitution of destinations.

Based on Veenendaal (2008) and Stationsweb (2009) the historical railway network development in the Netherlands was reconstructed in a GIS database, which additionally contains population counts from 1830 to 1930 in 1,076 municipalities.

The data, furthermore, builds on the same assumptions as in Koopmans et al. (2012), of which we now list the most important ones. A constant travelling speed of 30 kilometres per hour has been attributed to all rail lines. This is assumed to include waiting and transfer times at stations. Decreases in general travel cost by improved timetable integration or technological innovation are not modelled. Apart from transport over rail, the network allows for transport over road and water. We simulate road and water connections by drawing “as the crow flies” lines from every node to its ten nearest nodes. We consider roads and waterways to be regional substitutes, and treat them as one simplified network. We assume that this network has an average speed of 6 kilometres per hour. Consequently, railways are assumed to be five times cheaper (in terms of generalized costs) than other available transport modes. To assess the impact of this assumption, we additionally carry out a sensitivity analysis based on other assumptions about generalized costs.

3.1 Choice analysis method and choice sets

Sets of investor choices are assessed as distinct additions to the network built in a particular decade between 1839 and 1930. We apply a conditional logit model (McFadden 1974) to quantify, for each distinct addition to the railway network, the influence of the return on investment and other attributes on the decision to construct that specific addition rather than any plausible alternative. The model treats distinct choices O as separate trials, in which an observed addition to the railway network is chosen from a set B with alternatives. B contains a finite number of alternatives L with index $l = 1, \dots, L$, and known attributes. This choice set is composed of 25 randomly-generated additions, and one line from the set of observed additions. Then the probability that alternative o is realized equals:

$$P_o(v_o | B) = \frac{e^{V_o}}{\sum_{l=0}^L e^{V_l}}, \quad (1)$$

which is repeated for each choice situation. A range of alternative-specific attributes is observed in V_l so that:

$$V_l = \beta_{0pt} OPROI_l + \beta_{1p} SEAHARBOUR_l + \beta_{2p} PROV CAP_l + \beta_{3p} MINING_l + \beta_{4p} BORDERZONE_l + \varepsilon, \quad (2)$$

in which $OPROI$ is the rate of return on investment, proxied by the ratio of the increase in passenger mileage *on the operator network* and construction costs of

the link⁶. To test to what extent investors have decided cooperatively, we alternatively estimate β_{opt} with TROI, which is similar to OPROI but has increased mileage *on the whole network* as the numerator. We furthermore apply factors which affect the rate of return on investment but are not covered in the ROI indicators which just focus on returns based on passenger flows. Thus, SEAHARBOUR indicates whether a line connects to a port city, and MINING indicates whether a line connects mining areas. BORDERZONE indicates whether a line connects a municipality that borders a neighbouring country, thus reflecting possible international hauls not incorporated in the return on investment rates. Finally, PROVCAP indicates whether a line is directly connected with a provincial capital, which we assume proxies political ambitions to unify the country.

The Dutch government has intervened in network formation by constructing state lines (enacted in the 1860 and 1875 Railway Acts) and by relaxing technical requirements (in the 1878 'Local Line' Act). Because this public intervention can greatly influence the considerations to build lines, we separate the influence of all factors under different public regimes p into: private regular lines, private local lines, and state lines. Because potential returns vary per stage of network formation (Levinson 2005), we additionally separate the influence of rate of return on investment into three periods t that start in 1839, 1859 (in conjunction with the first Railway Act), and 1889 (in conjunction with the nationalization of NRS). Lastly, the length of built links varies substantially (see Table 4-2). We assume that the results of the applied models are more accurate in the case of longer links, and therefore weight the results of equation (1) by the length of built link o , normalized by the average of all o 's in period t so that the total number of observations in the choice model is not affected.

3.1.1 Definition of built links

The built links in the choice set are derived from the database of constructed railway links. This is not trivial since one might split up a railway link between two points into an arbitrary number of link segments, and consider these link segments as the unit of observation. Here, we have used the following notion to determine a fruitful definition of a link: a link has been realized by an investor as one integrated project within a limited number of years. As a way to operationalize this we followed Veenendaal (2008) who identifies individual construction projects based on one of the following three criteria: 1) distinct grants from the state to railway

⁶ If we assume that the marginal revenues and variable costs of operations are proportional to passenger mileage, OPROI is proportional to the return on investment.

investors; or 2) as distinct construction projects of railway companies; or 3) as distinctly planned routes specified in any of the Dutch Railway Acts.

Table 4-2. Average length of built links per period in kilometres

Period	Average	St.dev	5 th perc	95 th perc
1839 - 1859 (o = 6)	54.97	34.15	13.88	113.23
1860 – 1889 (o = 34)	59.86	48.12	4.70	169.38
1890 – 1929 (o = 24)	31.71	29.39	6.88	78.50

3.1.2 Random alternatives

Our approach implies that we compare built links with links that have not been built. The number of links that might have been built is, of course, very large. For example, given a country with more than 1,000 municipalities, over a million alternative links are possible, linking municipality pairs. However, computational limitations oblige us to work with smaller choice sets. This is justified on the basis of the property of the multinomial logit model demonstrated by McFadden (1978) that a random draw of a limited number of non-chosen alternatives leads to unbiased estimates, while keeping the estimation manageable⁷. We therefore resort to picking random samples, which are drawn for each modelled decade.

Our aim is to develop a procedure to generate a set of non-built links that might serve as meaningful alternatives in order to understand the criteria on which lines were built. Simply connecting two random nodes without detours leads to the odd situation that the line does not serve municipalities that it passes. Therefore, we generate random combinations of begin and end points of links (under certain conditions⁸), but detour to additional nodes to simulate links that have stops serving municipalities on the way. We follow Morrill's (1970, p. 115) expectation

⁷ An assumption underlying this approach in the context of the multinomial logit models is that the independence of irrelevant alternatives may be applied. There have been some recent developments to develop specific sampling strategies that may overcome this assumption (see, for example, Guevara and Ben-Akiva (2013)), but it is beyond the scope of the present paper to try and apply such methods, in particular since the generation of meaningful unbuilt links is not trivial, as can be seen in the rest of the paper.

⁸ To simulate capital availability, the distance between these nodes can be as long as the maximum length of the lines built in that decade; furthermore, one of the terminating nodes has to be connected to the built railway network by the end of the modelled decade. The model has also been run without the latter condition, which produced very similar results.

that optimal routes “depart from the straight line” when a detour results in a more profitable balance between benefits and costs, and heuristically determine such routes constrained by an (admittedly arbitrary) maximum detour factor of 1.2. From a set of graphs in which all i ’s and j ’s are directly linked we maximize the total benefit-cost ratio of a path between terminating nodes a and b . We do this by finding a least-cost path over the graphs with, as the costs of traversing a graph, the inverse benefit cost rates $BCR_{ijt} = c_{ij} / (P_{it} + P_{jt})^k$. In these rates, P signify population counts. Construction costs are c , the source of which is elaborated upon in a later section. The factor k is iteratively decreased from 4 to 0 until the length of the resulting least-cost path is maximally 1.2 times the length of the direct link a-b.

The built links connect to stations that are usually not in the centre of municipalities⁹. To approximate that off-centredness of the stations of built lines, the nodes of random links are moved a set distance (in a random direction) from the centroids of connected municipalities by means of a convenient intrazonal distance approximation (Koopmans et al. 2012). The set distance d_i is derived from the surface area S_i of a municipality:

$$d_i = \frac{\sqrt{S_i/\pi}}{2}. \quad (3)$$

3.2 Returns of link construction

In order to compute returns to investments we will first estimate a simple demand model. For each decennial reference network, and for each tested addition to that network, demand for passenger transport is calculated by means of a model based on Alonso’s (1978) general theory of movement (GTM). The resulting flows are assigned to the network by means of a route choice model, and subsequently used as the returns of line construction.

3.2.1 Demand model

Demand is calculated by means of a spatial interaction model that is based on, amongst other things, the assumptions that: 1) increasing interaction opportunities cause growth in the propensity of people to travel; and 2) no restrictions can be imposed on the number of trips into zones because train travellers’ motives for

⁹ No doubt because of the high costs of building within city limits, the built links usually connected to stations outside of city borders, so that the network includes an additional pedestrian connection from municipality centroids to stations.

visiting specific zones are unknown. Alonso's GTM enables parameterization of the degree to which opportunities and congestion affect demand, and encompasses all variants of Wilson's family of spatial interaction models as special cases (De Vries et al. 2001). The model is applied as:

$$T_{ij}^* = A_i^{(1-\gamma)} P_i B_j^{(1-\theta)} P_j F_{ij}, \quad (5.1)$$

$$A_i = \left\{ \sum_j B_j^{1-\theta} P_j F_{ij} \right\}^{-1}, \quad (5.2)$$

$$B_j = \left\{ \sum_i A_i^{1-\gamma} P_i F_{ij} \right\}^{-1}, \quad (5.3)$$

where T^* represents observed passenger flows; A indicates access to resources from the origin; B indicates competition for resources at the destination; P equals population size; and F is a travel cost decay function. In the applied model the number of trips to destinations is not restricted, so that θ is set to 1. The function F , and subsequently the value of γ , are estimated in two steps, similar to the method proposed by De Vries et al. (2001). We first estimate F by regressing the log specification of a singly-constrained gravity model, as proposed by Fotheringham and O'Kelly (1989):

$$\ln(T_{ij}^*) = \delta_i O_i + \alpha_1 \ln(P_j) + \beta_1 \ln(s_{ij}) + \varepsilon_{ij}, \quad (6)$$

where s equals the shortest travel time, and O is a municipality fixed-effect dummy. For zero flow observations we apply the suggestion of Sen and Sööt (1981) to use $\ln(T_{ij}^* + 0.5)$. We have estimated both exponential and power specifications of the distance-decay parameter. The latter consistently yielded better results. Data on travel flows is obtained from sold train tickets on the Amsterdam to Rotterdam rail line (HSM 1889)¹⁰. We find that $F_{ij} = s_{ij}^{-1.777}$, and use this to compute A_i , as defined in 5.2. We then regress:

$$\ln(T_{ij}^*) - \ln(P_i) - \ln(P_j) - \ln(F_{ij}) = (1 - \gamma) \ln(A_i) + \varepsilon.$$

All results of demand model estimation are presented in Table 4-3. Following an interpretation that is applicable to Alonso's model if θ is 1 (De Vries et al. 2001), T has a 0.3 elasticity to both accessibility and travel cost. This means that the total number of trips originating in i increases when the accessibility of i increases, the

¹⁰ For other years we find other distance-decay parameters (see also Koopmans et al., 2012). We use these other values in a sensitivity analysis.

elasticity being 0.3. To assess the impact of model specification on the results of the later choice analysis, we alternatively analyse link railway construction choices when changes in travel cost only cause substitution at the origin (i.e. γ is set to 0), which would imply that railway investments do not affect the total number of trips. To assess the sensitivity of this analysis for F , the data have been computed with alternate distance-decay parameters. Although changing the distance-decay parameter substantially influences absolute marginal returns, we find that the ratios of the marginal returns of lines are hardly affected. The applied function F thus has a small impact on our findings¹¹.

Table 4-3. Parameters estimated from sold railway tickets on the Amsterdam to Rotterdam line in 1888

	α	t	β_1	t	R^2	N
Estimation Eq. (6)	0.825	26.33	-1.777	-18.97	0.989	182
			Γ	t	R^2	N
Estimation Eq. (7)	-	-	0.304	41.44	0.905	182

Note: All parameters are significant at the 0.01 level.

3.2.2 Route choice assignment

A multiple-path logit model is used to allocate flows to the network. We borrow its definition from Stern and Bovy (1989):

$$P_r = \frac{\exp V_r}{\sum_h \exp V_h}, \quad (8)$$

with P_r being the probability that a traveller chooses path r ; and V_r and V_h being, respectively, the utilities of respectively path r and all paths h . Alternative paths are generated by means of a link elimination method (Bekhor et al. 2006). The utility of paths is wholly based on travel time, so that $V_r = \alpha * s_r$, with $\alpha < 0$. As the available interaction data do not allow estimation of the utility parameter, we resort to other literature. A parameter from Vrtic and Axhausen (2002) is applied, which is -2.398 (for hourly increases of travel time). We use this parameter because it is estimated on longer-distance train trips, implying a similar context as our study.

¹¹ The results are available on request.

3.3 Costs of railway construction

We use a set of cost parameters on soil conditions and river width to determine the construction costs of all modelled lines. We obtain these parameters from regressing observed line construction costs on the geographical characteristics of these lines, such as traversed soil types and the width of spanned rivers. The soiltype data are obtained from Alterra (2006). The construction costs are obtained from the records of the investments of the State Railways¹². We expect weaker soil and wider rivers to linearly increase construction costs C (see 9):

$$C_l = \beta_0 RIVER_l + \beta_1 SAND_l + \beta_2 LOAM_l + \beta_3 CLAY_l + \beta_4 PEAT_l + \varepsilon, \quad (9)$$

where RIVER is the width of spanned rivers, and kilometres of traversed soil types are indicated (in order of increasing weakness) by SAND (sand or gravel), LOAM (loam or 'zavel', mixed sand-clay soil), CLAY, and PEAT. For the estimated parameters see Table 4-4. The table confirms that spanning rivers leads to very high construction costs per kilometre: 90 times higher than the reference case of sand.

Table 4-4. Regressed costs of railway construction

Traversing a kilometre of	Coef.	t	Cost index per 100 m (sand = 1.00)
River	4253.0*	2.68	91.97
Sand or gravel	46.2	1.54	1.00
Loam or mixed sand-clay	55.7	1.14	1.20
Clay	110.4*	5.43	2.39
Peat	115.9	1.24	2.51

Table notes: $N = 38$, $R^2 = 0.684$. Coefficients marked by * are significant at the 0.05 level. All others not.

Using the cost indices, a 100m raster of construction costs is established, from which we obtain the construction costs of built lines. We assume that relevant

¹² Additional investments cited for a particular year (e.g. for bridge construction) have been added to a year's flow. The investment flows are spread proportionally over the years between construction start and line openings. Yearly investments are then adapted to relative yearly price levels (compared with 1913) to finally obtain total real cost stock at the 1860 price level.

unbuilt links also follow least-costly trajectories, and therefore obtain construction costs c_{ij} for the random links by applying a least-cost path algorithm on the raster.

4 Results

After the determination of the demand and cost parameters in Section 3 we are now able to compute proxies of the rate of return on investment, i.e., as the ratio of additional passenger mileage and construction costs. The marginal returns of railway link construction have been computed for a number of combinations of key parameters that are distinguished according to the ratio of generalised travel cost of railway links to the reference network, and according to the elasticity of the total number of trips with respect to travel cost (see Table 4-5). The reference case is 'A5'. The costs and returns of all built lines are reproduced in Appendix B for the reference case.

Table 4-5. Methods to calculate marginal returns

Elasticity to travel cost	Railway link reduces generalised travel cost by	
	Five times	Three times
A: 0.3	A5	A3
B: 0.0	B5	B3

Note: The reference case is A5.

4.1 Costs and benefits

The average per-kilometre construction costs of built lines are lower than those of unbuilt lines (Table 4-6), which confirms that railway investors preferred 'cheap' routes (Rietveld & Bruinsma 1998). Note that since we keep track of which links are used by which railway companies, our model allows us to compute the effects of adding a link by a certain operator on the mileage of other operators. With regard to the network of the operator that constructs a link, the average mileage increase per added kilometre is significantly higher for the built lines, which indicates that investors indeed tried to maximize the returns on their own network. Note, however, that there is considerable variance in the value of per-kilometre benefits; the benefits of some of the built lines are nearly zero. Such low benefits may be found for lines for which the demand model is unable to accurately estimate benefits, such as connections with other countries. With regard to the effect of new links on the mileage on other operators' networks, decision makers were heterogeneous or inconsiderate, as the even larger confidence intervals of these effects show.

Table 4-6. Descriptives of costs and benefits of built and random network additions.

Costs and benefits per kilometre	Average	St. dev.	5 th pc.	95 th pc.
Built (N = 64)				
Costs	21.59	11.69	10.00	38.34
<i>Change in mileage (case A5):</i>				
on operator network ¹	303.41	545.85	7.00	821.23
on remainder of network*	-39.18	177.23	-402.72	207.32
Random (N = 1671)				
Costs	26.05	26.13	9.98	54.70
<i>Change in mileage (case A5):</i>				
on operator network ¹	116.74	129.30	-0.51	392.57
on remainder of network ¹	-23.18	62.03	-132.50	70.74

Table notes: Benefits are from the reference case (A5). ¹ Flows in thousands of trips per year.

4.2 Benefits over time

We proceed by breaking down the development of the network and passenger mileage over time. Note that we ignore the undoubtedly large effects of changing real income per capita, which did increase by 245 per cent between 1840 and 1930 (Maddison 2003). The spatial distribution of growing mileage over the network can be found in Appendix C.

Figure 4-3 shows the development of per-capita railway passenger mileage in the Netherlands, and concentration of passenger mileage in competing firms. Until 1879, per-capita passenger mileage develops in line with the network and its well-known S-shaped growth curve (Grübler 1990; Levinson 2005; Nakicenovic 1995). After 1879, the per-capita mileage either remains close to its 1879 level or continues to grow at a slower pace, if demand is assumed elastic to transport costs (A3 and A5). The prolonged development in the latter case occurs because accessibility, and thus demand, continues to increase with population and decrease with travel cost. Lastly, low market concentration, in particular in the decades before 1889, demonstrates the 'severe' competition (Veenendaal 1995) on the Dutch railways during those decades.

Figure 4-3 further shows that the returns of link construction are related to the generalized cost reduction that the fast transport mode offers, compared with the slow mode. Links from faster transport modes absorb passengers from greater areas, and so cause fast initial growth in passenger mileage. However, in the case of fast transport modes, new links are more likely to compete over the same areas with existing links.

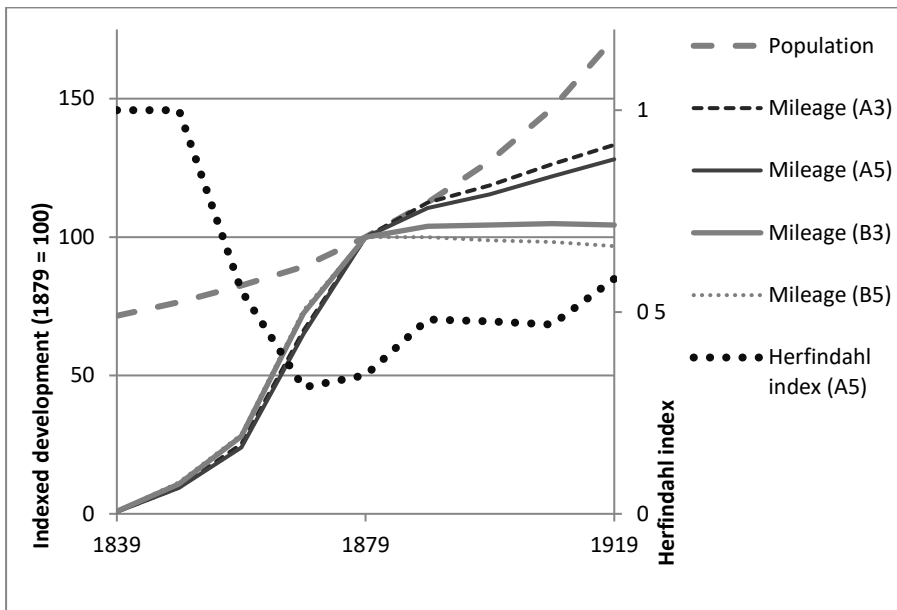


Fig. 4-3. On the left axis: development of population and predicted per-capita railway passenger mileage (1879 = 100; income is assumed to be constant); on the right axis: market concentration of passenger mileage on operator networks, measured by means of the Herfindahl index in the A5 case

The consequence is that new fast links in *mature* transport networks increase mileage less; compare the 3's and 5's in Figure 4-3. Hence, achievable network density is linked to the generalized cost reduction that a transport network offers. Networks that offer greater time savings have lower feasible network densities. Assuming that, over time, railway operation becomes faster, this mechanism explains why countries that started to develop railway networks earlier obtained higher railway network densities (Nakicenovic 1995).

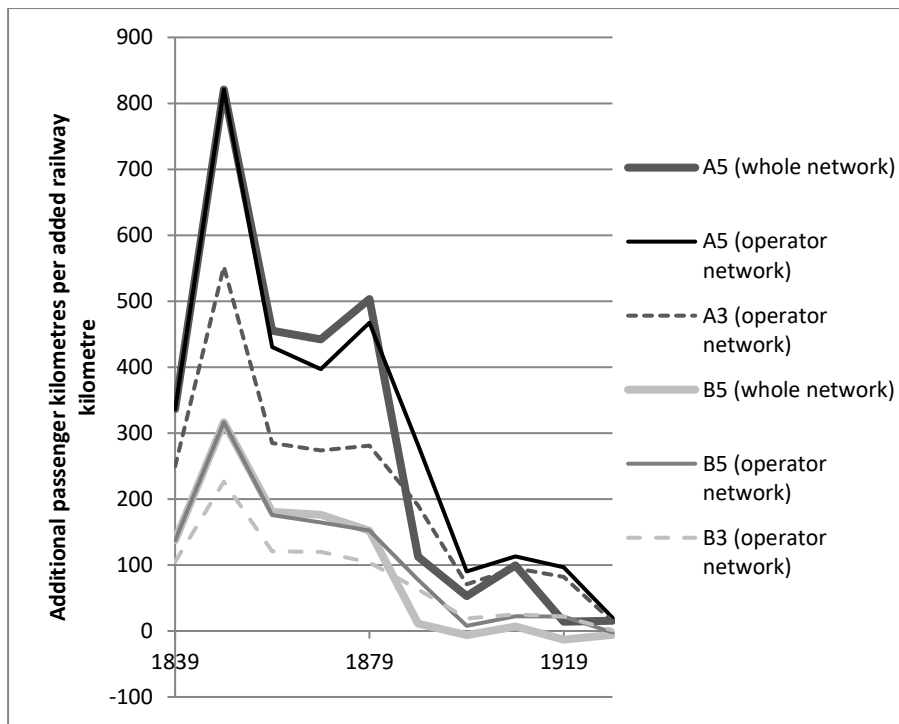


Fig. 4-4. Predicted increase of passenger mileage on operator networks and the whole network caused by link construction, per kilometre of added railway (A3 and B3 whole network data are excluded for clarity)

Figure 4-4 displays how much passenger mileage was increased on the whole network, and on the networks of investing operators, by the addition of 1 kilometre of railway. The figure shows clear economies of network size during the first decade of network development (additional mileage *increases*). After 1849, additional mileage remains substantial but starts to decline gradually. After 1879 there is a rapid decline, bringing additional mileage close to zero after 1919. Comparing Figures 4-3 and 4-4 we find that network development gradually increased the total per capita passenger mileage on the network until 1879, but that the construction of new links did not substantially increase total passenger mileage after that year. We further find that, until 1879, mileage on the whole network developed faster than on the operator networks, which supports the finding that transport network development has positive network externalities in the first stages (Levinson 2005). We take such network externalities to be the change in passenger mileage on the total network, minus passenger mileage on the newly-added link. Thus, positive network externalities are defined as an increase in

passenger mileage on the remainder of the network, and negative externalities vice versa. After 1879 network growth becomes saturated, and although new links caused mileage growth on operator networks, the construction of new links hardly increased passenger mileage on the whole network. This indicates that, after 1879, investors built links largely at the expense of their competitors' returns.

4.3 Benefits and link classification

Taaffe et al. (1963) separated stages of rail network development by the subsequent construction of 1) penetration lines; 2) feeders; and 3) interconnecting links. We separate *penetration links* (which increase the geographic extent of the network) from *density-increasing links* (feeders and interconnecting links that both mainly shorten existing routes). Pi-indices (πI) indicate the density of a network compared with its geographic extent (Rodrigue et al. 2006), with higher values indicating denser networks. We compute the change in network density caused by addition o as $\Delta\pi I_o$, which we weight by the length of the addition (see Appendix A), and use its average to separate penetration links ($\Delta\pi I_o \leq \frac{1}{n} \sum \Delta\pi I_o$) from density-increasing links ($\Delta\pi I_o > \frac{1}{n} \sum \Delta\pi I_o$). Most penetration links are part of a sparse 'skeleton' network (see Figure 4-5). Conform Taaffe et al. (1963), the development of the Dutch railway network began by increasing its geographic extent: between 1839 and 1860 only penetration links were built; between 1860 and 1890, 30 per cent of all built links were penetration links; after 1890, 95 per cent of all links were of the density-increasing type.

We have already established that link construction has positive network externalities in the first stages of network development. Such network externalities of link construction, as previously defined, are related to link type. We compute an indicator of network externalities, *RNE* (see Appendix A). A positive RNE indicates that an added link increased passenger mileage on the remainder of the network. In the reference case (A5) the resulting values range from circa -230 per cent to +180 per cent. Note that an RNE of under -100 per cent indicates a net loss of mileage. When comparing the RNEs of penetration links and density-increasing links we find that, on average, the construction of penetration links has positive network externalities, and the construction of density-increasing links has negative externalities (see Table 4-7). Network externalities occur because the increasing availability of destinations increases the value of the network (Economides 1996). We deduce that increases in the number of available destinations were chiefly caused by penetration links.

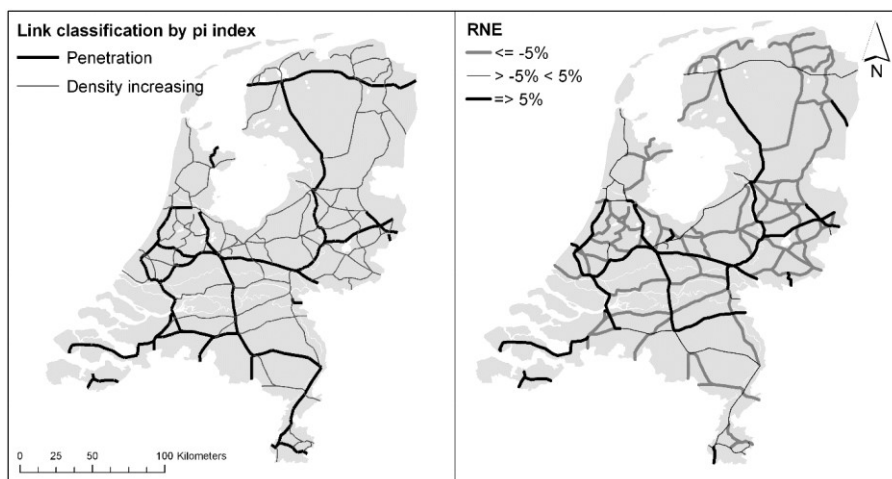


Fig. 4-5. Links by pi index classification $\Delta\pi I_o$ (left) and rail network externalities (RNE) of network additions in the reference case, A5 (right)

Table 4-7. Link classification and effect of link construction on mileage on the remainder network

Link classification by pi index (n)	Percentage effect on the remainder network (RNE)			
	Average	St.dev	5 th perc	95 th perc
Penetration links (17)	11.25	33.59	-35.43	65.94
Density increasing links (46)	-55.90	45.08	-113.89	24.45
All	-31.55	52.33	-110.95	43.13

Note: The first built railway link is excluded because RNE is unavailable.

4.4 Link construction choices

We now move to a reconstruction of the decision rules of railway investors. The average values of OPROI and TROI are computed for three periods, as shown in Table 4-8. These averages show that built lines and unbuilt alternatives are equally subject to diminishing returns, which indicates that the previously found decreasing returns of link construction are the result of network saturation rather than poorly informed construction decisions.

Table 4-9 demonstrates the results of the applied discrete choice analyses in different cases. According to the pseudo R-squares, A3 and A5 fit better with the analysed choices, which suggests that overall transport demand was slightly elastic to opportunities (or at least investors believed so). When assessing the

construction decisions in a discrete choice context, we find that the (expected) return on investment from passenger transport was the key determinant in the formation of the Dutch railway network.

Table 4-8. Average values of OPROI and TROI in different periods

	A5		A3		B3		B5	
	Built	Unbuilt	Built	Unbuilt	Built	Unbuilt	Built	Unbuilt
OPROI								
1839 - 1859 (o = 6)	18,589	8,407	12,484	5,943	5,211	2,609	7,402	3,596
1859 - 1889 (o = 34)	16,416	8,063	10,973	5,585	3,914	2,297	5,072	3,094
1889 - 1929 (o = 24)	6,945	1,358	6,831	1,128	1,774	348	2,056	331
TROI								
1839 - 1859 (o = 6)	18,951	7,873	12,078	5,479	4,982	2,397	7,425	3,331
1859 - 1889 (o = 34)	13,787	6,713	9,395	4,311	2,996	1,753	3,498	2,496
1889 - 1929 (o = 24)	3,666	84	3,375	16	420	-44	-335	-80

State lines were at least as much driven by the rate of return on investment as private enterprises were. The effect of the rate of return on investment on local track investment is higher than on other lines between 1859 and 1889, possibly because these local lines had another cost structure. Additionally, models have been estimated with OPROI replaced with TROI. In most cases, these models have lower explained variance and TROI estimators have lower z-values¹³. This indicates that investors in the Dutch railway network were set on increasing their own revenues, possibly at the cost of other investors.

State and local lines preferred to connect provincial capitals. In the case of state lines, this preference is likely due to the unification ambitions of the national government. In the case of local lines, provincial capitals were presumably preferred as hubs for connecting to the existing network. State and regular private lines display a preference to connect sea harbours to inland destinations. No doubt an interest in the competitive position of Dutch sea harbours, and the promise of transporting goods to the hinterland played an important role in this preference. Only the state endeavoured to provide transport to mining areas, where mines were in many cases owned by the state (Veenendaal 2008).

¹³ Results are available upon request.

Table 4-9. Results of weighted discrete choice analysis in different cases, in which return on investment is alternatively defined for competitive or cooperative investors

	A5		A3		B3		B5	
OPROI 1839 - 1859	coef	z	coef	z	coef	z	coef	z
Private regular lines	0.134	1.86	0.191	1.8	0.422	1.8	0.311	1.89
OPROI 1859 – 1889								
Private regular lines	0.134*	3.00	0.248*	3.36	0.554*	3.05	0.301*	2.48
Private local lines	0.472*	3.10	0.623*	2.68	1.415*	2.31	1.287*	2.88
State lines	0.132*	4.02	0.280*	4.54	0.580*	4.01	0.254*	3.22
OPROI 1889-1929								
Private regular lines	0.834*	2.45	0.922*	2.00	2.051	1.74	2.594*	2.18
Private local lines	0.910*	4.04	0.894*	4.15	2.449*	4.21	1.453*	3.22
State lines	1.074*	2.41	1.158*	2.39	3.789*	2.69	2.189*	2.20
Provincial capital								
Private lines	0.685	1.04	0.682	1.05	0.815	1.30	0.829	1.31
Private local lines	1.005	1.45	1.407*	2.30	1.523*	2.57	1.449*	2.64
State lines	1.408*	2.56	1.678*	3.03	1.611*	2.94	1.662*	3.10
Sea harbour								
Private lines	1.814*	2.68	1.774*	2.65	1.826*	2.81	1.816*	2.81
Private local lines	1.807	1.85	0.813	0.87	1.005	1.13	1.491	1.94
State lines	1.531*	2.62	1.767*	2.95	1.635*	2.81	1.455*	2.61
Mining area								
Private lines	0.672	0.53	0.812	0.63	0.569	0.45	0.468	0.37
Private local lines	0.578	0.38	0.872	0.62	0.876	0.67	0.616	0.49
State lines	3.030*	3.18	2.917*	3.18	2.811*	3.12	2.517*	2.83
Borderzone								
Private lines	1.793*	3.01	1.757*	2.95	1.730*	2.94	1.683*	2.92
Private local lines	0.562	0.77	0.388	0.61	0.690	1.15	1.066	1.81
State lines	0.018	0.03	0.311	0.49	0.204	0.33	-0.016	-0.02
Pseudo R ²	0.398		0.395		0.344		0.263	

Table notes: All parameters marked by * are significant at the 0.05 level; all others are not. No local or state lines were built between 1839 and 1859.

Lastly, only private regular lines reveal a preference to connect border zones, with the implied promise of lucrative international transport. Local lines apparently had a strictly regional aim. The state connected to border zones in the unconnected East and North of the Netherlands, and to existing lines going towards the exterior in the South. We therefore interpret the state's apparent neglect of border zones as a preference to integrate existing border zone connections in its network.

4.5 Geographic determinants of link construction

If return on investment determined railway construction, how decisive was the Dutch geography in determining where network development started? Take the construction of a line of fixed length between two nodes. In the case of fixed length and no further network connections, the comparative return on investment of linking two nodes is wholly determined by the ratio of the populations of connected nodes ($P_i P_j$) and construction costs (c_{ij}). When averaging to provinces, we find that in the first province with a railway: North Holland, the average construction costs and population densities were, respectively, 1.67 and 1.73 times higher than in the province with the lowest construction costs: Limburg. These averaged construction costs exclude the costs of spanning water bodies. If population and construction costs were uniformly distributed¹⁴ within provinces, an equally long line was $(1.73)^2 / 1.67 \approx 1.8$ times as profitable in North Holland as in Limburg, which indicates that higher population counts made early railway construction in the West of the Netherlands very plausible, despite its weaker soils. Note, however, that although weak soils did not decisively influence early railway construction, the much higher costs of spanning water bodies must have been a barrier to early network development. Indeed, it took several decades before railway lines crossed broad rivers.

4.6 The role of state involvement

Although the state had previously taken an interest in constructing railways, active state involvement only began when Dutch railway growth lagged behind other European countries (Filarski & Mom 2008; Veenendaal 1995). In the Netherlands the rivers Rhine and Meuse posed a barrier for network development. In order to break the deadlock, state involvement was deemed necessary (Veenendaal 1995).

¹⁴ Naturally, population and distribution were not distributed uniformly; railway constructors made good use of this, for example, by first connecting the two close *largest* cities (Amsterdam and Haarlem), and subsequently constructing over the least-costly soils towards the Hague and Rotterdam.

The state lines that finally bridged the Rhine and Meuse were up to three times more expensive per kilometre than the average built line. Model findings nonetheless indicate that these lines had an above-average return on investment *and* substantial positive network externalities¹⁵. We conclude, therefore, that state involvement in spanning the major rivers was necessary not because of low profit expectations, but because private investors could not amass sufficient capital. Capital was presumably unavailable, because in the mid-19th century, building long bridges over large rivers was a major technological challenge with high commercial risks. Here, state involvement was likely to be crucial for network expansion. Spanning rivers substantially increased revenues on other operators' networks. However, the state built more lines and introduced a new operator (SR) on the networks. As our results show, the state chiefly endeavoured to increase the return on investment on its own lines, and the lines it built have high return on investment. Presumably, therefore, many of the lines built by the state would have been built by private companies if sufficient capital had been available.

The introduction of SR intensified competition, and by 1869 SR had a 51 per cent share in the Dutch railway passenger transport market. Previous analyses suggest that competition between railway investors spurs investors to materialize the potential returns of network expansion sooner, effectively speeding up network growth (Knick Harley 1982). Thus in a non-cooperative setting the risk of overinvestment is higher. If we assume that, in contrast, *cooperating* investors would not have built the lines that decreased passenger mileage on the whole network, we obtain from our model that 138 (A3) to 661 (B5) kilometres of railways would not have been built¹⁶. Moreover, link construction opportunities for increasing passenger mileage on the whole network were exhausted even before the opportunities for increasing passenger mileage on operator networks were exhausted (see Table 4-8 and Figure 4-4), which displays that it is unlikely that *cooperating* investors would have built more, or other lines. This is further supported by the fact that, after pro-cartel policies were enacted in 1917, Dutch railways network growth nearly came to a halt. In conclusion, competition on the

¹⁵ Between 1869 and 1879 the main rivers were spanned by the following lines, with modelled OPROI within parentheses: Rotterdam – Breda (21,690), Utrecht – Boxtel (48,543) and Nijmegen – Arnhem (8,920). All have positive RNEs.

¹⁶ Note that this is a conservative estimate, because it is likely that cooperating investors would have been hesitant to build those lines that only slightly increased passenger mileage on the whole network (Knick Harley 1982).

Dutch railways has caused a higher final network density compared with a cooperative setting.

5 Conclusions

In this analysis the returns on investment of built and unbuilt railway lines in the Netherlands were estimated. These returns on investment and additional factors were subsequently used to assess the choices that investors made when forming the Dutch railway network. The development of the Dutch railway network is modelled from 1839 to 1929. Our findings display that investors tried to maximize pay-off with minimal construction costs, which confirms that economic considerations were key in railway link construction. The pay-off of link construction is incorporated in this paper as increasing passenger mileage. The costs of link construction are based on relative costs associated with the physical geography that a link overcomes. We confirm (in line with Filarski and Mom, 2008; Rietveld and Bruinsma, 1998; Veenendaal, 2008) that the high costs or commercial risks associated with crossing large rivers has slowed down Dutch railway network expansion in the first stages of network evolution.

Following Taaffe et al. (1963), we separate railway lines into *penetration lines* and *density-increasing lines*, and confirm that network evolution starts with constructing penetration lines. We find that, in general, such penetration lines have higher network externalities. As Economides (1996) explains, these lines add to the value of a developing network by increasing the number of available destinations. The majority of constructed lines in the Netherlands mainly increased network density. We find that the networks of transport modes that provide smaller travel-cost improvements can achieve a higher final density, but that, regardless of the size of travel-cost improvement, the Dutch railway network kept developing long after railway construction stopped yielding substantial marginal returns. In line with findings in the international literature (Knick Harley 1982), competition between railway investors at least in part caused this prolonged growth of the railway network in the Netherlands. Another reason must have been that income and population growth increased ridership. We estimate that cooperative investors would have built at least 175 to 661 kilometres less railways in the Netherlands.

State policies affected railway-network formation by setting market conditions and by active participation. Our findings suggest that the 1878 Act on Local Railroads (Veenendaal 2008) led private enterprises to construct lines with, compared with

regular lines, differing cost structures. Public intervention so allowed an even further increase in network density. State participation in railway construction was chiefly necessary to amass sufficient funding for spanning the major rivers (Veenendaal 1995). However, the Dutch state built a great deal more than that. An analysis of state construction choices reveals that the state was just as set on maximizing revenues on its own network as its private counterparts were. Our analysis suggests that, without state involvement, many of these built lines would still have been built. As expected (Dobbin & Dowd 1997), the resulting, in part politically-incited competition between various private operators and the state railways had adverse effects on network integration and the vitality of private railway enterprises (Fremdling 2000; Veenendaal 1995). We conclude that, if the state wanted to urge network development, it could have realized a similar network with less involvement.

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Appendix A: Applied indicators

To measure network externalities, first the change in passenger mileage on the whole network is computed as $\Delta NM_o = NM_o - NM0$. Here NM_o is passenger mileage on all railway lines *with* addition o and including mileage on the new link, and $NM0$ is passenger mileage on all lines before adding o . Then compute the percentage effect on passenger mileage on the remainder of the network $RNE_o = [(\Delta NM_o - AM) / AM]$ in which AM is the passenger mileage on the added link.

The density of unconnected subnets is indicated by means of the pi index: $\pi I_n = (NL_n / ND_n)$, in which NL is the total length of the subnet, and ND is the diameter of a subnet, i.e. the length of the shortest path between the two most distant stations on a subnet. We derive this pi index from Rodrigue et al. (2006). The degree to which a built line contributed to increasing the density of the network is subsequently computed by means of the weighted change in network density:

$\Delta\pi I_o = [\sum_{n=1}(\pi I_{on} - \pi I_{0n})]/L_o$. Here the π index of the network *with* addition o (πI_{on}) is subtracted from its value *before* adding o (πI_{0n}), and divided by the length of the addition, L . We treat first links on a new subnet as $\Delta\pi I_o = 0$.

Appendix B: Costs and returns of built lines (case A5)

Year	Operator	Length		Passenger kilometres on reference network (thousands)		Increase of passenger kilometres (thousands)	
		Costs	(km)	Whole net	Operator net	Whole net	Operator net
1829	HSM	333	13.9	0	0	4,670	4,670
1839	HSM	1,165	67.0	4,670	4,670	55,000	55,000
1849	GCB	759	54.1	65,600	0	2,830	3,360
	GCB	1,093	30.7	65,600	0	616	629
	NRS	3,453	113.2	65,600	0	79,200	74,300
	NRS	1,216	51.0	65,600	0	30,700	29,000
1859	GCB	249	22.0	181,000	4,020	353	445
	LM	179	11.2	181,000	0	610	217
	NCS	1,633	99.7	181,000	0	69,800	68,800
	NRS	204	8.5	181,000	123,000	-2,130	1,310
	SS	3,214	126.9	181,000	0	25,600	25,800
	SS	4,703	164.0	181,000	0	157,000	123,000
	SS	1,318	84.6	181,000	0	20,300	16,800
	SS	2,726	175.7	181,000	0	46,500	48,800
	SS	196	18.3	181,000	0	524	934
1869	GCB	727	30.3	530,000	11,500	830	830
	HSM	3,086	94.3	530,000	55,100	21,800	25,500
	HSM	3,262	169.4	530,000	55,100	16,900	53,000
	NBDS	1,007	51.6	530,000	0	21,700	15,200
	NRS	802	33.6	530,000	148,000	12,800	11,700
	NRS	637	27.7	530,000	148,000	4,650	9,370
	SS	1,688	76.1	530,000	239,000	22,500	20,700
	SS	3,755	51.7	530,000	239,000	114,000	81,400
	SS	1,196	18.5	530,000	239,000	11,400	10,700

Year	Operator	Length		Whole net	Operator net	Whole net	Operator net
		Costs	(km)				
1869	SS	2,283	59.5	530,000	239,000	136,000	111,000
(cont.)	SS	919	76.3	530,000	239,000	7,400	3,740
	SS	932	46.3	530,000	239,000	476	681
1879	HSM	1,216	49.9	916,000	178,000	7,060	10,300
	HSM	449	18.8	916,000	178,000	-99	253
	HSM	117	4.7	916,000	178,000	15,400	17,300
	HSM	833	31.4	916,000	178,000	3,250	7,940
	HSM*	1,544	130.2	916,000	178,000	4,060	6,950
	HSM*	1,651	108.1	916,000	178,000	3,700	23,700
	HZSM	70	7.0	916,000	0	-84	171
	NZOS	1,214	64.4	916,000	0	8,720	38,300
	SS	895	37.4	916,000	473,000	4,360	4,640
	SS	583	39.8	916,000	473,000	1,610	1,010
	SS	2,871	92.5	916,000	473,000	20,400	58,700
	SS	1,084	62.9	916,000	473,000	5,900	20,800
	SS	1,178	49.3	916,000	473,000	4,530	7,170
1889	HSM	471	23.5	1,140,000	305,000	3,570	5,380
	HSM	408	16.8	1,140,000	305,000	-558	1,290
	HSM*	119	9.8	1,140,000	305,000	-453	931
	NCS	112	10.4	1,140,000	98,800	281	-95
	SS*	642	26.8	1,140,000	721,000	667	1,040
	SS	935	52.3	1,140,000	721,000	4,640	4,810
	SS*	379	26.3	1,140,000	721,000	672	1,600
1899	HSM*	103	10.0	1,350,000	382,000	183	211
	HSM*	69	6.9	1,350,000	382,000	3,500	541
	HSM*	506	21.4	1,350,000	382,000	688	6,180
	NCS	70	7.0	1,350,000	115,000	406	566
	NCS*	287	28.4	1,350,000	115,000	1,800	4,740
	SS*	1,802	142.0	1,350,000	841,000	15,400	12,700

Year	Operator	Length		Whole net	Operator net	Whole net	Operator net
		Costs	(km)				
1909	HSM	503	35.2	1,640,000	472,000	-401	3,190
	HSM*	988	40.9	1,640,000	472,000	2,120	5,700
	HSM*	1,548	63.0	1,640,000	472,000	1,640	441
	HSM	111	8.6	1,640,000	472,000	-1,260	849
	HSM*	1,876	78.5	1,640,000	472,000	2,580	5,410
	SS	302	28.4	1,640,000	1,010,000	1,760	10,800
	SS*	779	44.1	1,640,000	1,010,000	-1,050	-400
	SS*	379	34.3	1,640,000	1,010,000	-706	6,180
1919	SS*	413	17.3	2,020,000	1,420,000	325	445
	SS	675	35.5	2,020,000	1,420,000	-245	81
	STAR	200	20.0	2,020,000	0	1,040	945

Note: State lines are indicated in **bold**; local lines are indicated with an asterisk (*).

Appendix C: Modelled yearly passenger flows

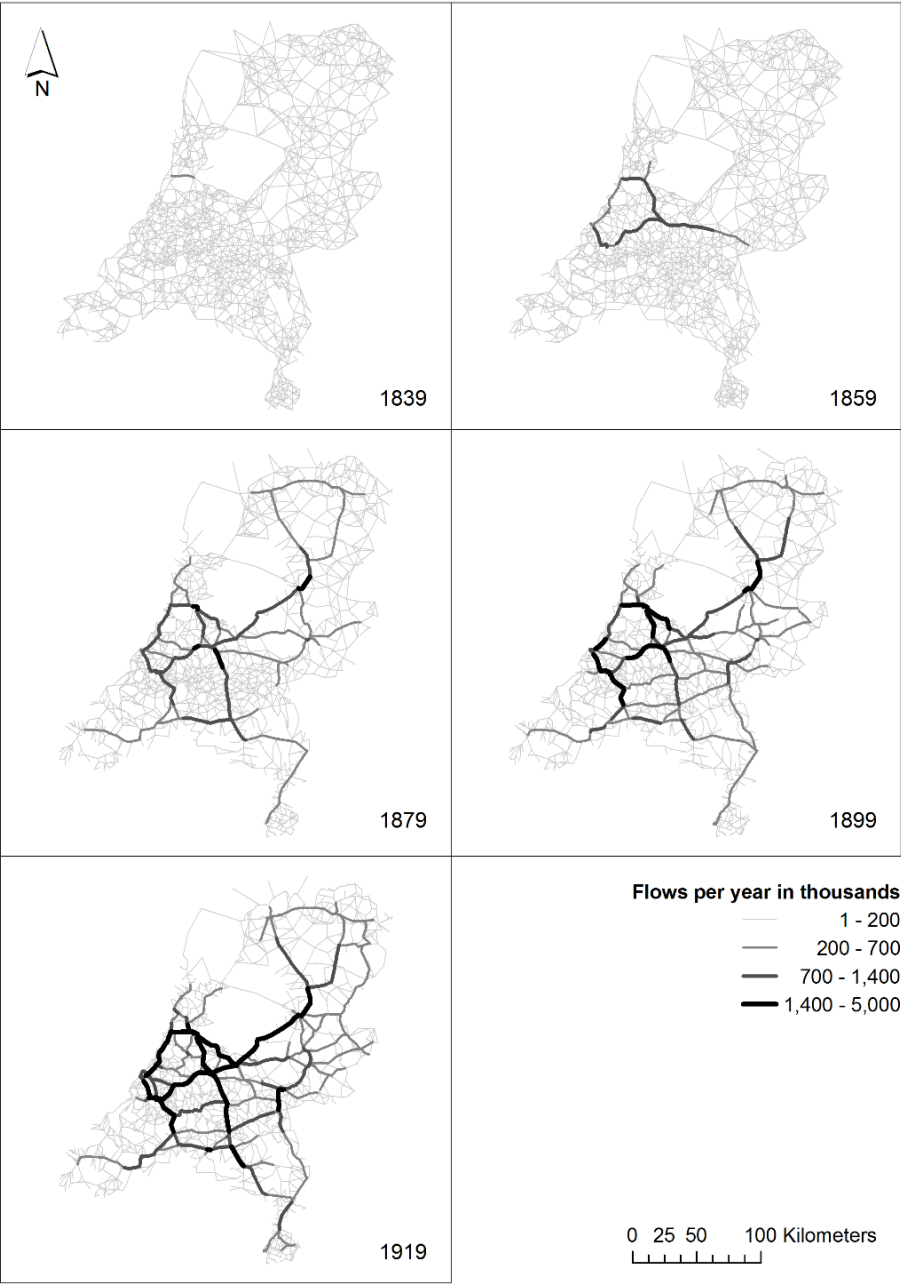


Fig C.1: Modelled yearly passenger flows in five years between 1839 and 1919

Chapter 5. Simulating geographic transport network expansion through individual investments

Abstract: *This chapter introduces a GIS-based model that simulates the geographical expansion of transport networks by several decision makers with varying objectives. The model progressively adds extensions to a growing network by choosing the most attractive investments from a limited choice set. Attractiveness is defined as a function of variables in which revenue and broader societal benefits may play a role and can be based on empirically underpinned parameters that may differ according to private or public interests. The choice set is selected from an exhaustive set of links and presumably contains those investment options that best meet private operator's objectives by balancing the revenues of additional fare against construction costs. The investment options consist of geographically plausible routes with potential detours. These routes are generated using a fine meshed regularly latticed network and shortest-path finding methods. Additionally, two indicators of the geographic accuracy of the simulated networks are introduced. A historical case study is presented to demonstrate the model's first results. These results show that the modelled networks reproduce relevant results of the historically built network with reasonable accuracy.*

Key words: Transportation, Network growth, Agent-based modelling.

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1 Introduction

The expansion of transport networks is considered an important factor for the spatial distribution of activities and receives considerable politic and academic attention. It is commonly perceived as a technology diffusion process in which the innovation spreads geographically (Grübler 1990; Nakicenovic 1995). The geographical paths that the developed networks assume have important societal and economic ramifications. Ideally these paths constitute a social optimum considering construction costs and generalized travel costs. However, due to often non-cooperative decision makers (Knick Harley 1982; Dobbin & Dowd 1997; Xie & Levinson 2011), potential transport network expansion outcomes may be limited to Nash equilibria (Bala & Goyal 2000; Anshelevich et al. 2003) that can entail considerable extra costs to reach a target state of connectivity.

Although it is known that transport network expansion may follow a clear rationale, largely based on e.g. expected transport flows versus costs (Rietveld & Bruinsma 1998; Xie & Levinson 2011), relatively little is known about how economic and institutional conditions affect transport network expansion. This is partially because, in contrast with other instruments available to transport planners such as land-use and transport demand models, ex-ante models of transport network expansion are few and they are hardly ever empirically validated. For a comprehensive overview of transport network modelling we refer to Xie and Levinson (2009). In the 1960s conceptual and empirical modelling efforts have been undertaken by quantitative geographers (Taaffe et al. 1963; Warntz 1966; Kolars & Malin 1970). More recently, network optimality and bi-level optimization methods (Patriksson 2008; Youn et al. 2008; Li et al. 2010), the role of self-organization (Xie & Levinson 2011) and the role of ownership (Xie & Levinson 2007) have been investigated in controlled conditions. This has been followed by empirically based exercises to test heuristic network design optimization methods (Vitins & Axhausen 2009) and to understand the driving forces of network growth (Rietveld & Bruinsma 1998), the role of first mover advantages (Levinson & Xie 2011) and to forecast future network investments in a fairly mature transport system (Levinson et al. 2012).

An instrument to evaluate geographically explicit network expansion outcomes in settings with multiple decision makers is not yet available in the literature. This is presumably because of limited data availability, computational limitations and difficulties in reproducing topologically realistic links or 'shortcuts' (Li et al. 2010). The aim of this paper is to introduce Transport Link Scanner (TLS), an agent-based model that simulates the overall geographic diffusion of a transport network through the individual investment decisions that drive network expansion, and to demonstrate that it is able to reproduce a historical network expansion process reasonably accurate. The model allows the inclusion of multiple decision makers with varying objectives; institutional conditions and the level of cooperation between decision makers can be explicitly modelled. A novel heuristic method is integrated to generate the plausible geographic paths of potential investments that aim to maximise fares. It does so in a manner that is consistent with the model's transport demand module and is responsive to previously selected links. The principal model output is a network of transport links, which enables the measurement of model performance based on graph-theoretic indicators such as diameter and node degree (Rodrigue et al. 2006), and indicators relevant to transportation networks such as accessibility and network efficiency (Jacobs-

Crisioni et al. 2016). The model is illustrated with a case study in which the start and expansion of the Dutch railway network in the 19th and early 20th century is simulated, but the model itself is developed in such a way that other applications may be configured reasonably easily.

The theoretical basis, overall structure and key assumptions are outlined in section 2. Subsequently, particular aspects of TLS are described in more detail in section 3. The case study is described in section 4, and simulation results for that case study are shown in section 5. This is followed by general conclusions on the development of TLS and ideas for further research in section 6. Lastly, the estimation of cost and demand functions, a breakdown of model results per investor type and a table of nomenclature are given in appendices. Before the model and case study are introduced, it is worth mentioning that this model is programmed in the Geo Data and Model Server (GeoDMS) software (ObjectVision 2014), which is presumably best known as the platform that supports land-use models such as Land-Use Scanner and the Land-Use-based Integrated Sustainability Assessment modelling platform (LUISA) (Hilferink & Rietveld 1999; Baranzelli et al. 2014). GeoDMS is rather different from commonly used GIS packages, and we emphasize here that its availability has been a key prerequisite for the development of TLS. It is an open-source platform that interprets scripts into a sequence of operations, and executes these operations on dynamically defined C++ arrays. Just like geospatial semantic array programming tools such as the Mastrave library (de Rigo et al. 2013), GeoDMS adheres to large scale modelling and assessment tasks. The major advantages of using GeoDMS for the work presented in this paper are considerable gains in computation speed, reproducibility of modelling steps, flexibility and control over data operations, and straightforward links between various data types such as raster and vector type spatial data. The TLS program and the data that have been used for this paper are freely available through http://www.jacobs-crisioni.nl/publications/download_tls.

2 Model structure and key assumptions

Transport network expansion is commonly initiated by a technical innovation that can substantially lower generalized travel costs, such as the introduction of steam power or the invention of motorways (Nakicenovic 1995). The expansion process itself is the result of sequential decisions to construct transport links for that new technology. Transport link investments generally come with considerable set-up costs and sunk costs and are physically bound, thus making it hard for investors to

move their enterprise (Xie & Levinson 2011). The involved decision makers may be private or public, and may have very different objectives, including economic and societal factors, but are generally concerned with providing transport service for which the built infrastructure is instrumental. Because of the high costs of market access, in many cases the transport market is an oligopoly subject to fierce competition (Knick Harley 1982; Veenendaal 1995). Thus, potential final network outcomes consist of Nash equilibria rather than a social optimum (Anshelevich et al. 2003; Xie & Levinson 2007; Youn et al. 2008).

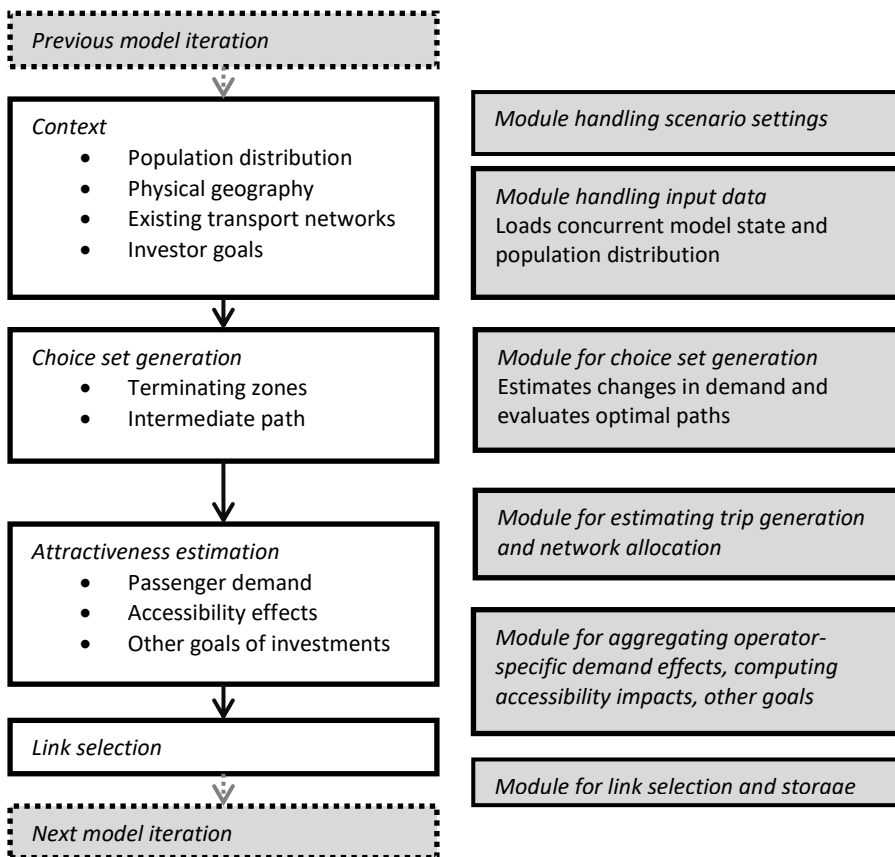


Fig. 5-1. The structure of one model iteration in TLS and the model's various modules. In each iteration one investment, identified as a link between two zones, is allocated to the current transport network.

Given high costs of link construction, it stands to reason that investment decisions are taken with deliberation and that an investor will decide to construct the link

that best fits investor objectives. The high costs involved in link construction create local monopolies when largely exhausted revenues block competitor investments in the same space (Xie & Levinson 2011). The position of the first investor is further boosted by the existence of network externalities that imply that newly added links may increase revenues for the existing network. This leads to advantages for the established playing field, as can be seen in the first mover advantages and lock-in described by network economics. For an overview of network economics we refer to Economides (1996). All in all, sequential link construction is a dynamic process in which previous decisions organize the potential for future decisions. The characteristics of network expansion processes are the basis for the ‘strongest link’ assumption of transport network expansion (Xie & Levinson 2011) which is adopted in this paper. In such an approach any agent selects a most attractive investment for construction, if a sufficiently attractive option is available. After that decision, investments are reconsidered and construction decisions are taken iteratively until the pool of sufficiently attractive investments is exhausted.

2.1 Model structure

Especially when network expansion is driven by economic motives, the spatial distribution of suitable terrain and potential transport revenues may be presumed to be important aspects of the choice process. This may be one reason why railways prefer paths with high potential interaction values (Warntz 1966; Kolars & Malin 1970). The geographical nature of these factors supports GIS-based modelling such as in TLS. In TLS network investments are drawn from a pool of potential network extensions with plausible geographic paths. That selection of extensions is based on a set of adaptable rules. The modelled network investments are discrete choices. The model is turn-based and dynamic: thus, one investment decision from one investor is allocated in any iteration, causing one distinct link to be added to the modelled transport network. The transport link allocated in that iteration affects the market conditions that are relevant for the generated choice set and for the estimated revenues of investments in subsequent turns. The model allows multiple investors to construct network links, such as private investors or governments. The partaking investors are allowed differing investment objectives.

The model is comprised of four modules that are tasked with: 1) the preferences and the financial capacity of partaking investors; 2) the generation of a choice set; 3) the estimation of investment attractiveness; and 4) the selection of an investment. The model structure is outlined in Figure 5-1. All elements of the model will be treated in the following sections.

2.2 Key assumptions

The investment decisions are assumed to be determined by repeatedly selecting the most attractive combination of investment and investor from a limited number of alternatives. The attractiveness of these options is governed by a conditional logit model (McFadden 1974), which is chosen because the multi-investor nature of TLS causes that variables differ for different investors. That condition excludes the mixed logit models used by for example Levinson and Karamalaputi (2003). Distinct choices are treated as separate trials, in which an observed addition to the railway network is chosen from a set H of alternative-investor combinations. H contains a finite number of alternative-investor combinations O with index $l = 1, \dots, L$, and known attributes. This choice set is composed of a number of likely additions. Then the probability that alternative o is realized equals:

$$P_o(S_o | O) = \frac{e^{S_o}}{\sum_{l=1}^O e^{S_l}}, \quad (1)$$

which is repeated for each choice situation. It contains the estimated attractiveness function S_l for a line l given investor type p , which takes this form:

$$S_l = \beta_{0p}ROI_l + \beta_{np}X_{nl} + R_p + R_l + \varepsilon, \quad (2)$$

where ROI_l indicates the return on investment that investors presumably seek. This is modelled by the estimated increase in passenger mileage on an investor's network, divided by the estimated costs of building the link; X_n is a vector of variables used to capture other factors that affect the attractiveness of investment options; R_p and R_l are alternative-specific and investor-specific random components that ensure that the model does not yield multiple alternatives with identical probabilities; and ε is a random disturbance.

The attractiveness of alternatives may differ per investor and may contain a variety of different social or financial objectives. In the presented case study investor-specific attractiveness functions have been estimated using railway investment choices taken while constructing the Dutch railway network, and mainly aim at increasing the revenues (reflected by passenger kilometres) on the investor's network; in other cases these attractiveness functions needs to be modified to reflect case-specific investor goals or transport revenue types.

The selection of investment choices and the computation of investment attractiveness is constrained by the following assumptions: 1) the territory is

divided into a given number of zones with estimable numbers of potential passengers and/or movable goods, observed as origins (i) and destinations (j); furthermore, 2) all zones are already connected by a preceding base communications network ($base$), so that spatial interactions already exist before the transport mode is introduced. This network is expected to have maximum plausible connectivity, so that the i to j travel distances L_{ij}^{base} obtained from this network are the minimum realistic link lengths between two zones. A last constraining assumption 3) is that the introduced transport mode is expected to lower generalized travel costs per kilometre with a fixed relative cost improvement factor φ .

We must emphasize that the value of φ has a considerable impact on results of the network allocation model. In this study relative general cost improvements depend on the transport speeds on the base network (V^{base}) and the transport speeds on the introduced network (V^{intr}), so that $V^{intr}/V^{base} = \varphi$. One implication of the model's assumptions is that the links l in the modelled network have travel costs c based on $c_l^{base} = L_l/V^{base}$ or $c_l^{intr} = L_l/V^{intr}$, where L_l indicate link lengths. In the case of public transport, it seems fair to adapt travel cost estimates with travel cost penalties cp to simulate the effort involved in entering and exiting the introduced transport network. This leads to fixed maximum obtainable travel cost improvements between two zones, which can be computed as a ratio between minimum new-mode travel costs c_{ij}^{min} and existing travel costs c_{ij}^{base} over the base network. Maximum obtainable travel cost improvements are expressed as:

$$c_{ij}^{base}/c_{ij}^{min} = (L_{ij}^{base}/V^{base})/[(L_{ij}^{base}/V^{intr}) + 2cp], \quad (3)$$

in which maximum factor improvements are computed as base travel costs divided by minimum achievable travel costs. Those factors in turn are computed as network length divided by base transport mode speed, and minimum travel costs are computed as the time used to transverse the same network length using the introduced transport mode plus fixed travel cost penalties to enter and exit the introduced transport mode. Thus, travel costs improvements are assumed to have a fixed maximum, which has important ramifications for the selection of a choice set. This can be seen in the following sections.

3 Choice set generation, investment selection and model accuracy measures

Although in continuous space infinite potential links exist, computational limitations force us to work with a limited choice set. This is justified by the property of the conditional logit model demonstrated by McFadden (1974) that drawing a limited number of alternatives leads to consistent estimates, provided that the true choice process is described by the estimation procedure¹⁷. TLS establishes a set of discrete choice set alternatives by drawing samples with a reasonable probability of selection using heuristic generation methods. In the attractiveness estimation procedure the built links are added to the choice set. Because of the dynamic nature of TLS the choice sets used in prediction are bound to differ from those used in the estimation process, and we must therefore assume that the validity of estimated attractiveness functions holds as long as investment options are selected with the same criteria as the choice set used in the estimations.

We furthermore assume that link construction is incremental, which implies that the most profitable link construction investments are selected first, and later, other links are built as extensions to the investor's network. To generate investment options given these assumptions a two stage method is applied, that first deals with the selection of terminating zones, and later selects a plausible path between the terminating points using corridor-location searching methods. For a recent overview of corridor-location search methods we refer to Scaparra et al. (2014). For this section it is necessary to explicitly discern links (*l*), which we consider as complete investments between two terminating zones, and segments (*s*), that are the separately observed lines in the model of which a link is composed.

3.1 Selecting terminating zones

The investment options are picked from a subset of zone pairs with high revenues compared to costs. We compute a first estimate of the relative revenue-to-cost ratio RCR of a potential new link by dividing additional passenger kilometres by construction costs *C*:

¹⁷ An assumption of multinomial logit models is independence of irrelevant alternatives. There have been some recent attempts to develop sampling strategies that may overcome this assumption; see for example Guevara and Ben-Akiva (2013). However, it is beyond the scope of the present paper to try and apply such methods, in particular since the generation of meaningful links is not trivial, as can be seen in the rest of the paper.

$$RCR_{ij}^{est1} = L_{ij}^{base} (T_{ij}^{est1} + T_{ji}^{est1} - T_{ij}^{curr} - T_{ji}^{curr}) / C_{ij}^{est1}, \quad (4)$$

where L_{ij}^{base} is a first estimate of link length defined as the shortest distance between i and j in kilometres over the base network; T is the potential number of trips in both directions with (est1) and without (curr) the new link; and C_{ij}^{est1} is a first estimate of construction costs.

Lengths and costs are assumed to be symmetric for both directions. We must emphasize here that the link lengths and flows for potential investments are rough estimates, because at this step in the selection procedure the optimal path of a potential link between i and j is not yet known and as a consequence, neither are the definitive travel times. The construction costs are obtained by finding the least-cost path between zones given estimated construction costs for each potential network segment. These construction costs are imposed on a fine-meshed network of regularly distributed segments, which is elaborated upon later.

Potential trips T between zones are computed using a spatial interaction model derived from Alonso's General Theory of Movements (GTM) (Alonso 1978). It must be emphasized that in the model these formulations can be easily substituted by any other spatial interaction formulation, for example to take into account spatial dependencies (Patuelli & Arbia 2013), heterogeneity or endogeneity (Donaghy 2010). For the selection of terminating zones we compute trips T in three cases:

$$T_{ij}^{base} = \left(A_i^{base(1-\gamma)} \right)^{-1} P_i P_j f(c_{ij}^{base}), \text{ and } A_i^{base} = \sum_j B_j^{1-\theta} P_j f(c_{ij}^{base}); \quad (5a)$$

$$T_{ij}^{curr} = \left(A_i^{curr(1-\gamma)} \right)^{-1} P_i P_j f(c_{ij}^{curr}), \text{ and } A_i^{curr} = \sum_j B_j^{1-\theta} P_j f(c_{ij}^{curr}); \quad (5b)$$

$$T_{ij}^{est1} = \left(A_i^{est1(1-\gamma)} \right)^{-1} P_i P_j f(c_{ij}^{est1}), \text{ and } A_i^{est1} = \sum_j B_j^{1-\theta} P_j f(c_{ij}^{est1}); \quad (5c)$$

where P represents zonal populations; c_{ij}^{base} describes travel costs over the base network; c_{ij}^{curr} describes current travel costs obtained from the network at the start of the model's iteration, thus including already allocated investments; c_{ij}^{est1} approximates travel costs if the potential investment is in place, and is computed as $c_{ij}^{est1} = L_{ij}^{base} / V^{intr}$; $f(.)$ is a distance decay function; γ and θ are parameters that govern transport consumption elasticity for reduced travel costs; and B_j is a destination-specific constant that may be used to model congestion at destinations.

The computed levels of RCR_{ij}^{est1} are instrumental to select a pool of potentially high revenue-to-cost ratio investments from which investment options in O are selected. To exclude lines that offer relatively small total travel cost improvements between two terminating zones, the line proposed in c_{ij}^{est1} must offer minimally half the maximum travel cost improvements that may be obtained by substituting a base network link with the link considered. Furthermore, intrazonal links and symmetrical elements in the matrix are excluded. These criteria yield the following selection dummy Z_{ij} :

$$Z_{ij} = \begin{cases} 1 & \text{if } (c_{ij}^{est1}/c_{ij}^{curr}) \geq 0.5(c_{ij}^{est1}/c_{ij}^{base}) \text{ and } i < j \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

The criterion is admittedly chosen ad-hoc, but seems to be a reasonable assumption. This selection criterion is necessary to obtain a small choice set with reasonably plausible alternatives. Note that, in the case that $cp > 0$, proposed links between i and j also have an absolute minimum distance, because with lower distances the rail link's travel cost including waiting times does not offer sufficient travel cost advantages. Finally, a fixed number of links between i and j with the highest values of $RCR_{ij}^{est1}Z_{ij}$ are selected as investment options.

3.2 Finding plausible paths

Simply connecting two zones without detours leads to the odd situation that the link does not serve the zones that it passes. Optimal transport lines may "depart from the straight line" when a detour improves the balance between revenues and construction costs (Morrill 1970). The links between selected terminating zone pairs are therefore allowed to detour. Three factors are taken into account in the path selection mechanism, namely potential revenues, construction costs and the overall length of the link. These are used to obtain optimal paths given revenue-to-cost ratios based on differently weighted combinations of the three factors. In all cases, optimal paths are searched that meet a minimum travel cost improvement. Thus, the maximum length of a link $L_{ij}^{intr max}$ is a logical consequence of the maximum travel cost improvements in (3), φ , and the criterion given by Eq. (6):

$$L_{ij}^{intr max} = V^{intr} [(c_{ij}^{base} - 2cp)/0.5(\varphi)], \quad (7)$$

so that, to achieve the maximum link distance, the maximum acceptable travel costs are multiplied with the speed of the introduced transport model. To obtain optimal paths, the continuous space in which built lines are determined is approximated by a regularly formed network of potential line segments, in which

equally distributed nodes connect the nearest nodes in a set number of directions (see Figure 5-2). This is a common approach in corridor location problems (Goodchild 1977; Scaparra et al. 2014). The spatial resolution of this network is one kilometre x one kilometre x 32 directions so that network density $r = 4$. The used method differs somewhat from known solutions to corridor location problems. The key difference is that the used method depends on the outcomes of previous model iterations and may yield different results in subsequent model iterations. To allow for this, the regularly latticed network is combined with the network already built at the start of the model's iteration, and with segments that connect the simulated rail network to zone centroids. The combined network and a shortest path finding algorithm are used to obtain a path with an optimal combination of revenues, construction costs and length.

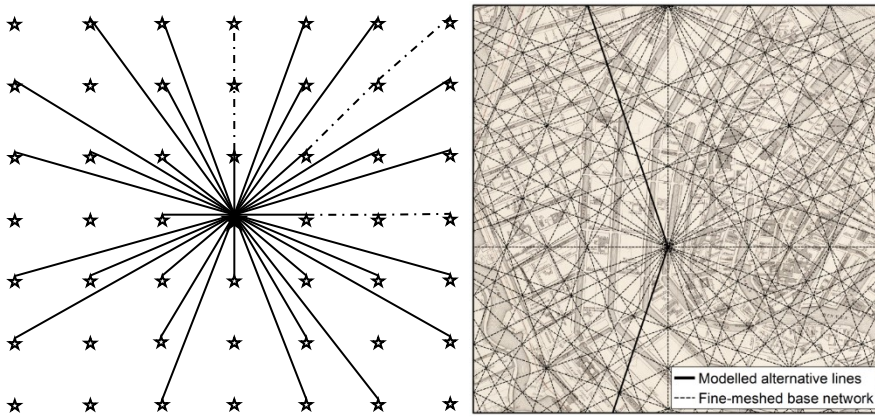


Fig. 5-2. Schematic example of a regularly formed network with equally dispersed nodes shown as stars, segments from the centre node shown as regular lines and exemplary additional segments shown as dashed lines (left); example of the regularly formed network shown as dashed lines and potentially derived link shown as regular bold line positioned over a map of Amsterdam in 1842 (right).

The revenue-cost indicators per segment s are computed as:

$$RC_s = (R_s/C_s)^{1-k} / L_s, \quad (8)$$

where R_s indicates estimated revenues obtained from the segment; C_s indicates costs of segment construction; and L_s indicates segment lengths. This formula puts a high weight on the revenue-to-cost ratio for low values of k , while the least lengthy path is favoured in case $k=1$. The method to estimate segment revenues will be explained later. Construction costs are obtained from terrain characteristics.

To model additive network construction, already built railway segments are given a very low cost of one. Note that more sophisticated cost structures for existing links can be configured to simulate specific cooperation conditions. Finally, segment lengths are primarily taken into account to ensure that the found path respects $L_{ij}^{intr} < L_{ij}^{intr max}$.

The inverse RC_s^{-1} is used as a measure of friction for each segment. Subsequently Dijkstra's least-friction path algorithm is applied to find a path between the terminating zones with the lowest total friction. Clearly, this approach provides the possibility to obtain optimal paths according to a limited set of parameterised factors. Because methods to obtain real parameter values for path selection are not yet available, we iterate the importance of segment revenue-to-cost ratios using the k parameter. Thus the shortest path finding algorithm with RC_s^{-1} is repeated in 40 iterations, in which k is gradually increased from zero to one. The total inverse revenue-cost indicator of a path is:

$$RC_{TOT}^{-1} = \sum_{s=1}^n RC_s^{-1} = \sum_{s=1}^n L_s / (C_s / R_s)^{1-k} \quad (9)$$

For $k=0$, this amounts to a distance-weighted sum of inverse revenue-to-cost ratios, while for $k=1$ it is simply total distance.

Estimating segment revenues

The revenues for each segment are estimated using a relatively straightforward method. Explicitly taking into account revenues with different railroad line geometries might require repetitive re-estimation of transport demand with various path alternatives, which is computationally infeasible. We therefore take the potential fare of a link as a proxy for potential revenues. This can be partially done by taking into account the amount of people in the zones that a link connects. To take into account that zones which are already connected to the network might suffer from transport market saturation, we also include MS , which approximates transportation market saturation at the origin and destination, so that:

$$MS_i = \sum_{j=1}^n \frac{([L_{ij}^{base} T_{ij}^{est1} - L_{ij}^{base} T_{ij}^{base}] - [L_{ij}^{base} T_{ij}^{curr} - L_{ij}^{base} T_{ij}^{base}])}{([L_{ij}^{base} T_{ij}^{est1} - L_{ij}^{base} T_{ij}^{base}])}, \quad (10)$$

in which the relative amount of passenger kilometres that can be obtained by connecting a zone is estimated, given a base level of passenger kilometres ($L_{ij}^{base} T_{ij}^{base}$), the current level of passenger kilometres ($L_{ij}^{base} T_{ij}^{curr}$) and the

presumed maximum number of passenger kilometres ($L_{ij}^{base} T_{ij}^{est1}$). MS_i is zero if the market is fully saturated and one if there is no saturation whatever. Finally, the segments' revenue levels are estimated as average non-saturated potential revenues in the zones in which both the first and the last point of a segment is located:

$$R_s = \frac{1}{2} \left[\sum_{i=1}^n MS_i (P_{is1} + 1) + \sum_{i=1}^n MS_i (P_{is2} + 1) \right], \quad (11)$$

where revenues R of segments s are computed by means of the population P of zone i in which the segment's first point ($s1$) and last point ($s2$) are located and the zone's saturation factor MS_i . One person is added to each zone to ensure that values of R_s are above zero and thus warrant the computation of Eq. (9).

Optimal path selection

The iterative path-finding method leaves 40 alternative paths with varying lengths. These varying lengths signify a varying mix of revenue-cost optimisation and length reduction. We must acknowledge that in some cases the method captures many alternatives with similar geometries, thus causing inefficiencies in the alternative path generation. An extension of the model using recent advances in corridor location problems such as those proposed by Scaparra et al. (2014) may be explored in the future to solve this. To find the likely most profitable path, the passenger kilometre increases obtained are recomputed for the whole i to j matrix, for which the travel costs and travel distances between connected zones are repeatedly re-estimated for every value of k . To do so, a dummy variable Q_i indicates whether zone i is connected to the alternative path at hand. Subsequently the estimated travel costs c_{ij}^{curr} and travel distances L_{ij}^{base} between all connected zones are updated so that $c_{ij}^{est\ k}$ and $L_{ij}^{est\ k}$ are defined for each alternative path k as:

$$c_{ij}^{est\ k} = \begin{cases} \text{path travel costs if } Q_i Q_j = 1 \\ c_{ij}^{curr} \text{ otherwise} \end{cases} \quad (12)$$

$$L_{ij}^{est\ k} = \begin{cases} \text{path travel distance if } Q_i Q_j = 1 \\ L_{ij}^{base} \text{ otherwise} \end{cases} \quad (13)$$

which enables a more accurate estimate of revenues within the scope of the connected zones. L_{ij}^{base} is used in (13) because a shortest length finding method on the current network would always represent the geographically more efficient base

network, regardless of the state of the introduced transport mode. As with the first estimate, revenues from not directly connected zones are neglected here. This is a necessary evil to prevent excessive computational requirements in this stage of the modelling exercise. Furthermore, the sum of segment construction costs is taken so that the overall cost of the path for the iteration is known as $C^{est\ k}$. These new cost and revenue estimates are used to estimate path revenue-cost indicators using:

$$T_{ij}^{est\ k} = \left(A_i^{est\ k(1-\gamma)} \right)^{-1} P_i P_j f(c_{ij}^{est\ k}), \text{ and } A_i^{est\ k} = \sum_{j=1}^n B_j^{1-\theta} P_j f(c_{ij}^{est\ k}). \quad (14)$$

Finally, the overall length of the link is computed as $L^{intr\ k}$ and used to obtain the final revenue-cost ratios of all paths, so that:

$$RCR^{est\ k} = \begin{cases} \sum_{i=1}^n \sum_{j=1}^n [L_{ij}^{est\ k}(T_{ij}^{est\ k})] / C^{est\ k} \text{ if } L^{intr\ k} < L_{ij}^{intr\ max} \\ (L^{intr\ k})^{-2} \text{ otherwise} \end{cases}$$

In Eq. (15) the length of links is purposely squared to enforce that the shortest path is only selected if no path is found that meets the $L_{ij}^{intr\ max}$ criterion. Subsequently the path with the highest value of RCR is selected. In this way, the path with the highest estimated revenue-to-cost ratios is selected if a path that meets the length criterion is found, and else the method picks the path with the shortest overall length.

It is important to note that two additional restrictions are imposed on the path decision method: first, we assume that railway network construction is incremental, so that a) in all cases, if a link starts or terminates in a zone already connected by a built line, the generated line must connect to the line already built there, and b) the links of an investor's already existing network has negligible costs for the considered expansion; second, to simulate that built railway links terminated outside contemporary urban areas, the link may not start on a node less than 500 meters away from the zone's centroid. This approximates the distance between stations and urban area centres that are observable in the historically built network.

3.3 Investment selection

Subsequently the attractiveness of the investment options is computed. A wide range of variables that deal with investor objectives can be computed here. Increasing mileage, total transport flows or reduction of congestion due to insufficient transport network capacity are, presumably, generally important reasons for transport network investments. TLS therefore includes a module to model expected transport flows on potential network extensions, on the investor's remaining network or on the whole transport network.

For all investment options generated in the choice set, the attractiveness is estimated with the methods shown in the previous section, yielding values of S_i specific for each investor in a vector that is as long as the number of active investors times the number of options. A very small random component is added to the computed attractiveness values to warrant that two options do not have identical attractiveness. Based on the estimated values, Eq. (1) is solved to obtain probabilities for the considered investments. Ultimately, the investment with the highest probability is selected. The new link and its relevant attributes are added to the already existing network in a new file; this file may form the basis for the evaluation of a subsequent investment if need be.

3.4 Measuring model accuracy

The primary goal of this paper is to demonstrate that modelling transport network development with reasonable geographic accuracy is feasible. Xie and Levinson (2011) use rank correlations to verify to what degree their model captures the sequence of links accurately. Unfortunately this only works if the modelling is restricted to the topology of the observed network, which is not the case in TLS. A visual inspection of allocation results yields useful insights, but does not provide the possibility to assess the accuracy of the model at hand in a balanced and objective manner, for which accuracy indicators and a baseline comparison are necessary. Although many network-based indicators to compare modelling results are conceivable such as the ones provided by Rodrigue et al. (2006), we concentrate on two indicators that deal with geographically relevant aspects of the results. One indicator measures to what degree the same zones are connected as have been connected by the historically built line; and the other indicator measures differences in travel-times. Because we assume that model accuracy is more critical for populous areas, all indicators are weighted by population. Weighted connection error *WCE* is thus measured as:

$$WCE = 1 - \left(\sum_{i=1}^n (P_i^{observed} X_i^{modelled} X_i^{observed}) / \sum_{i=1}^n P_i^{observed} X_i^{observed} \right), \quad (16)$$

where X is a zone-specific dummy that takes the value one when a municipality is connected by the modelled and observed railway networks, and zero otherwise.

Essentially this measure indicates to which degree the zones that were connected by the really built network, are being connected by the modelled network and it thus only measures double positives. We believe this is sufficient for the scope of this paper but plan to develop a wider range of indicators in further exercises. The weighted mean average absolute percentage travel time error ('WMAPE') is measured as:

$$WMAPE = \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^n \left(\frac{P_i^{observed} Abs[c_{ij}^{observed} - c_{ij}^{modelled}]}{P_i^{observed} c_{ij}^{observed}} \right), \quad (17)$$

where the absolute population-weighted differences between the observed and modelled travel times are expressed as percentage of the observed travel times, and the final results are subsequently averaged. Naturally, in both the modelled and historical networks the same rules regarding waiting times and travel speeds are upheld to enable a fair comparison of travel-times.

To ensure a meaningful comparison, modelled networks are compared with the state of the historically built network that is closest to the modelled network in terms of length. Thus, if in the fourth investment turn, a modelled network has a length of 1,000 kilometres, subsequent individual historical investments are tested for cumulative length until the historical investment is selected that brought the historically built network the closest to a 1,000 kilometre cumulative length. The network comprising that and previous investments is selected for comparison. In addition, the population levels of the year in which the selected historical investment is built are selected to serve as weights for the presented indicators.

4 Case study

In this section we present an effort to simulate the development of the Dutch railway network in the 19th and early 20th century using TLS. Investment attractiveness functions were fitted on observed transport network investments. First the history of the development of that railway network is summarized, after

which the model set-up, main assumptions and estimation of transport link attractiveness are outlined.

4.1 The development of the Dutch railway network

The first railway in the Netherlands opened in 1839 (Veenendaal 2008). It was operated by the ‘Holland Iron Railway Company’ (HSM), and linked Amsterdam to Haarlem. It was soon extended towards Rotterdam. Subsequently, competing companies built their own lines in the Netherlands. More than ten operators have separately provided railway services on railway links in the Netherlands. The Dutch government began participating actively by building state lines defined in the Railway Acts of 1860 and 1875. Most of those state lines were run by the ‘State Railways’ (SR), a private company which leased lines owned by the state. In 1878 a third Act followed that allowed for the cheaper construction of railways, if operated with slow light trains. Supported by attractive loans from the Dutch State and subsidies from local governments (Doedens & Mulder 1989), this Railway Act incited the construction of ‘local tracks’ that typically connected rural areas to the main railway network (Veenendaal 2008) and were often subsidised by local governments. In this paper we treat state involvement as the introduction of other types of investors with distinct preferences in the railway development playing field.

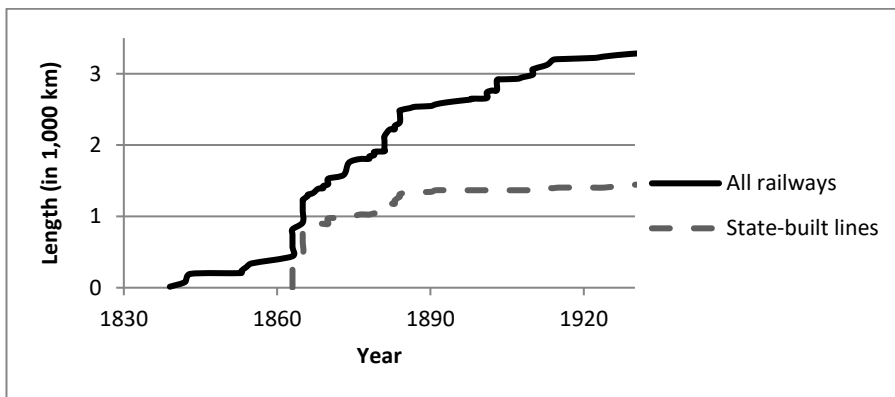


Fig. 5-3. Length of railway lines in the Netherlands over time.

After an initial slow start, railway development began to pick up speed in the 1850s when additional operators and the Dutch state began to participate in network development (see Figure 5-3). In total, 25 operators have operated rail lines in the country according to the data observed in this study. Increasing competition led to

considerable growth in the length of the railway network between 1860 and 1890. Many operators could not keep up, and in 1890 the infrastructure of the third largest railway operator ('NRS') was nationalized. After this the railway transport market was almost completely in hands of HSM and SR. In 1917, decreasing revenues forced HSM and SR to cooperate within an institutional framework in which Dutch policies regarding railroad operations shifted from pro-competition to pro-cartel. Finally, in 1936 all railway infrastructure was nationalized, and operations were continued by the state. By 1936, opportunities for further railway network expansion evidently were exhausted and the network did not expand any further until the 1980s.

4.2 Population distribution, network speeds and network ownership

Based on Veenendaal (2008) and Stationsweb (2009), the historical railway network development in the Netherlands has been reconstructed in a GIS database that also contains population counts from 1830 to 1930 in 1,076 municipalities. The data, furthermore, builds on the same assumptions as in Koopmans et al. (2012), of which we now list the most important ones. The study area is assumed to already have an underlying network of paths that connects all municipalities with each other. In the 19th century horse-drawn boats through the country's tow-canals were the main long distance travel mode, and often the only alternative to walking to most people. They operated at a speed that was but slightly faster than walking. We must acknowledge that the historical networks of paved roads and tow canals are not taken into account explicitly; instead, just as Koopmans et al. (2012), we consider both networks to be regional substitutes for each other that are approximated using one simplified network. In the case study, that network connects each municipality with its five nearest neighbours. A speed $V^{base} = 6 \text{ km/h}$ is maintained as the average speed to traverse this network to proxy movement over roads and waterways. We assume this is a reasonably accurate assumption for the Netherlands. One model variant is run with $V^{base} = 4 \text{ km/h}$ to test model sensitivity for this setting.

Municipalities are represented by means of their geographical centres. The base network has direct connections between those centroids. The rail network is connected to those centroids through connector road links. Train schedules or the accelerating and decelerating of trains are not explicitly modelled, but are approximated by imposing relatively low average speeds for the introduced transport links. To proxy that passengers lose some time with entering and exiting

the rail network as well as with transferring between physically separate rail networks, a relatively small travel cost penalty $cp = 10 \text{ minutes}$ is given to all connectors between rail networks and municipalities.

When assessing the attractiveness of investments, links of the previously modelled network extensions are included as well as the underlying network. As can be seen in section 4.3, passenger transport demand is an important reason for investment. The level of demand depends on generalized transport cost, which is proxied by travel time, and on price elasticity. This makes the modelled speeds on the railway network and assumptions on price elasticity a key factor for network outcomes. To take these factors into account we present scenarios with varying travel time improvements and with varying assumptions on price elasticity of passenger transport demand. Construction costs, passenger demand and price elasticity have been estimated using observed data. Details of the method used, data and results can be found in appendices A and B.

To model railway network expansion in a case with multiple investors with varying objectives, five independent investors are simulated. This set of investors consists of two regular private investors, two private local line investors and the state and roughly resembles the playing field during Dutch railway construction. The regular private investors partake in investments from the model start. The state partakes from 1860; local line investors from 1879. At any point the investment-investor combination with the highest probability is selected. All investors are eligible to the same investments with attributes that may differ per investor; ten investment options are available in every round. The built lines are assumed to be operated by the building investor, so that all revenues from an investor's line are therefore assumed to fall to that investor. In the presented case study the modelled investment sequence starts in 1839, with one investment allowed every year. After an investment, an operator is excluded one round to simulate financial recuperation and evaluation of the investment. Municipal population counts are updated every decade. If the model does not find any suitable investments, it skips years to a following decade; if it does no longer find suitable investments in 1930, the network expansion sequence ends.

Because both travel speed improvements and price elasticity can only be roughly estimated, we present a range of scenarios in which those assumptions vary considerably. In one scenario train speeds are three times faster than the pedestrian network, so that average speed of train trips is defined as $V^{intr} = 18 \text{ km/h}$ and $V^{base} = 6 \text{ km/h}$, and total municipal transport consumption is

affected by changes in travel times (scenario A). The level of elasticity is given as γ as in Eq. (5a). In scenario C, trains speeds are 7.5 times faster than the pedestrian network, with $V^{intr} = 30 \text{ km/h}$ and $V^{base} = 4 \text{ km/h}$, while municipal transport consumption is inelastic (scenario C). In four other scenarios train speeds are five times faster, with $V^{intr} = 30 \text{ km/h}$ and $V^{base} = 6 \text{ km/h}$, while municipal transport consumption is again inelastic (scenarios B1 to B4). In scenario B1 only train speed and transport consumption are changed. To understand the sensitivity of the model for other model assumptions, further variations in rules are simulated in scenarios B2 to B4. In scenario B2, investors are not excluded in the round directly following an investment. In scenarios B3 and B4, only regular private investors are modelled, so that state lines and local line investors are excluded in the simulations. In scenario B3, investors are assumed to be competitors, while in scenario B4, investors are assumed to be co-dependent. Co-dependency is approximated by adding the relative change in passenger mileage on the competitor network to the attractiveness function of an investment. All used scenarios are summarized in Table 5-1. We must acknowledge that this is not a complete sensitivity analysis in which all assumptions are varied independently. That is an almost impossible task, given the number of assumptions in the model and the minimum ten days needed for one model run even on a, at the time of writing, high-end 2.6Ghz Xeon PC. In any case such a sensitivity analysis is outside of the scope of this paper. For future applications we propose to pinpoint parameters that are crucial to conclusion validity, and test model sensitivity for these parameters.

Measuring performance is meaningless without a baseline comparison of accuracy. To compare relative model performance the model described by Rietveld and Bruinsma (1998) has been approximated using the TLS framework. The Rietveld and Bruinsma method repeatedly adds a straight line between the two cities that yield the highest expected return on investment. Only the 35 most populous cities in the country are taken into account. Costs are equal to length, with the exception of links that cross large waterbodies; those links cost a factor 20 more. No fixed costs or minimum travel times are applied, and varying investor differences are not accounted for. This model is implemented in TLS by selecting the highest value of Eq. (4), taking into account only the original subset of 35 cities. One link is added in every model iteration. All links are assumed to be private lines. The plausible paths method in subsection 3.2 is adapted to exclude variation in estimated link revenues. The allocation procedure is finished when the pool of available cities is exhausted. We must note that a comparison with a socially optimal network (Li et

al. 2010) is also useful here; further work is needed to establish norms for optimality and generate a meaningful optimum.

Table 5-1. The scenarios used.

Scenario	Description	φ and (V^{intr} / V^{base})	γ
A	Slow trains, elastic consumption	3 (18/6)	0.3
B1	Fast trains, inelastic consumption	5 (30/6)	0
B2	As B1, but investors are not excluded directly after an investment	5 (30/6)	0
B3	As B1, but only private investors	5 (30/6)	0
B4	As B3, but change in passenger mileage on competitor network is a factor for investment attractiveness	5 (30/6)	0
C	Slower walking speeds, B5 parameters	7.5 (30/4)	0
Rietveld and Bruinsma	Reproduction of Rietveld and Bruinsma (1998)	5 (30/6)	0

Notes: Parameter φ indicates relative speed improvement as a ratio of the speed of the introduced transport mode V^{intr} versus the speed of prior transport modes V^{base} ; see subsection 2.2. Parameter γ indicates transport consumption elasticity, see Eqs. (5a) - (5c).

4.3 Investment choices

Because inland water transport provided the Dutch freight sector a cheap substitute for rail, passenger transport was a particularly important service for Dutch railway investors (Filarski & Mom 2008). Furthermore, railways have been considered to possess unifying qualities (Veenendaal 2008), which were presumably sought after by the Dutch administration in the 19th century. Although the 'United Provinces' created in the 17th century had become a centrally-led monarchy by 1806, the country was only starting to form a political union when the railways began to develop (Kossmann 1986).

To investigate the motives of investment decisions in the development of the Dutch railway network the conditional logit choice model in (1) has been fitted on sets of built and unbuilt railway links. Investments were separated into regular private lines, private lines that comply with local track legislation, and state lines. As noted before, return on investment is assumed to be the key driving force. Revenues are expected to be linear with travelled distances; this cannot be validated because data on historical ticket pricing structures is currently unavailable. We thus implicitly assume that pricing levels were equal throughout

the country regardless of regulation or level of competition. This is presumably not true, and the consequences are worth exploring in follow-up research.

Next to return on investment a number of other variables are taken into account in the attractiveness function. Amongst those, changes in the level of inequality of accessibility values proxies the endeavour of in particular government investors to reduce national disparities in economic opportunity. It is computed as changes in the Theil index of municipal accessibility levels. This variable takes this form:

$$IA_l = 100 \left[\frac{1}{n} \sum_{i=1} \left(\frac{A_i^{opt\ l}}{A^{opt\ l}} \cdot \ln \frac{A_i^{opt\ l}}{A^{opt\ l}} \right) - \frac{1}{n} \sum_{i=1} \left(\frac{A_i^{curr}}{A^{curr}} \cdot \ln \frac{A_i^{curr}}{A^{curr}} \right) \right], \quad (18)$$

$$A_i^{curr} = \sum_{i \neq j} P_j f(c_{ij}^{curr}); A_i^{opt\ l} = \sum_{i \neq j} P_j f(c_{ij}^{opt\ l}), \quad (19)$$

so that differences in the distributions of current accessibility levels A_i^{curr} and accessibility levels $A_i^{opt\ l}$, which include the investment option l are taken into account. Thus, A_i^{curr} is a measure of accessibility with initial travel times; and $A_i^{opt\ l}$ describes accessibility levels when including the travel costs improvements from the potential investment.

Furthermore, two dichotomous variables indicate if a link connects to other links in the entire railway network and in particular to links on the operator's network. Connecting to the existing rail network is presumed to add option values for revenues of later connections to further cities; operational cost reductions for an operator because inventory can be kept at one centralized point; and furthermore, operators might consider that having an extensive connected network brings prestige. Another dichotomous variable indicates whether a link provides a first connection to provincial capitals or to the country capital city, Amsterdam. Connecting to these cities might be attractive if investors expected larger growth of the passenger market in those cities and might have prestige value as well. Yet another dichotomous variable indicates if a link connects municipalities on the country border. This variable represents attempts to profit from international passenger and mail transport. A last dichotomous variable indicates whether a link connects to a sea harbour. This variable represents endeavours to connect Dutch sea harbours with their hinterlands by means of rail for the sake of goods transport.

Table 5-2. Results of fitting a conditional logit model on the attributes of the built and automatically generated unbuilt lines in the Dutch railway network.

Scenario	A (n = 3,160)		B1 (n = 3,193)	
	Coefficient	Z-score	Coefficient	Z-score
Return on investment				
Private lines	0.64**	(3.84)	1.28**	(3.81)
Private local lines	0.11	(0.58)	0.38	(0.79)
State lines	0.46	(1.64)	0.40	(0.81)
Change in accessibility inequality				
Private lines	6.59**	(3.03)	8.16**	(3.10)
Private local lines	-21.00**	(-3.83)	-20.53**	(-3.70)
State lines	-20.89**	(-4.48)	-23.20**	(-5.10)
Connects operator network				
Private lines	1.69	(1.76)	1.69	(1.78)
Private local lines	2.42**	(3.11)	2.22**	(2.87)
State lines	3.83*	(2.57)	4.07**	(2.76)
Connects railway network				
Private lines	-0.65	(-1.05)	-0.71	(-1.17)
Private local lines	0.05	(0.12)	0.14	(0.31)
State lines	-2.68**	(-3.41)	-2.77**	(-3.36)
First connection to a provincial capital				
Private lines	3.86**	(4.62)	3.77**	(4.55)
State lines	-1.67	(-1.34)	-1.90	(-1.47)
Connects border zone				
Private lines	3.45**	(4.96)	3.71**	(5.26)
Private local lines	-0.59	(-0.52)	-0.52	(-0.45)
State lines	0.06	(0.06)	-0.10	(-0.10)
Connects sea harbour				
Private lines	-0.35	(-0.53)	-0.43	(-0.64)
Private local lines	-0.11	(-0.17)	-0.01	(-0.01)
State lines	1.46*	(2.15)	1.41*	(2.11)
McFadden's Pseudo-R2	0.57		0.57	
AIC	262.95		265.37	

Table notes: Coefficients marked by * are significant at the 0.05 level; those marked by ** are significant at the 0.01 level. All others are not. No local line connected a capital first.

The built links in the choice set were derived from the database of constructed railway links. We have used the following definition of a link: a link connects at least two existing nodes (railway junctions, stations or municipalities), and has been realized by an investor as one integrated project within a limited number of years. We assume that the results of the applied models are more accurate in the case of longer links, and therefore weight the results of Eq. (1) by the length of built link o , normalized by the average length of all built links in period t so that the total number of observations in the choice model is not affected. To generate a choice set of unbuilt links we applied the following procedure: 1) a set of 50 alternatives was generated for all links that were built in one decade; 2) to simulate that investors presumably had limited capital in particular in the early stages of network development, the costs of railway construction of an alternative could not exceed the costs of a built railway in a longer period (either 1839 – 1859, 1859 – 1889 or 1889 – 1929); 3) selection of terminating municipalities and the routing of the intermediate path were not affected by the transport market saturation of municipalities MS .

Going through the results in Table 5-2, one finds that private line investors were focused on high return on investments, while, compared with other alternatives with reasonably good return on investments, local line and state investments were rather indifferent to maximizing their returns on investment. We must note that the results of an alternative model specification that included passenger mileage change on the whole network in the return on investment yielded worse results for all operators (results available upon request). We thus conclude that, consistent with other findings (Xie & Levinson 2011), the various operators were primarily preoccupied with the results for their own network. While private lines increased the disparities in accessibility in the country, private local lines and state lines aimed to decrease those disparities. The state presumably had political aims to decrease disparities in accessibility. These aims were, clearly, further enforced through subsidies and loans that accompanied the local railway act. All parties aimed to connect their new investments to their own network. The poor significance values in case of regular private lines presumably are due to the relatively large number of operators starting new networks in the early stages of network development. Private investors were apparently indifferent to whether their networks connected to competitors; while, surprisingly, state investments actively avoided connecting to other networks. Establishing the first connection to provincial capitals was sought after by private investors. Connecting border zones (and, implicitly, foreign railway networks) was also sought after by private line

investors. In contrast, connecting sea harbours was sought after only by the Dutch state, possibly to provide a stimulus to the Dutch ports or for defensive purposes. The lack of interest from private parties seems to confirm that in the Netherlands, there was a very limited market for the overland transport of goods (Filarski & Mom 2008).

5 Simulation results

The historically built network and the allocation results for various scenarios are plotted in Figures 5-4 and 5-5. The modelling efforts have yielded networks that are particularly dense in the Western, most urbanized part of the country. In contrast, the northern, eastern and southern parts of the country are much less served. Especially the southwest of the country seems to gain more investments than built in reality, while especially lines in the eastern and south-eastern parts of the country are underrepresented in the modelling results. An in-depth investigation of this bias is planned in follow-up research.

The differences in network shapes and network ownership are striking. In all cases private lines mostly function as trunk lines, with the state providing peripheral extensions to the trunk network and local lines providing connections between trunk lines. With the exception of scenario C, local lines do not seem to have a dominant feeder function. The density of the trunk line network depends on overarching conditions: for example, with a lower value of φ the trunk network appears to be more extensive (cf. scenario A vs scenario B1). Interestingly, in the B2 variant, one operator obtains complete monopoly in the private lines, and expands that network much more than happens in a more competitive setting (cf. scenario B1). Possibly the existence of greater network externalities allows for a greater density in the final network of the monopolist.

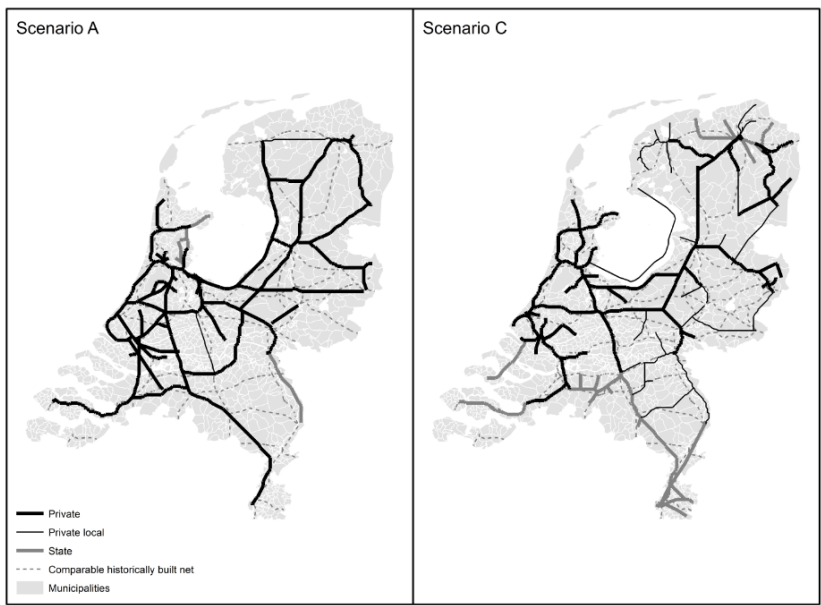


Fig. 5-4. TLS investment allocation results of the scenarios A and C.

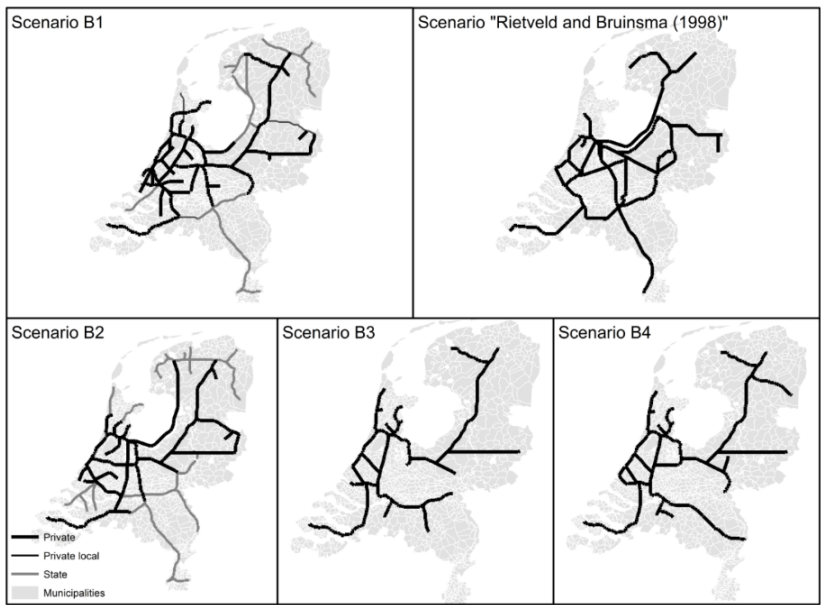


Fig. 5-5. TLS investment allocation results of Rietveld and Bruinsma (1998) and the B1, B2, B3, B4 scenario variants.

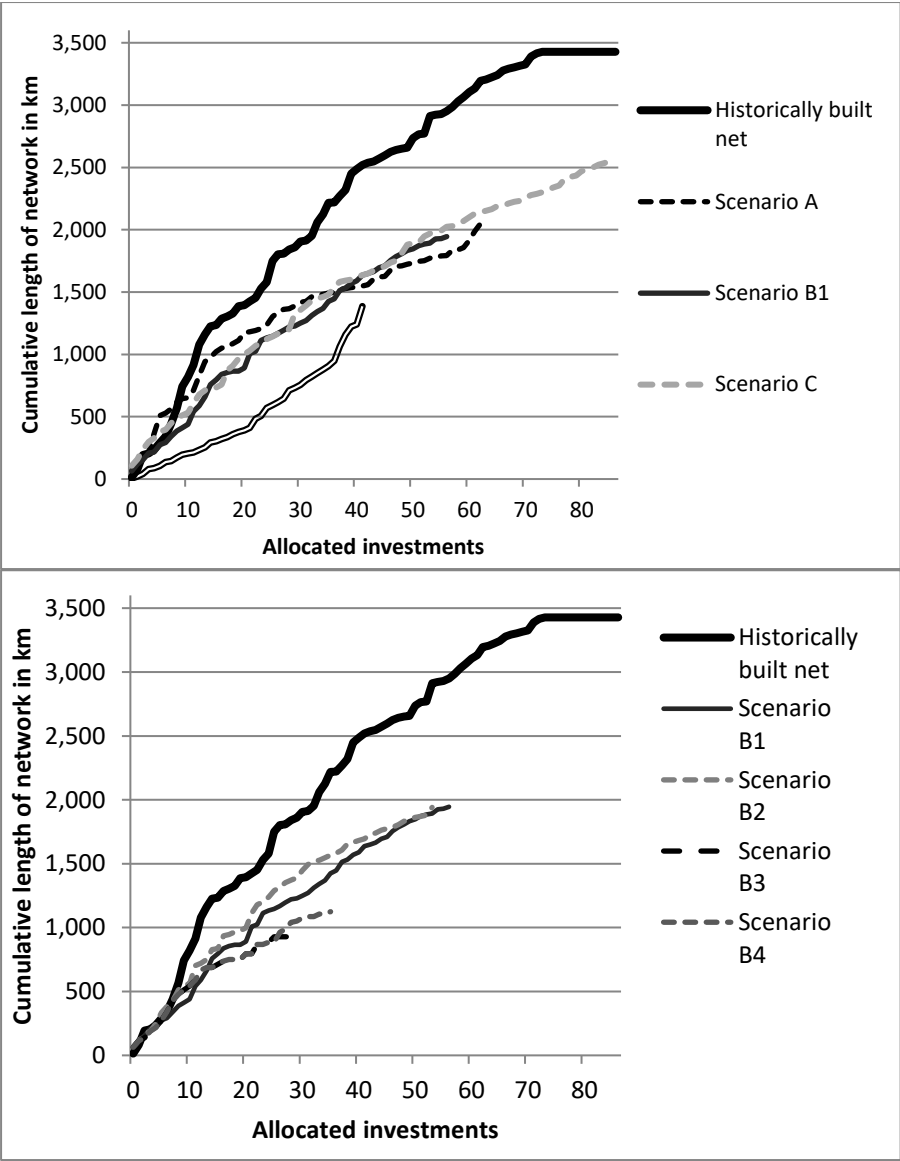


Fig. 5-6. Cumulative lengths of the modelled railway lines according to the scenarios A, B1 and C and the method proposed by Rietveld and Bruinsma (1998) (above); and the cumulative lengths of modelled railway lines in the B1 to B4 scenarios (below). The cumulative length of the built network has been added to both graphs for comparison.

The total cumulative length of the historical and modelled networks is shown in Figure 5-6. It is clear that after the first five investments or so, the model allocates network investments in smaller chunks than the historically built network, causing the lower per-investment growth of the modelled networks. This bias deserves to be tackled in follow-up research. In all cases the modelled networks reach a smaller length than the historically built network. That the simulated networks are smaller is either because the modelling framework fails to provide sufficiently attractive alternatives, or because state involvement and the ensuing fierce competition on the Dutch railway network caused overinvestment in the network, as suggested by Knick Harley (1982) and Veenendaal (1995). The latter explanation is further supported by the B3 and B4 variants which restrict the playing field to two private parties that are mainly driven by return on investment. In these scenarios, the early depletion of additions that increase passenger mileage cause much shorter final networks. Additional evidence can be found in the breakdown of network lengths per operator type in Appendix C, which shows a striking dominance of state-built lines in the historically built network. Lastly, lower growth and shorter final network length are particularly conspicuous in the Rietveld and Bruinsma network. The reasons for this are that method's known bias for short links (Rietveld & Bruinsma 1998) and the early depletion of the pool of 35 connectable cities. Experiments with removing the a-priori selection of connectable cities failed, because the adapted method only yielded very short connections.

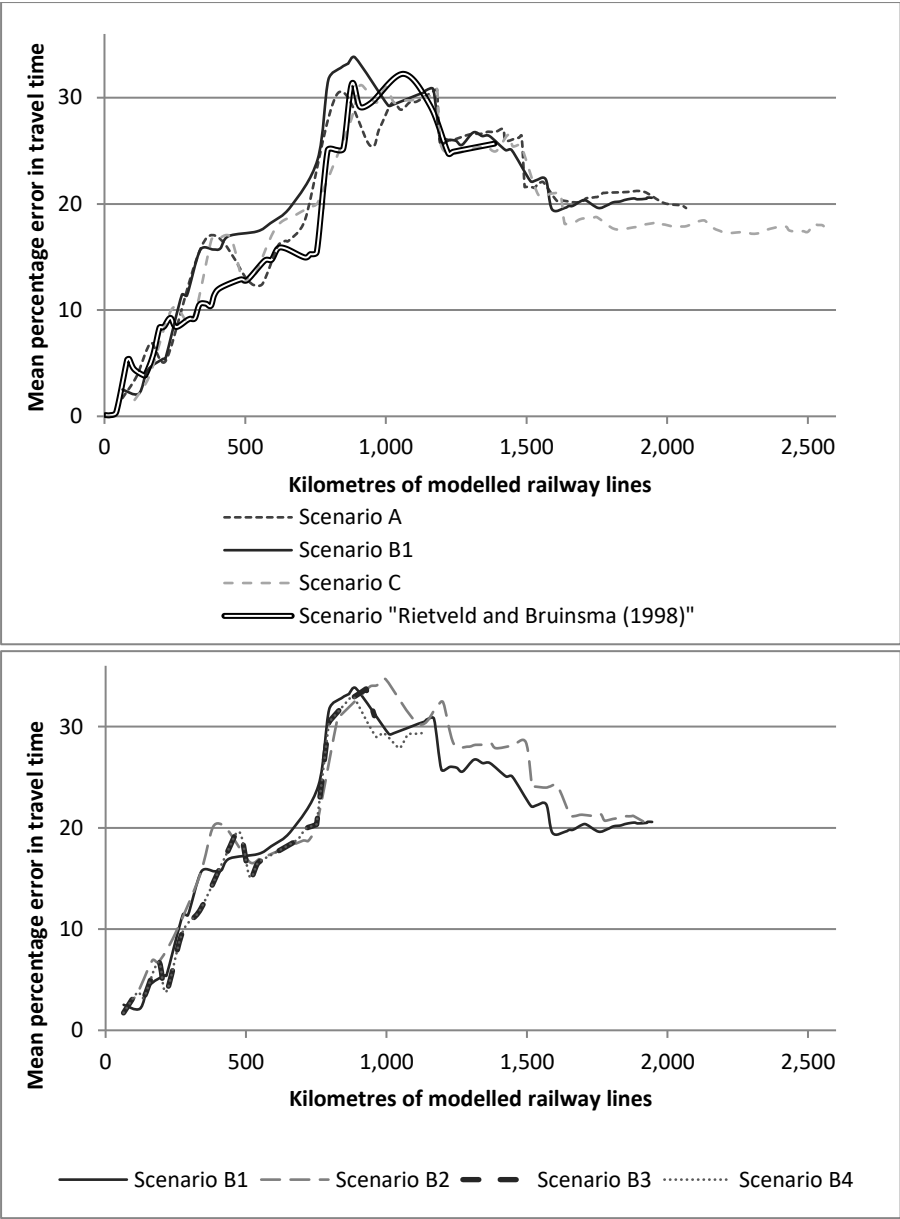


Fig. 5-7. Traveltime errors in the scenarios A, B1 and C and the method proposed by Rietveld and Bruinsma (1998) (above), and travel time errors in the scenarios B1 to B4 (below). Travel time errors are obtained by comparing with the result of the built network at an approximately similar length.

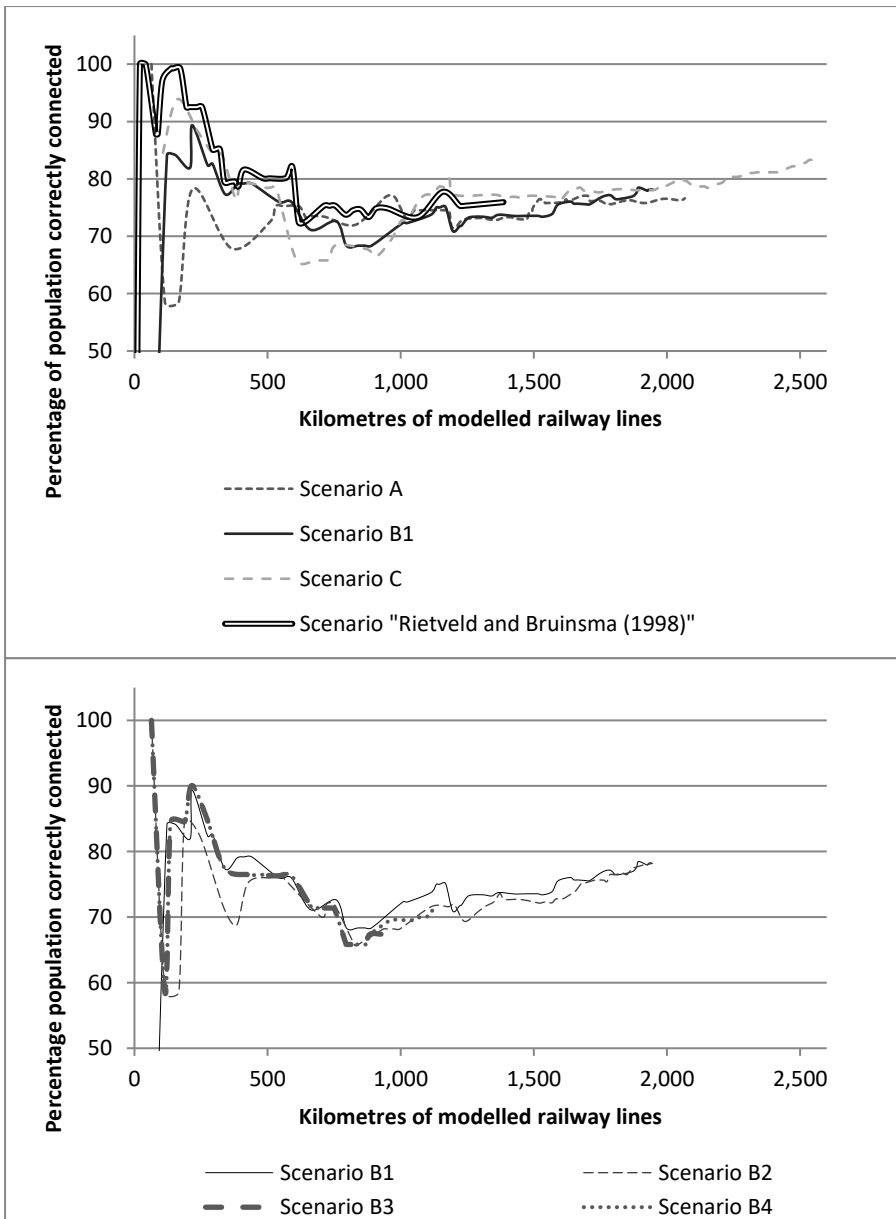


Fig. 5-8. Connection accuracy expressed as percentage of population correctly connected by railway lines in the scenarios A, B1, C and the method proposed by Rietveld and Bruinsma (1998) (above), and connection accuracy in the scenarios B1 to B4 (below). Connection accuracies are obtained by comparing with the result of the built network at an approximately similar length.

As noted before, two indicators were used in this paper to measure the relative geographic accuracy of the presented model. The computed accuracy indicators are plotted against investment sequences in Figures 5-7 and 5-8. Comparing both accuracy indicators, two contradicting trends become apparent. Where travel time errors increase as the railway network develops, connection errors decrease with network growth, as it becomes more likely the municipalities connected by the random network coincide with municipalities connected by the historical network. The simulation results start with a substantial increase in percentage travel-time error. These errors decrease after roughly 1,250 kilometres of allocated railway network. Both connection accuracy and travel-time errors remain relatively stable afterwards. This indicates that the model does a better job at reproducing the final form of the network than it does at the precise sequence of investments; it also shows implicitly that earlier network additions have a much larger impact on the distribution of travel times than last additions. We additionally note that, seemingly at odds with the variation in network shapes, model accuracy hardly changes between scenarios. This raises the question to what degree the presented weighted travel time errors are affected by transport network shape.

6 Closing remarks

This paper presents Transport Link Scanner, a model that simulates the expansion of transport networks. Based on a conditional logit method the model repeatedly selects one most attractive link from a choice set to add to the expanding network. That choice set is generated using heuristics with the goal to obtain a limited set of relevant, geographically plausible links. The model outlined in this paper explicitly allows the empirical estimation of preferences in a context with multiple actors with possibly different characteristics. It allows to test, amongst others, the impact of investor preferences, transport revenue structures and network effects on the final outcomes of a transport network.

A practical application of the model is presented as well. This exercise focuses on the expansion of the Dutch railway network in the 19th and early 20th century and compares the model's accuracy with a previous attempt by Rietveld and Bruinsma (1998). The results presented show that the early expansion of the Dutch railway network is simulated by TLS with similar accuracy as by Rietveld and Bruinsma, without the necessity of an a-priori selection of connectable cities. The results corroborate findings that transport network expansion follows a clear rationale (Rietveld & Bruinsma 1998; Xie & Levinson 2011; Levinson et al. 2012), show that

the modelling rationale can simulate network expansion processes with some success, and illustrate that institutional and economic settings may have a profound effect on network expansion outcomes. Future research may be necessary to further improve the accuracy of the model and measure its performance in terms of characteristic spatial network metrics (Rodrigue et al. 2006). One other useful addition would be the inclusion of socially optimal networks (Li et al. 2010) that would enable exploration of how competitive investment decisions can be directed towards social optima (Anshelevich et al. 2003). Nevertheless, we conclude that the model appears to become a useful tool for academic studies and policy evaluations.

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Appendix A: Transport link construction costs

In the choice set generation and in the estimation of investment attractiveness the construction costs of distinct investments come into play. In this study, the costs that are taken into account are a fixed cost and costs linked with the geography that the proposed link overcomes. For the sake of simplicity the costs for maintenance, personnel and inventory are currently ignored in the model. In the case study, the costs of constructing a link have been estimated using an ordinary least squares (OLS) regression of the following equation:

$$C_l = \beta_0 RIVER_l + \beta_1 HARDSOILS_l + \beta_2 SOFTSOILS_l + \varepsilon \quad (A.1)$$

in which guilders of recorded costs of 19th century rail construction projects in the Netherlands are explained by a constant and traversed meters of river, hard and soft soils. The hard soils class contains gravel, sand and loam. The soft soils class contains clay and peat. The recorded costs describe the costs imbued by the Dutch state in a number of network expansions between 1860 and 1880. These costs have been inflated to the 1913 level, and are assumed to be fixed (in real terms) over time. For the comparison of investment options, the geographic distribution of cost factors is much more important than temporal variations. Therefore we expect that this assumption does not substantially affect the results of this article. The OLS estimation results are given in Table A.1. Unfortunately, the exact locations of built-up land in the Netherlands in the 19th century and the costs of building railways through such built-up areas are not precisely known, so that we cannot model the presumably high costs of constructing railways in already urbanized areas. We note, however, that the Netherlands were a mainly rural country in the 19th century. Moreover, railway stations and railway lines were mainly built at the edges of the then existing cities.

Table A.1. estimated factors contributing to the costs of constructing a railway line.

	Coefficient	t-statistics
Constant	1,980,280.00*	2.39
Meter of river	2760.61	1.76
Meter of hard soil	12.38	0.55
Meter of soft soil	64.57*	2.57

Note: * indicates estimates significant at the 0.05 level. $N=38$. $R^2=0.14$

Appendix B: Passenger transport revenues

We assume that all links in the Dutch railway network have been built for the purpose of maximizing passenger transport profits (Veenendaal, 2008; Filarski and Mom, 2008). Clearly, return on investment played an important role in the development of the Dutch railway network. Revenues of railway network construction are computed here as increases in passenger mileage on an investor's network. Estimating these returns requires repetitively estimating a spatial interaction model and allocating the resulting flows on various proposed network configurations. The spatial interaction model applied in the case study is based on empirically obtained parameters and, amongst others, the assumptions that: 1) increasing interaction opportunities cause growth in the propensity of people to travel; and 2) no restrictions are imposed on the number of trips into zones because train travellers' motives for visiting specific zones are unknown. Alonso's GTM enables parameterization of the degree to which opportunities and competition or congestion affect demand, and encompasses all variants of Wilson's family of spatial interaction models as special cases (De Vries et al. 2001). We do not take the effects of competition or congestion at the destination into account, so that we effectively apply:

$$T_{ij}^* = A_i^{(1-\gamma)} P_i P_j f(c_{ij}) \quad (\text{B.1})$$

$$A_i = \left\{ \sum_{j=1}^n B_j^{1-\theta} P_j f(c_{ij}) \right\}^{-1} \quad (\text{B.2})$$

where T_{ij}^* represents observed passenger trips from i to j , A_i indicates origin-specific potential accessibility, P is population size, and $f(c_{ij})$ is a travel cost decay function. In the model the number of trips going to a specific destination is not restricted, so that θ is set to one. The function $f(c_{ij})$, and subsequently the value of γ , are estimated in two steps as proposed by De Vries et al. (2002). We first

estimate $f(c_{ij})$ by regressing the log specification of a singly-constrained gravity model, as proposed by Fotheringham and O'Kelly (1989):

$$\ln(T_{ij}^*) = \delta_i O_i + \alpha_1 \ln(P_j) + \beta_1 \ln(c_{ij}) + \varepsilon_{ij} \quad (\text{B.3})$$

where c_{ij} denotes the shortest travel time from i to j , and O_i is an origin-specific fixed-effect dummy. To estimate this spatial interaction model that may include zero flow observations, we use $\ln(T_{ij}^* + 0.5)$ to replace $\ln(T_{ij}^*)$ as suggested by Sen and Sööt (1981). We have estimated the distance-decay parameter in both exponential and power specifications of the distance-decay function. The latter consistently yielded better results. Data on travel flows was obtained from sold train tickets between the 14 stations on the Amsterdam to Rotterdam rail line (HSM 1889). We find that $f(c_{ij}) = s_{ij}^{-1.777}$, and use this to compute A_i , as defined in Eq. (B.2). Although changing the distance-decay parameter substantially influences absolute marginal returns, we find that the ratios of the marginal returns of different lines are hardly affected. The value of β appears to have only a small impact on our findings¹⁸. We subsequently regress:

$$\ln(T_{ij}^*) - \ln(P_i) - \ln(P_j) - \ln(s_{ij}^{-1.777}) = (1 - \gamma) \ln(A_i) + \varepsilon.$$

All results of demand model estimation are presented in Table B.2.

Table B.2. Parameters estimated from sold railway tickets on the Amsterdam to Rotterdam line in 1888.

	α	t	β	t	R^2	N
Eq. (B.3)	0.825	26.33	-1.777	-18.97	0.989	182
			γ	t	R^2	N
Eq. (B.4)	—	—	0.304	41.44	0.905	182

Note: All parameters are significant at the 0.01 level.

T has a 0.3 elasticity to both accessibility and travel cost. This means that the total number of trips originating in i increases when the accessibility of i increases. To assess the impact of model specification on the results of the later choice analysis, we alternatively analyse link railway construction choices when changes in travel

¹⁸ The results are available on request.

cost only cause substitution at the origin (i.e. γ is set to zero), which implies that railway investments do not affect the total number of trips.

A multiple-path logit model is subsequently used to allocate flows to the network (see Stern and Bovy 1989):

$$P_r = \frac{\exp V_r}{\sum_{h=1}^n \exp V_h} \quad (\text{B.5})$$

with P_r being the probability that a traveller chooses path r ; and V_r and V_h describing the travel values of path r and all paths h , respectively. Alternative paths are generated by means of a link elimination method (Bekhor et al. 2006). In the case study the utility of paths is defined as $V_r = \alpha(c_r)$, with $\alpha < 0$ and c indicating travel times. As the interaction data available for the case study do not allow estimation of the utility parameter, we resort to other literature. A parameter from Vrtic and Axhausen (Vrtic and Axhausen 2002) is applied, which is -2.398 (for hourly increases of travel time). We use this parameter in Eq. (B.5) because it is estimated on longer distance train trips, implying a similar context as in our study.

Appendix C: Results per operator type

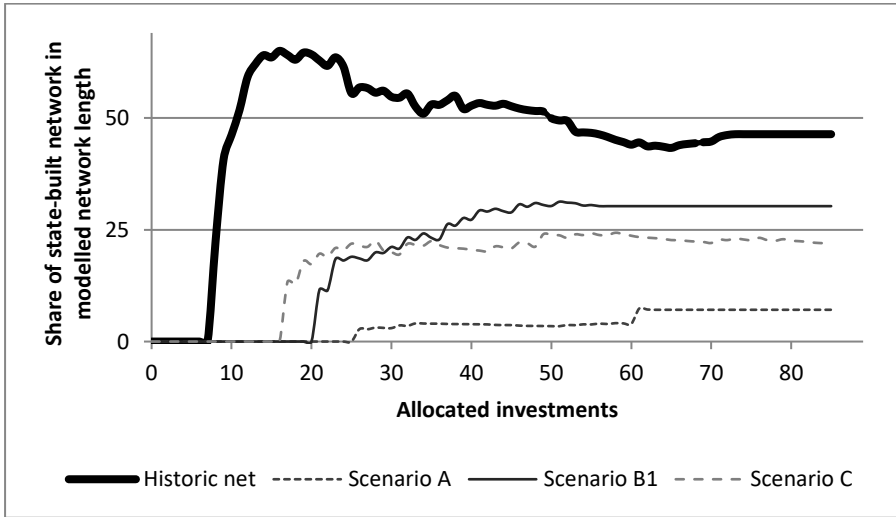


Fig. C.1. Shares state-built network length in total network length.

In this appendix, simulation results per operator type are discussed for the scenarios A, B1 and C, and where relevant also for the results of the Rietveld and

Bruinsma (1998) model. The emphasis is put on scenario comparison and implications for network expansion modelling.

In Figure C.1 the lengths of the state-built network in the scenarios discussed are shown as shares of total network length. From the results it is clear that, in contrast to the historically built network, all networks modelled obtain a much smaller share of state-built links. Larger values of ϕ result in larger state involvement, presumably because potential investments with good return on investment are depleted faster. The very early onset of state involvement in the historically built network is particularly striking. State involvement was relatively early because network expansion in the study area was particularly slow at the start (see Veenendaal, 1995). This was the case either because of market imperfections left out of consideration, or because the almost exclusive reliance of the transport network on passenger transport that yielded poor absolute revenues.

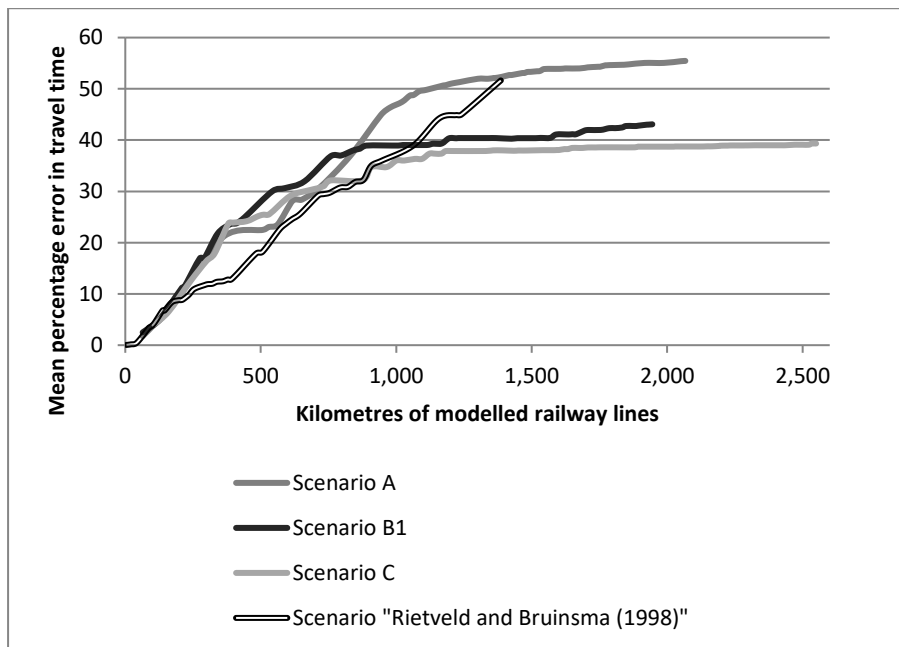


Fig. C.2. Mean percentage error in traveltime on regular private railway lines.

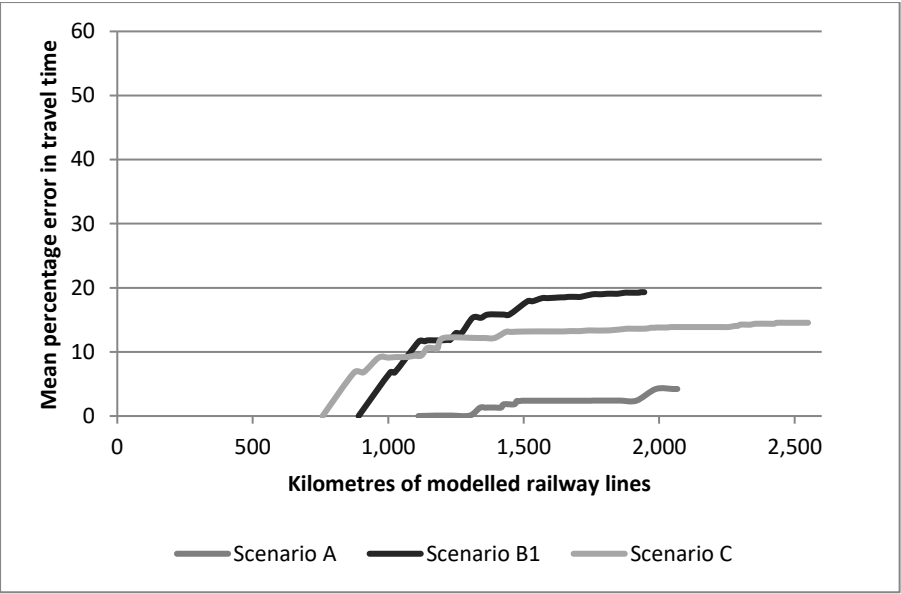


Fig. C.3. Mean percentage error in traveltime on state-built lines.

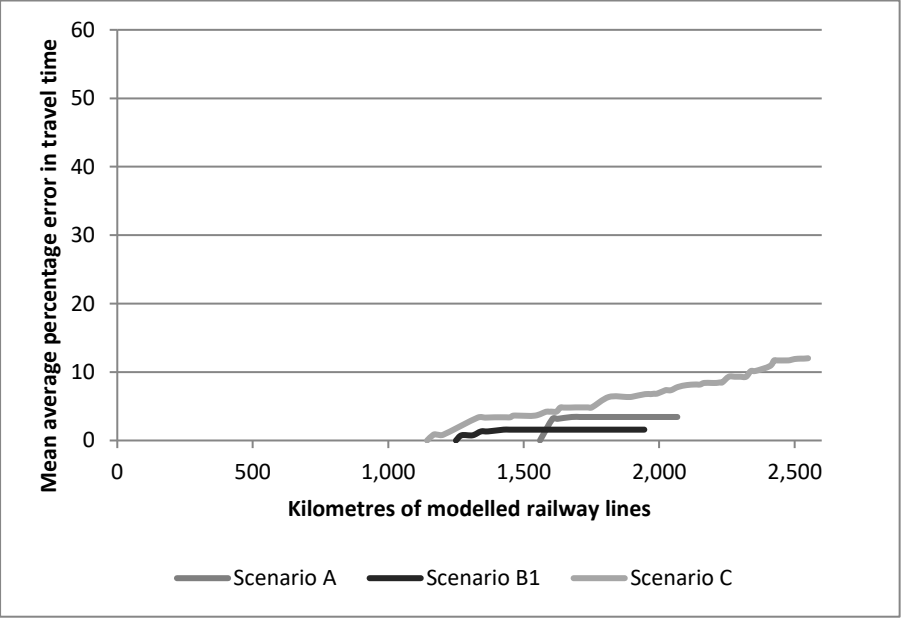


Fig. C.4. Mean percentage error in traveltime on local private lines.

Figures C.2 to C.4 show the mean errors in travel time when only considering the networks built for regular private lines, state lines and local private lines,

respectively. The travel times on the subnets are compared with similar subnets of the historically built network in which the total reference network is about as long as the total network modelled. Thus, the demonstrated mean errors reflect both discrepancies in shares per operator type and errors in travel times modelled. From these results it is clear that the scenarios B1 and C are the best performers, thus leading to the conclusion that a value of φ of at least five has been obtained by the railways. When comparing the different operator types, the population-weighted errors presented here mostly reflect the transport relevance of the various operator types. Regular private lines served the largest cities, and network allocation errors on the regular private networks consequently cause emphasized relative errors. In contrast, the errors on state and local lines have a much lower weight.

Appendix D: Nomenclature

A_i	Interaction options at the origin (destination accessibility).
Alternative	Potential addition to the network represented by a link.
Base	Network before introduction of modelled transport mode or characteristic of existing transport mode.
B_j	Interaction options at the destination (origin accessibility).
C	Construction costs of link or segment.
c	Generalized travel cost of link or segment.
cp	Penalty for entering and exiting the introduced transport mode.
curr	Network state at start of model iteration.
est(x)	Estimated network state with treated investment choice in place (multiple versions indicated by x).
i	Origin municipality.
INEQACC	Changes in the Theil's index of accessibility due to a considered investment option.
intr	Characteristic of introduced transport mode.
Investor	Agent deciding on investments and obtaining revenues from the investment.
j	Destination municipality.
k	Parameter used while iterating plausible paths with changing importance of path length.
L	Length of link or segment.
Link (l)	Connection between two municipalities (i and j) physically represented by a path.

MS	Market saturation of i or j , computed as potential number of trips to be gained from link connection given the current and future network state.
Operator	Agent deciding on investments and obtaining revenues from the investment.
Option	Potential addition to the network represented by a link, considered for investment by an investor.
P	Municipal population.
Path	Combination of segments that forms the physical representation of an alternative.
R	Crudely estimated revenues of a link or segment, instrumental in the generation of plausible paths, computed by averaging connected population multiplied with MS.
RC	Revenue-cost indicators per segment, instrumental in the generation of plausible paths, computed as ratio of R vs C.
RCR	Factor to be optimized in choice set generation computed as ratio of estimated increase in passenger mileage versus the costs of link construction.
ROI	An alternative's expected Return on Investment, computed as the ratio between estimated transport flows on the investor's network and the costs of constructing the alternative.
Segment (s)	Individual, unseparable lines from which paths are composed.
T	Trips between municipalities i and j .
V	Speed of transport mode.
WCE	Population-weighted connection error, used as accuracy indicator.
WMAPE	Population-weighted average errors in traveltimes between municipalities, used as accuracy indicator.
Z	Selection dummy used to obtain a limited set of alternatives in the first step of choice set generation.
B	Parameter governing distance decay model.
γ	Parameter governing transport consumption elasticity to travel cost at the origin.
δ	Parameter governing trip production for each municipality as a fixed effect.
θ	Parameter governing congestion effects at destination on destination attractiveness.
φ	Parameter indicating relative travel cost decrease offered by introduced transport mode.

Part IV: Assessing spatial planning related impacts of the interactions between land-use patterns, local and long-distance interaction opportunities

Chapter 6. Evaluating the impact of land-use density and mix on spatiotemporal urban activity patterns

Abstract: *Dense and mixed land-use configurations are assumed to encourage high and prolonged activity levels, which in turn are considered to be important for the condition of urban neighbourhoods. We used mobile phone usage data recorded in Amsterdam, the Netherlands, as a proxy for urban activity to test if the density in different forms of urban land use increases the level of activity in urban areas, and if mixed land uses can prolong high levels of activity in an area. Our results indicate that higher densities correspond with higher activity levels, mixed land uses do indeed diversify urban activity dynamics and colocating particular land uses prolongs high activity levels in the evening hours. We proceed to demonstrate that mixed activity provisions and high urban activity levels coincide with urban neighbourhoods that are considered attractive places in which to live and work, while lower activity levels and markedly low activity mixes coincide with neighbourhoods that are considered disadvantaged.*

Key words: Mobile phone usage, land-use density, land-use mix.

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1 Introduction

Since at least the 1990s there has been increasing political support for planning approaches that aim to achieve dense and mixed urban land-use patterns (Grant 2002; Stead & Hoppenbrouwer 2004; Vreeker et al. 2004). The desired land-use patterns are expected to improve urban vitality, safety and quality of life, and make cities more sustainable and attractive (Coupland 1997). As Hoppenbrouwer and Louw (2005) point out, many of the arguments used in favour of dense and mixed land use are still based on Jacobs (1962), who argued that such land-use configurations increase and prolong activity intensities in a neighbourhood. In her seminal work Jacobs observed that (1) safe and pleasant public spaces are the distinguishing characteristic of vibrant urban neighbourhoods, and (2) public spaces in large cities have very specific requirements in order to function effectively. Jacobs argued that in the public spaces of vibrant urban neighbourhoods an ad hoc social structure exists that maintains order (i.e., provides natural animation; Petterson 1997) and stimulates residents to watch or

engage in the daily events in public space (i.e., provides natural entertainment; Montgomery 1995). Such a social structure, upheld by residents and strangers passing by, would emerge naturally when diverse people are almost continuously present on a neighbourhood's streets. Jacobs (1962) argued that in order to have sufficient, continuous human presence in public space, urban areas need to support activities with sufficient intensity and diversity in terms of temporal participation patterns, so that pedestrians populate the streets for substantial parts of the day.

Dense land-use configurations are expected to contribute to vibrant neighbourhoods by increasing urban activity intensities. One may argue that increasing land-use densities might instead lead to unwanted crowding effects, but perceived crowding and available physical space per capita are often unrelated (Bonnes et al. 1991; Fischer et al. 1975) and perceived crowding depends much more on other factors (Chan 1999). Mixed land-use configurations are expected to extend activity intensities, and diversify the 'ebbs and tides' of people coming and going into an area to participate in the activities provided (Roberts & Lloyd-Jones 1997: p.153). Mixed land use is furthermore presumed to generate multiplier effects that help extend activity intensities by retaining people in an area that they initially visited for another activity (Jacobs 1962; Rodenburg et al. 2003).

Contemporary planners have adopted Jacobs's ideas, and found that encouraging higher and extended activity intensities by developing dense and mixed land-use configurations can have disappointing results. This is particularly unfortunate because dense and mixed developments are often very difficult to achieve (for experiences with establishing such developments, see Coupland 1997; Grant 2002; Majoor 2006; Petterson 1997; Rowley 1996). There are reasonable arguments why developing denser and more diverse land uses might not contribute to neighbourhood success at all. First and foremost, there is no proven impact of the physical environment on behaviour, as emphasised by Gans (1991). Another problem is that the demand for the specific type of urban environments at which densification and mixed development aim is presumably limited, and as Gans notes, may only stem from the upper middle class and young urban professionals. Furthermore, existing social environments in the city may already have established a hierarchy of preferred places to which their events and activities are closely tied (Currid & Williams 2010). If such environments are indeed tied to particular places, the development of new activity spaces is successful only if the new spaces provide

additional facilities that do not compete with the established hierarchy, or if a new type of social environment emerges.

Clearly more work is needed to find if dense and mixed land-use patterns can indeed foster vibrant neighbourhoods. Besides Jacobs's work, only a few case studies have linked land-use density to desirable aspects of vibrant neighbourhoods such as attractiveness (Gadet et al. 2006) and low crime rates (Coleman 1985; Petterson 1997). These studies neither yield conclusive evidence on this subject, nor address the overall link between land-use intensity and activity levels. A data source that has recently become available – mobile phone usage data – is used in this article to evaluate empirically the potential impact of dense and mixed land use on urban activity intensities. We used phone usage densities as a proxy for urban activity intensity and, for each hour of the day, statistically analysed the link between, on the one hand, activity levels and, on the other hand, the densities of various land uses and the interactions between colocated land uses. We did so in order to verify if higher land-use densities correspond with higher activity intensities, if the activities associated with those land uses have diverse temporal patterns and if multiplier effects exist between particular activities supporting each other when colocated. Subsequently, to test if high and extended activity intensities do indeed coincide with favourable neighbourhood conditions, we compared observed and modelled phone usage densities in (1) districts that experts consider successful in attracting members of the creative class, and (2) districts that according to experts are accumulating persistent social, economic and physical problems. We must emphasise here that we explored the coincidence of activity patterns and neighbourhood conditions, but have not verified the causal link proposed by Jacobs (1962) between activity intensities and neighbourhood success. In fact, there are many factors affecting the neighbourhood conditions analysed, and a thorough study of the mechanics that govern those conditions is well beyond the scope of this paper. In the following section we expand on the data and methods used; in the subsequent sections we demonstrate our evidence in favour of dense and mixed land-use configurations.

2 Data, methods and limitations

For this study, mobile phone data recorded between January 2008 and November 2010 has been obtained from KPN, one of the main telecommunication service providers in the Netherlands. Such mobile phone usage data have been emphasised as particularly suitable for urban analysis (Ratti et al. 2006). Recent

contributions using such data have explored seasonal migration and the composition of traffic flows in Estonia (Silm & Ahas 2010; Järv et al. 2012); linkages between phone usage and city characteristics in Rome (Reades et al. 2009) and the locations of personal 'anchor' activity bases in Estonia (Ahas et al. 2010: p. 4). The activity patterns that Ahas et al derived are very similar to the spatial distribution of the population as observed in census data, and the authors therefore concluded that mobile phone usage is suitable for studying urban activities. The present study also presumes such a link between human activity patterns and mobile phone usage.

One important issue arises regarding privacy considerations that relate to the storing and analysing of personal communications, such as in the data used. The data obtained contain only aggregate usage statistics per mobile phone cell, and characteristics of the mobile phone users were not recorded. Thus, the data cannot be used to identify individual users and we therefore assume that privacy concerns are not problematic for this study. We elaborate on the mobile phone usage data, the modelled linkages with land-use and activity patterns and some methodological limitations in the next sections, after addressing the study area. A scheme of this paper's approach can be found in Figure 6-1.

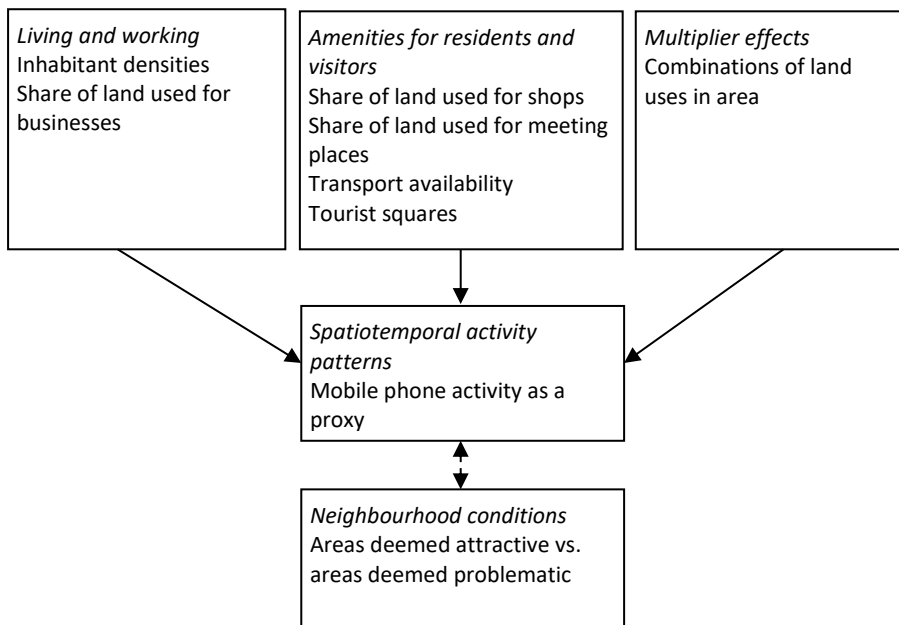


Fig. 6-1. Conceptual scheme for this paper's analyses, and the operationalisation of the main variables applied.

The city of Amsterdam in the Netherlands, entailing considerable geographical differences in urban density and in the degree of land-use mix, will serve as a case. Because the mixed-use literature seems to concentrate on land-use mixing in residential areas (see, for example, Cervero 1996; Jacobs 1962), we also limit our study to areas that have a residential purpose. We therefore only use data from antennas within urban districts with a population density of at least 200 inhabitants per km². Note that Amsterdam's average population density is 3,800 inhabitants per km². Only rural and dominantly industrial areas on the outskirts of the city are excluded: for example, the largest excluded area is the port in Northwest Amsterdam. A map of the study area depicting key variables is shown in Figure 6-2.

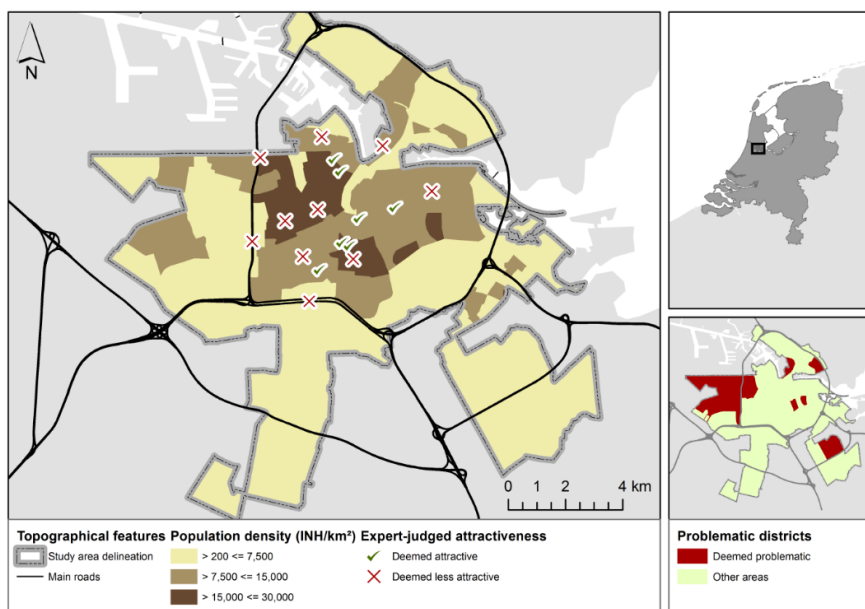


Fig. 6-2. Amsterdam, its population densities, the boundaries of the studied area, the suggested attractiveness of locations (Gadet et al. 2006), districts deemed problematic (Bicknese et al. 2007) and the location of Amsterdam in the Netherlands.

2.1 Describing the mobile phone usage data

Mobile phone usage data are spatially explicit because mobile phone network mechanisms make it possible to infer caller locations with more or less accuracy, depending on the characteristics of the available data. In some cases, triangulation

of individual caller locations is possible (ACA 2004) and phone usage can be accurately mapped on a fine resolution grid (Calabrese et al. 2007). In other cases, usage statistics are only available in an aggregated form per antenna, and then attributed to portions of space where callers using that antenna are presumed to be. Examples are cases in which mobile phone usage has been interpolated into a continuous surface (Ratti et al. 2006) or attributed to superimposed catchment areas (Ahas et al. 2010). The mobile phone usage data provided for this paper are attributed to a similar network-specific zonal topography named 'best-serving cells'. These cells are the results of sampling and subsequently mapping which antennas provide the best connection and they represent the areas that are *usually* connected to a particular antenna. Temporary changes in the network structure are not taken into account. This topology is created by the mobile phone service provider, who unfortunately does not allow disclosure of its mapping work.

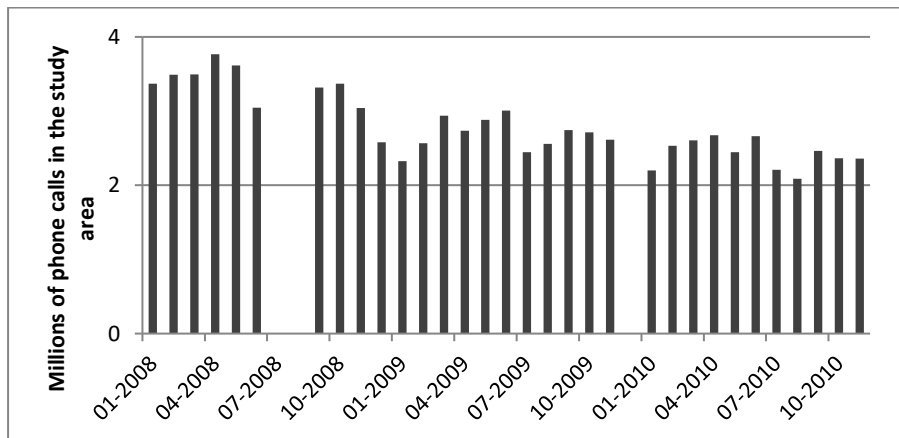


Fig. 6-3. Monthly averages of new calls per day via the 2G network. Data for some intermittent months were not provided. The decrease in phone usage over time is caused by an increasing proportion of calls carried through the 3G network.

Phone usage on the provider's network in the Amsterdam region has been made available for this study, save a number of months for which data are missing. There is a distinction between mobile phone usage data in which all phones *connected* to the network are recorded and data in which only phones that are *using* the network are recorded. The obtained phone usage data describe aggregate use: for example, the number of newly initiated calls per mobile phone cell per hour per day. Figure 6-3 indicates that, on average, more than 2 million phone calls were

made over the 2G network each day in the observed period in the Amsterdam region.

We observed Y_{it} as the average number of newly initiated mobile phone calls¹⁹ per hour (t) through antennas (i) per square kilometre of the best serving cell. The average number of new calls has been computed here as the average number of newly initiated phone calls per hour on all recorded working days from January to June 2010. Those data were used in 24 cross-sectional regressions, one for each hour of the day. The analysis centres on observations from that period because they are reasonably close to the land-use data that are only available for 2012, while due to network changes, results from after June 2010 are structurally different (this is also discussed in the following section). We expected that because of the averaged nature of the dependent variable, sporadically occurring events such as the Queen's Day national holiday would not have a substantial effect on our results. To test the robustness of our findings, we have repeated our analyses with data for all available months.

Some pre-processing has been necessary to use the data. The data originally comprised phone usage statistics from two frequencies (900 and 1800 MHz), of which the antennas have overlapping but differently sized and shaped catchment areas. Network mechanisms such as capacity balancing mean that mobile phone usage statistics of the two frequencies are inextricably related, and therefore need to be analysed together. The data have therefore been integrated into summed statistics for the smaller 900 MHz frequency cells that handle the largest proportion of network traffic. Phone usage statistics of the 1800 MHz frequency have been disaggregated to that topology based on proportions of the overlapping areas.²⁰ When mapped, the data capture substantial temporal and geographical differences in activity levels (see Figures 6-4 and 6-5).

¹⁹ Other studies (Ratti et al. 2006; Reades et al. 2009) use bandwidth consumption ('Erlang'). We prefer newly initiated phone calls as an approximation of human presence because we expect that this indicator is less biased towards activities that accommodate a disproportional amount of bandwidth. Furthermore, we expect that the portion of calls related to transportation is lower in new phone calls because we assume that people who are travelling (by car or by bicycle) are less likely to initiate a mobile phone call. This is useful because we want to focus on the presence of people in a place, rather than the flows of people in space.

²⁰ Thus, if 1% of one 1800 MHz area overlaps one particular 900 MHz cell, 1% of traffic recorded in the 1800 MHz area is attributed to that 900 MHz cell, and so on.

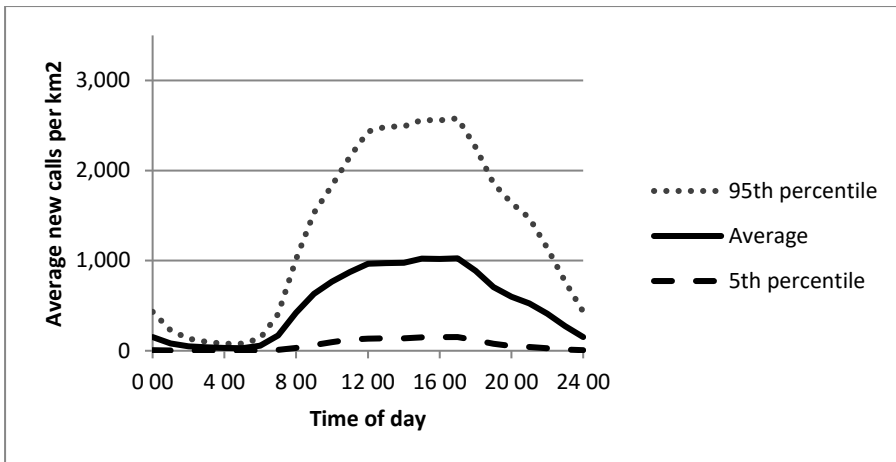


Fig. 6-4. Fifth percentile (perc.), 95th percentile and average number of new calls over the course of the day per km².

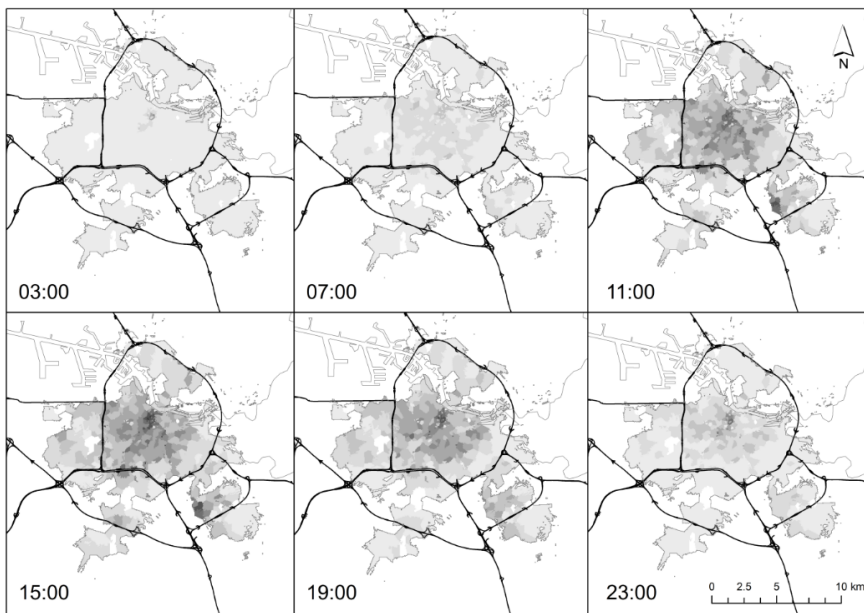


Fig. 6-5. Spatial distribution of new calls per km² in Amsterdam and its environs (workday averages 2008–2010). Dark black lines indicate motorways. The study area is gray with a darker outline, except for the white areas within it, which indicate missing data.

2.2 Explaining spatiotemporal patterns in mobile phone usage

We assume that the time and location of mobile phone usage is related to general human activity patterns and the location where these activities take place. The temporal activity patterns in the Netherlands have been rather stable since at least the 1970s (De Haan et al. 2004). The average weekday participation rates of the Dutch population in a selection of activities are shown in Figure 6-6. These national participation rates are likely to differ from the participation rates of the population studied here, but a comparison with Figure 6-4 shows a clear relation between overall participation in activities and mobile phone usage. From Figure 6-6 we can hypothesise that, given the dominant participation rates for working and leisure activities (whether at home or outdoors) throughout the day, these activities will likely have the largest impact on mobile phone usage densities.

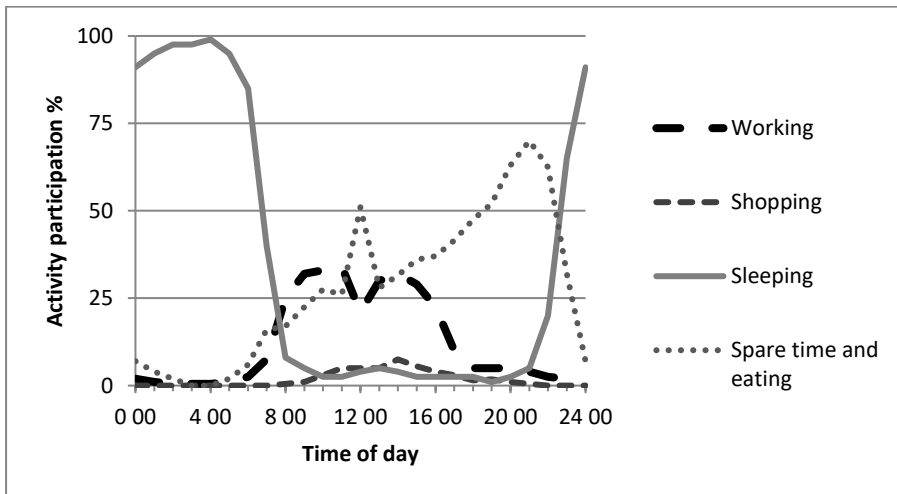


Fig. 6-6. Temporal variation in a selection of weekday activities by percentage of Dutch people older than 12 years of age who participate in them (Breedveld et al. 2006; Cloin et al. 2011).

The activities distinguished in Figure 6-6 are likely to take place at different locations, so we propose an explanatory framework that combines the basic activities with a spatial representation of the locations where these activities are concentrated. This spatial context is offered by detailed land-use maps that highlight the locations where working, shopping and leisure activities at home and outdoors are concentrated. In this explanatory framework we fitted mobile phone usage densities on different land-use types that can be associated with the main types of human activity (Table 6-1). This approach allows us to explain

spatiotemporal variation in mobile phone usage and provides insight into the importance of land-use density in generating the concentrations of people active in the urban environment. By specifically looking at the impact of different combinations of land-use types, we are also able to assess the importance of land-use mixing in generating urban activity.

Table 6-1. Land-use types and their definition.

Leisure at home	<i>Inhabitants per square kilometre, reflecting leisure opportunities at home</i>
Working	<i>Proportion of area used by factories, offices and schools, reflecting working opportunities</i>
Shops	<i>Proportion of area used by shops, reflecting shopping opportunities</i>
Outdoor leisure	<i>Proportion of area used by various building types dedicated to social meetings such as cafés, restaurants, churches, conference rooms and discotheques, reflecting outdoor leisure opportunities</i>

The land-use data are obtained from two data sources. Activities at home are observed by means of inhabitant densities per km², aggregated to the best serving cells from approximately 18,000 postcodes in the study area (CBS 2006). Working, shopping and social activities are approximated by means of land-use densities that are computed as the summed sizes of partial or total building footprints designated to a particular land use versus the total area of the catchment area. The building footprints and designations are derived from detailed building footprint data (Kadaster 2013) in which the land-use designations of all independent units (e.g., apartments or offices) within all buildings in the Netherlands are recorded. To compute land-use densities from those independent units, the total areal footprint of buildings is distributed equally over all the independent units that a building contains, and the total footprints of those independent units are summed per land-use type per mobile phone cell. Thus, if a building with a 60 m² footprint contains three independent units, of which two are designated to land-use A and one to land-use B, 40 m² of the building's footprint is attributed to A and 20 m² is attributed to B. We must acknowledge that information on floor space per independent unit is not included in this data, which may possibly skew the density figures because building heights will be higher in particular areas of the city. However, the data applied still provide a much more detailed description of land uses than the remotely sensed data that are often used in land-use studies, and we

believe that the data used are a workable alternative as long as more accurate sources such as information on floor space are unavailable.

2.3 Methodological limitations

The data used impose a number of important limitations. A first limitation is that some activities likely encourage phone use more than other activities. Thus, mobile phone usage is presumably biased towards certain activities. We assumed this is not problematic because all activities are captured to some degree in the modelling exercise, which is sufficient for this study. Another limitation is that, while neighbourhoods supposedly need pedestrians, the data used does not discern callers that are outdoors or indoors. We thus have to assume that higher activity intensities and more diverse temporal activity patterns lead to more pedestrian activity. This likely holds true in Amsterdam, a city that actively discourages private car use.

Another concern related to the used mobile phone data is that only phone usage data from the so-called 2G network have been obtained, while during the observed period, mobile phone services were provided in the Amsterdam region by both second generation (2G) and third generation (3G) network technology. Especially in 2010 a substantial share of mobile phone usage, 36%, has used the 3G network (see KPN 2011), which causes the previously mentioned shift in results after June 2010. Nevertheless, the majority of phone calls used the 2G network even in 2010, and we therefore believe that the shift in traffic from 2G to 3G has not severely affected our findings.

Other limitations are related to the spatial nature of phone usage data. The zones used cover an area of 0.5 km² on average, and are thus of a relatively fine spatial resolution, but still much larger than the streets and blocks analysed in other studies of land-use mixing (Hoppenbrouwer & Louw 2005; Jacobs 1962; Rodenburg et al. 2003). Because of the fixed resolution of the available data, the detail of those previous studies cannot be repeated here, and we cannot account for relevant aspects of urban land-use configuration such as street connectivity and grain size. We nevertheless expect that the spatial and temporal comprehensiveness of the data used is valuable for understanding the effects of land-use density and mix on activity levels. Another difficulty of using data based on presumed antenna catchment areas is that, because the antenna providing the best connection to one place may vary with temporal conditions, changes in the built environment or even chance reflections in water, the link between caller

location and the connecting antenna is of a stochastic rather than deterministic nature. Thus, callers are often falsely attributed to neighbouring catchment areas (see also Ahas et al. 2010). We presume that this is one cause of spatial autocorrelation in the data. To overcome spatial autocorrelation in the data, a spatial error model is applied (see Anselin 2001; LeSage & Fischer 2008). Furthermore, the use of discretely bordered areal units brings forth the modifiable areal unit problem (Openshaw 1984), of which the differences in areal sizes of zones in particular can bias statistical findings (Arbia 1989). These biases can in part be overcome by normalising observations by average cell size (see Jacobs-Crisioni et al. 2014, for a recent overview), which we do by means of equation (1):

$$S_i = A_i / \left(\frac{1}{n} \sum A_i \right), \quad (1)$$

where weight S is computed for each cell i by means of geographical area A .

3 The impact of land-use density and mix on hourly urban activity patterns

To estimate the impact of land-use densities and mixes on mobile phone usage in zones ($i = 1, 2, \dots, 362$), we fit the spatial error model shown in equation (2) repeatedly on the selected time frame's averaged new call densities for one hour of the day ($t = 0, 1, \dots, 23$):

$$\begin{aligned} Y_{i,(t=0,1,\dots,23)} = & \beta_0 + \beta_1 INH_i + \beta_2 BUS_i + \beta_3 SH_i + \beta_4 MP_i + \\ & \beta_5 (BUS_i * MP_i) + \beta_6 (SH_i * MP_i) + \beta_7 (BUS_i * SH_i) + \beta_8 TS_i + \\ & \beta_9 METRO_i + \beta_{10} STATION_i + \beta_{11} MWAY_i + \rho W_{ij} \varepsilon_j + \mu_i, \end{aligned} \quad (2)$$

in which the observations i are additionally weighted with the weighting values S_i discussed in Section 2.1. In our approach the impacts of densities of inhabitants (INH), businesses (BUS), shops (SH) and meeting places (MP) on phone usage levels are estimated. Furthermore, potential interaction effects between different land uses are captured. We are aware that land-use mix is an ambiguous concept which in all cases has to do with land-use diversity within cities, but which can occur on varying scales and with varying impacts on activity dynamics (Rowley 1996). Unsurprisingly, there are many methods to measure degrees of land-use mixing;

for an overview, we refer to Manaugh and Kreider (2013). We model land-use mixes by means of interaction effects between the densities of particular land uses colocated within one areal unit. On a side note, aggregate indicators of land-use mix based on the Herfindahl concentration index have also been tested, but did not yield useful results. The reason is no doubt that such aggregate indicators do not distinguish individual land-use interactions, while our results show that different interactions can have even contrary effects on urban activity levels at a given time. This problem with aggregate land-use diversity indicators is also noted by Manaugh and Kreider. The proximity of two squares that are popular tourist destinations is also modelled, because the other variables presumably underestimate the attraction that these locations have. This variable (TS) indicates whether a zone is within 250 metres of Amsterdam's 'Dam' or 'Museum' squares. Lastly, because transit places may affect the recorded dynamics of phone usage, the presence of metro stations (METRO), major railway stations (STATION) and motorways (MWAY) within a zone is estimated.

We repeatedly fitted phone usage densities per hour on cross-sectional data; thus, temporal shocks and dependencies are not explicitly modelled. We must acknowledge that this is an unusual approach to tackle longitudinal data compared with more common time-series methods. Although the method applied does not allow us to explore the causes that drive the dynamics of phone usage explicitly, it does allow us to explore how land-use configuration is related to phone usage, while spatial dependencies can be included in a relatively straightforward manner and serial autocorrelation should not problematically affect the results.

Table 6-2. Descriptive statistics of new call densities and explanatory variables.

Variable	5th perc.	Mean	95th perc.
New mobile phone calls per km2 (Y)	123.79	641.83	1,487.82
Inhabitants per km2 (INH)	0.00	6,546.88	17,050.99
Fraction of areas used for businesses (BUS)	0.05	3.04	8.87
Fraction of areas used for shops (SH)	0.00	0.82	3.59
Fraction of areas used for meeting places (MP)	0.00	0.82	3.24
Colocated businesses, shops (BUS x SH)	0.00	4.75	23.82
Colocated businesses, meeting places (BUS x MP)	0.00	4.09	21.16
Colocated shops, meeting places (SH x MP)	0.00	2.67	13.39

Note: N = 362; areal fractions have been multiplied by 100 in this table for better legibility.

Although land-use configurations are assumed to be static, one may expect that, in the longer run, they do respond to changes in activity levels; we ignore this in our modelling effort, but stress that further research on interdependencies between spatial configuration, land use and human presence is needed. As explained in Section 2.1, a spatial error model is applied. That model is fitted by separating the white noise error term μ from the spatially interdependent unobserved variables of contiguous neighbours (j) in ε . Spatial relations are defined as first-order contiguity according to the Queen's case, and are observed in the spatial weighting matrix W . As a sensitivity analysis strategy, alternative modelling approaches have been tested. Ordinary Least Squares (OLS) estimations yielded fairly similar results, but Geographically Weighted Regression yielded rather unstable estimators with various variable or kernel settings. This is presumably because of local multicollinearity in the explanatory variables (see Wheeler & Tiefelsdorf 2005). Note that, although multicollinearity may be problematic in geographically weighted windows, global multicollinearity is not problematic for this work's results (see Appendix A).

Summary statistics of all variables are given in Table 6-2; other characteristics of the explanatory variables are given in Appendix A. The estimation results are presented in Table 6-3. In order to save space only the estimation results for even hours are presented; results for the uneven hours are available upon request. Estimated contributions of average land-use densities on phone usage are shown in Figure 6-7. The last are computed by multiplying the estimated effects of land uses by the average land-use densities in Table 6-2, thus showing the average impact of the presence of various types of land use.

Table 6-3. Spatial error model estimation results of hourly new call density effects, working days from January to June 2010 (continued on next page).

Hour	Constant	Inhabitant density	Business density	Shop density	Meeting place density	Rho	Pseudo-R2
0	17.34 (0.82)	1.61** (8.77)	1.03 (0.36)	8.14 (0.86)	9.92 (1.12)	0.63** (16.34)	0.29
2	8.09 (0.72)	0.47** (4.75)	0.15 (0.10)	1.92 (0.37)	3.06 (0.63)	0.58** (14.73)	0.28
4	5.60 (1.01)	0.26** (5.32)	0.10 (0.12)	2.76 (1.03)	1.16 (0.46)	0.53** (12.10)	0.22
6	17.55** (3.23)	0.39** (7.83)	2.08* (2.41)	3.62 (1.18)	2.50 (0.90)	0.29** (4.51)	0.08
8	99.64** (2.60)	2.80** (7.98)	33.52** (5.61)	22.18 (1.06)	20.64 (1.07)	0.33** (4.65)	0.11
10	118.37 (1.46)	5.21** (7.03)	70.93** (5.65)	57.65 (1.31)	54.69 (1.36)	0.35** (4.72)	0.11
12	122.81 (1.28)	7.06** (8.01)	78.69** (5.21)	90.31 (1.69)	59.33 (1.22)	0.31** (4.25)	0.13
14	109.10 (1.11)	7.20** (7.98)	75.70** (4.85)	97.31 (1.75)	71.94 (1.42)	0.28** (3.72)	0.15
16	125.34 (1.27)	7.74** (8.55)	68.57** (4.36)	81.22 (1.45)	77.13 (1.51)	0.26** (3.56)	0.16
18	110.85 (1.36)	8.07** (10.79)	37.00** (2.87)	34.42 (0.75)	61.52 (1.48)	0.30** (4.58)	0.18
20	76.33 (1.48)	6.51** (13.79)	7.81 (0.98)	36.01 (1.31)	39.66 (1.57)	0.38** (6.59)	0.24
22	45.82 (1.12)	4.48** (12.20)	5.25 (0.89)	23.79 (1.19)	30.76 (1.66)	0.52** (11.02)	0.26

Table note: Z-scores are reported in parentheses. N = 362 for each hour of the day. Uneven hours have been removed from the results in order to save space – results are available upon request. Spatial dependencies in the error term are expressed by Rho. Inhabitant densities are divided by 100 for better legibility. All coefficients indicated with * are significant at the 0.05 level, and all indicated with ** are significant at the 0.01 level.

Table 6-3 (continued).

Hour	Businesses x shops	Businesses x meeting places	Shops x meeting places	Tourist square	Metro station	Railway station	Motorway
0	-4.67** (-4.21)	6.72** (3.90)	2.82* (2.03)	174.61* (2.01)	50.22 (1.38)	33.62 (0.55)	-4.98 (-0.25)
2	-2.18** (-3.58)	3.85** (4.06)	1.18 (1.54)	63.14 (1.34)	13.37 (0.67)	-1.95 (-0.06)	-1.60 (-0.15)
4	-1.04** (-3.32)	2.05** (4.19)	0.37 (0.95)	26.50 (1.11)	17.81 (1.73)	-5.98 (-0.34)	-0.47 (-0.08)
6	-0.49 (-1.41)	0.40 (0.73)	0.28 (0.62)	28.04 (1.14)	33.74** (2.97)	2.81 (0.14)	1.17 (0.19)
8	-2.46 (-1.03)	0.84 (0.22)	6.61* (2.16)	85.74 (0.50)	233.65** (2.98)	71.37 (0.52)	15.99 (0.38)
10	-1.79 (-0.36)	5.05 (0.64)	8.32 (1.30)	175.39 (0.48)	391.67* (2.38)	-18.48 (-0.06)	20.24 (0.23)
12	-1.28 (-0.21)	13.08 (1.37)	13.40 (1.72)	257.85 (0.59)	448.43* (2.26)	58.98 (0.17)	29.98 (0.28)
14	1.21 (0.19)	14.18 (1.43)	16.03* (1.98)	331.69 (0.75)	451.16* (2.19)	48.78 (0.13)	30.49 (0.28)
16	2.68 (0.42)	14.62 (1.46)	21.57** (2.64)	303.00 (0.68)	481.23* (2.31)	132.04 (0.36)	44.21 (0.40)
18	-1.30 (-0.25)	17.13* (2.10)	20.05** (3.02)	360.17 (0.98)	402.16* (2.37)	231.85 (0.78)	24.72 (0.27)
20	-5.48 (-1.74)	14.71** (2.97)	7.90* (1.96)	294.29 (1.27)	161.34 (1.56)	166.00 (0.92)	-27.16 (-0.49)
22	-7.36** (-3.18)	11.19** (3.09)	6.03* (2.07)	243.39 (1.38)	133.62 (1.76)	124.93 (0.96)	-15.04 (-0.37)

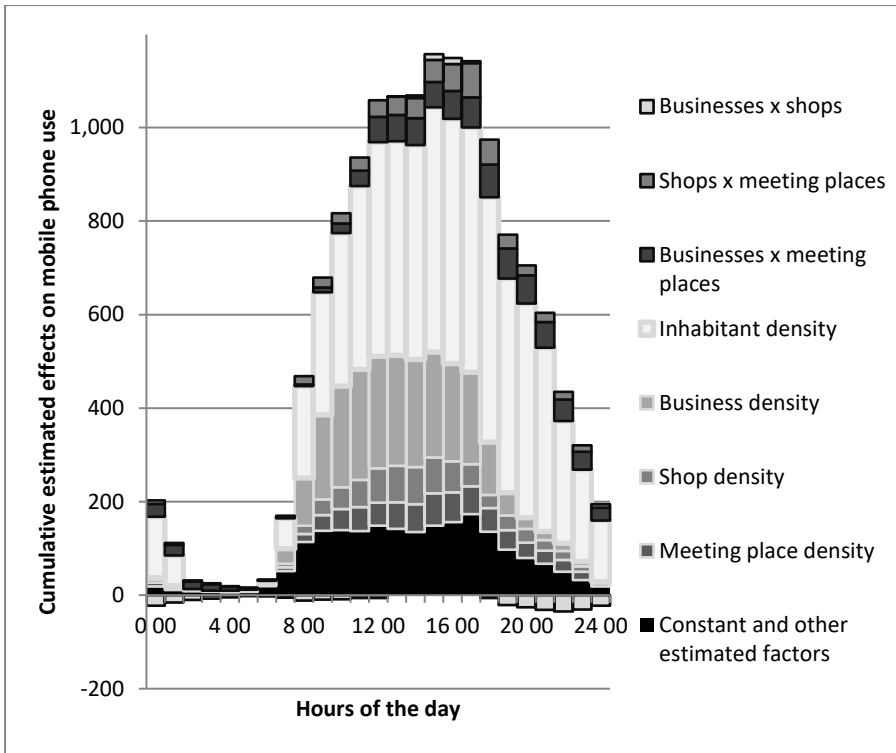


Fig. 6-7. Estimated mobile phone usage in a zone in Amsterdam with average scores for inhabitant density, land-use densities, land-use colocation and other estimators. For the sake of simplicity, spatial interdependencies are ignored here.

We find that inhabitant densities contribute to new call densities throughout the day. Nevertheless, this effect varies over time and peaks between 15.00 and 18.00 hours, which is the period in which workers are coming home (see Figure 6-6). Business densities contribute most to phone usage during common Dutch working times. Shop densities contribute to phone usage chiefly between 11.00 and 17.00 hours and peak at 14.00 hours, resembling common Dutch shopping times. In comparison with shops, meeting places contribute to phone usage over a longer period of time during the day, which may be related to the heterogeneity of activity types covered in this category. The colocation of businesses and meeting places increases human presence after working hours. The colocation of shops and meeting places increases human presence throughout the day, even before and after shopping times but peaking from 14.00 hours, when shopping participation is on the decrease. The colocation of shops and businesses does not significantly increase human presence. Amsterdam's tourist squares are associated with

relatively high phone usage densities throughout the day; this highlights the central function those squares have as public meeting places. Metro stops, motorways and railway stations are associated with phone usage most of the day, peaking in the afternoon rush hour from 16.00 to 18.00 hours. Unfortunately, the analysis yields disappointing explained variances; this is presumably caused by aspects of the spatial econometric specification, which in any case requires that pseudo- R^2 values are treated with caution (see Anselin & Lozano-Gracia 2008). In fact, OLS estimations yielded similar coefficients, but much higher R^2 values.

The above results show clear differences in the rhythms of the activity intensities associated with the modelled land uses. Thus, mixed land uses cause more diverse activity dynamics. Furthermore, the results confirm that mixing shops and businesses with meeting places has an additive effect on activity levels, in particular during times that shops and businesses per se do not cause much activity. This shows that local provisions of leisure opportunities outside the home are vital for any effort to extend activity intensities. We interpret the additive effect of meeting places as a multiplier effect of colocation that isolated land uses cannot produce, which indicates a change in the population's activity patterns. All in all, our results confirm Jacobs's (1962) expectations that mixed land uses can cause diversity in activity dynamics and, by means of multiplier effects, can extend activity intensities. Lastly, the results show that some home-related activity in neighbourhoods remains throughout the day; thus, even in the most monofunctional residential areas, daytime activity levels can be increased by densification.

To verify the robustness of our results, we have repeatedly executed the same analysis with average workday phone usage densities for every available month with reasonably consistent results. All obtained results have the same order of magnitude from 2008 to the first half of 2010. After June 2010 somewhat different results are obtained, but those still support our general conclusions. A selection of results is available in Appendix B.

4 Comparing activity patterns in advantaged and disadvantaged neighbourhoods

Dense and mixed land uses contribute to increasing and extending activity intensities, but do the desired activity patterns correspond with advantaged urban environments? In this section we compare phone usage densities in different areas, of which particular indicators of neighbourhood conditions have been

evaluated by experts. We use results from Amsterdam's planning department (Gadet et al. 2006), which evaluated from a subset of potentially attractive locations whether particular streets are able to draw new residents and businesses working in the creative sector. We consider the intended residents and businesses characteristic of the category of urbanites who for various reasons are able to choose their place of residence, and we consider urban districts that are able to attract such settlers advantaged. On the other side, we compare phone usage densities in urban districts that according to the former Dutch Ministry of Housing, Neighbourhoods and Integration are accumulating persistent social, economic and physical problems, and in fact are considered some of the most problematic neighbourhoods in the Netherlands (Bicknese et al. 2007). All in all, we compare temporal variations in phone usage in three groups of phone cells and in the study area on average. To do so we crudely classify the results of Gadet et al. into highly attractive and somewhat less attractive streets, and subsequently average phone usage densities in the cells that contain those streets. We furthermore average phone usage densities in the cells that have their centroid in a problematic neighbourhood. The list of locations can be found in Appendix C; observed temporal variation in phone usage intensities in all groups is shown in Figure 6-8.

The phone usage intensities in the locations of Gadet et al. (2006) coincide with their distinction as highly attractive and less attractive streets. Higher urban activity levels correspond with more attractive urban environments, while in comparison disadvantaged neighbourhoods have lower phone usage densities throughout the day. Disadvantaged neighbourhoods nevertheless have above average phone usage densities, indicating that poor neighbourhood conditions do not necessarily correspond with low activity intensities. One explanation may be that in problematic districts, reasonably high urban densities do provide anonymity to dwellers in public space, but the provision of activities is still inadequate to promote sufficient and continuous and human presence.

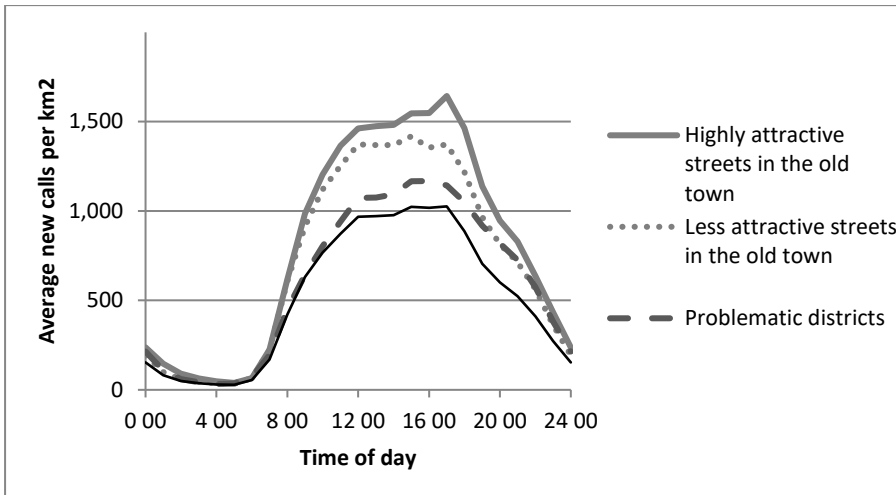


Fig. 6-8. Observed average phone usage per km² in the environs of Amsterdam streets classified by Gadet et al. (2006), in Amsterdam's most problematic districts and in the study area on average.

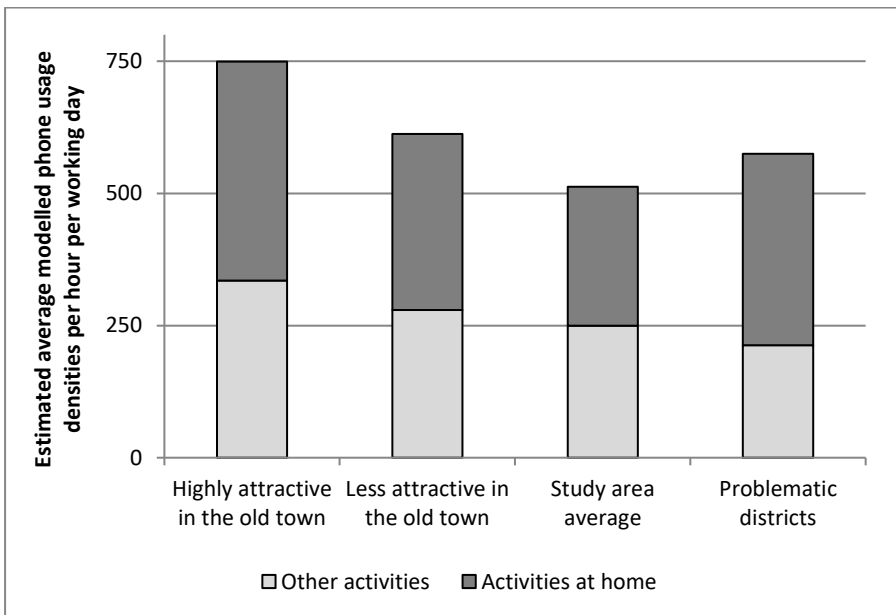


Fig. 6-9. Estimated average hourly contribution per day of activities at home and other activities to phone usage in the environs of Amsterdam streets classified by Gadet et al (2006), in Amsterdam's most problematic districts and in the study area on average. For the sake of simplicity, spatial interdependencies are ignored here.

Figure 6-9 shows average hourly effects of activities at home computed using inhabitant densities and their hourly estimated effects on phone usage divided by 24 versus the similarly computed effects of all other modelled activities. This figure clearly shows that neighbourhood attractiveness corresponds with land-use configurations that cause higher activity intensities and a greater degree of activity mixing. Here, in more attractive areas, there is a more equal distribution between home-related activities and other activities. On the other side of the coin, in Amsterdam's most problematic districts, activities away from home contribute much less to local activity intensities than they do on average in the study area. We conclude that neighbourhoods that fare better coincide with urban areas that, due to their land-use configurations, have higher activity intensities and more equal activity mixes. This agrees with Jacobs's (1962) observations.

5 Conclusions and discussion

In this paper we use mobile phone usage data recorded in Amsterdam, the Netherlands, to investigate expectations originally posed by Jacobs (1962) that dense and mixed land-use configurations are related to higher and prolonged urban activity intensities. Our evidence confirms that land-use densities are associated with activity levels; that different land uses are associated with different activity dynamics; and that colocated land uses have synergetic or multiplier effects that prolong activity levels. We additionally test Jacobs's expectation that neighbourhoods accommodating higher activity levels and mixed activity provisions coincide with advantaged neighbourhoods. Our results confirm that areas that are considered attractive have higher urban activity intensities, while in such areas the more mixed provision of activities stands out; in contrast, activity intensities are much lower and activities at home are overrepresented in Amsterdam's most disadvantaged districts.

Although the evidence uncovered supports the development of dense and mixed land uses, a number of factors need consideration before prompting such developments. First of all, the economic value of higher and prolonged urban activity levels is difficult to estimate, and its impact on vitality is unclear. The development of dense and mixed-use environments is complex and costly, and real estate developers therefore prefer simpler projects (Coupland 1997; Majoor 2006). Thus, especially in times of weak real estate markets, dense and mixed land-use projects are unlikely to be considered. We therefore agree with Rowley (1996) that, above all, it is important that urban planners should strive to preserve those urban areas where land-use patterns encourage high and extended activity

intensities, and perhaps apply flexible zoning schemes that allow new mixed land-use patterns to emerge.

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Appendix A: Spatial distribution of explanatory variables

In Table A.1 correlations between all explanatory variables are given, followed by Figure A.1, which shows the spatial distribution of those variables. The correlations were weighted using the method outlined in section 2.1 in the main article. Regarding the map series, it is important to note that the modelled best serving cells topology cannot be disclosed. Instead, administrative boundaries of 120 neighbourhoods in the study area have been used, to which all variables have been spatially aggregated from their original levels. The table and map make clear that land-use interactions have very similar spatial patterns, which may cause concerns regarding multicollinearity issues. However, omitting interaction effect variables did not greatly affect model results, and model results are furthermore reasonably consistent over time (see Appendix B). This leads us to believe there are no severe multicollinearity problems in the models presented.

Table A.1. Correlation between explanatory variables

	INH	BUS	SH	MP	BUS x SH	BUS x MP	SH x MP	TS	METRO
INH	1.00								
BUS	-0.15	1.00							
SH	-0.03	0.07	1.00						
MP	-0.08	0.04	0.30	1.00					
BUS x SH	-0.16	0.25	0.75	0.25	1.00				
BUS x MP	-0.16	0.31	0.41	0.73	0.59	1.00			
SH x MP	-0.17	0.01	0.76	0.47	0.64	0.55	1.00		
TS	0.00	0.05	0.27	0.25	0.31	0.36	0.32	1.00	
MS	-0.01	0.07	0.00	-0.01	-0.01	-0.02	-0.03	-0.04	1.00
MWAY	-0.25	0.00	-0.15	-0.13	-0.11	-0.10	-0.11	-0.08	-0.08
Railway station	0.03	-0.01	-0.01	-0.04	-0.02	-0.04	-0.03	-0.02	0.14

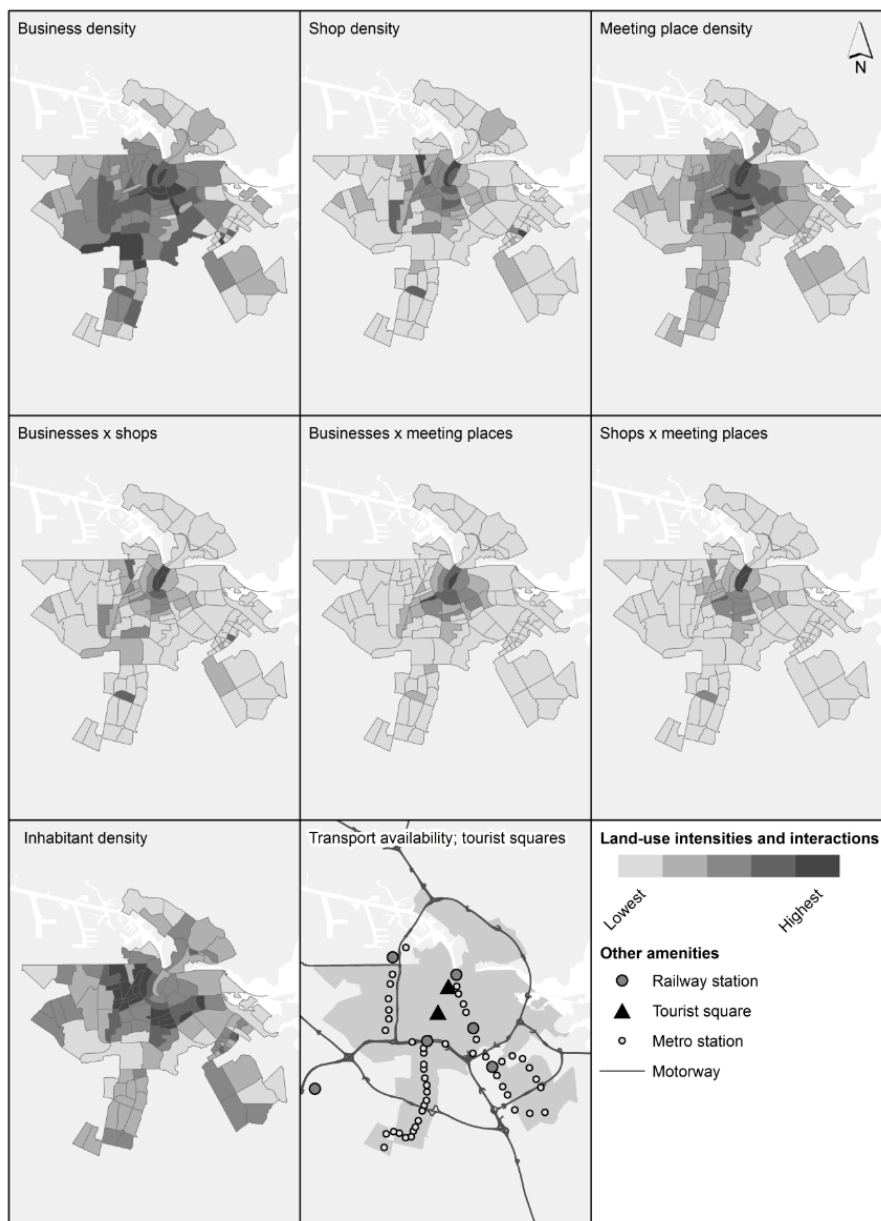
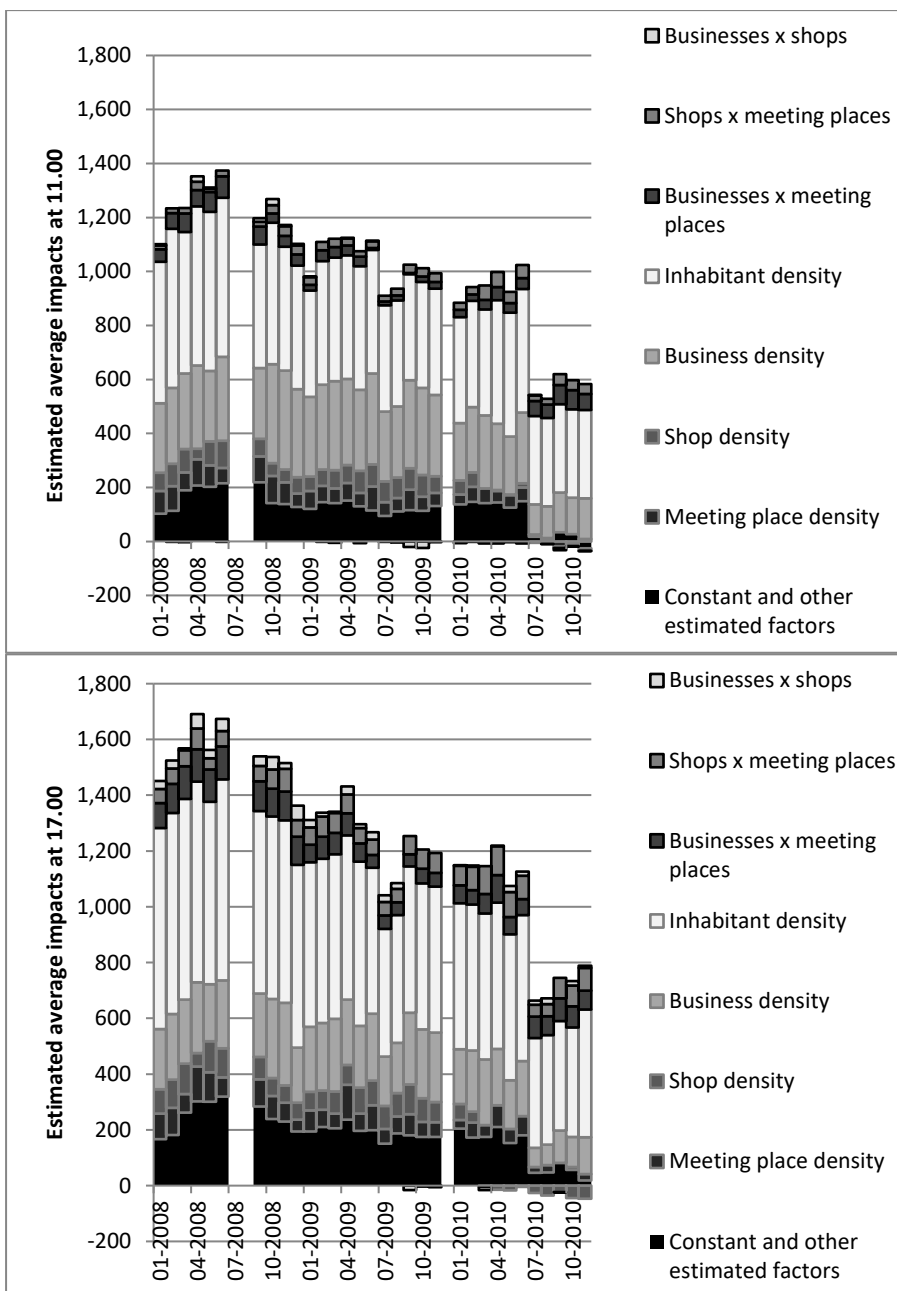


Fig. A.1. Maps of explanatory variables

Appendix B: Regression results using averaged phone usage densities from different time frames

Plotted in Figure B.1 are the estimated average impacts of land-use configuration and other modelled factors on phone usage densities for 11.00, 17.00 and 20.00 hours. In these results land-use configurations were assumed static, while the effect on phone usage densities has been re-estimated with averaged hourly phone use densities from each working day per month. The graphs presented are constructed in the same manner as Figure 6-7 in the main article. Figure B.1 also indicates changes in explained variance (computed as a pseudo- R^2 measure) and changes in spatial interdependence (ρ). In all cases, $N=362$ for each hourly cross-sectional analysis. Figure B.1 clearly indicates that in all months until June 2010, land-use densities have impacts on phone usage densities in the same order of magnitude; this supports the conclusions in the main article. In particular, the consistently positive impacts of shop and meeting place multiplier effects stand out. Results of fitting phone-usage data from other hours do not affect our conclusions either; these are excluded to save space. Except April 2009 and the period after June 2010, there are no large variations in levels of explained variance or spatial interdependence, although there seems to be a slight decline in total results over time. The most notable differences from June 2010 onwards are that many estimated effects are decidedly lower and that ρ yields considerably higher results. These sudden shifts mark changes in the 2G mobile phone network that have happened as a result of the increasing proportion of calls using the 3G network in 2010 (see the main article).



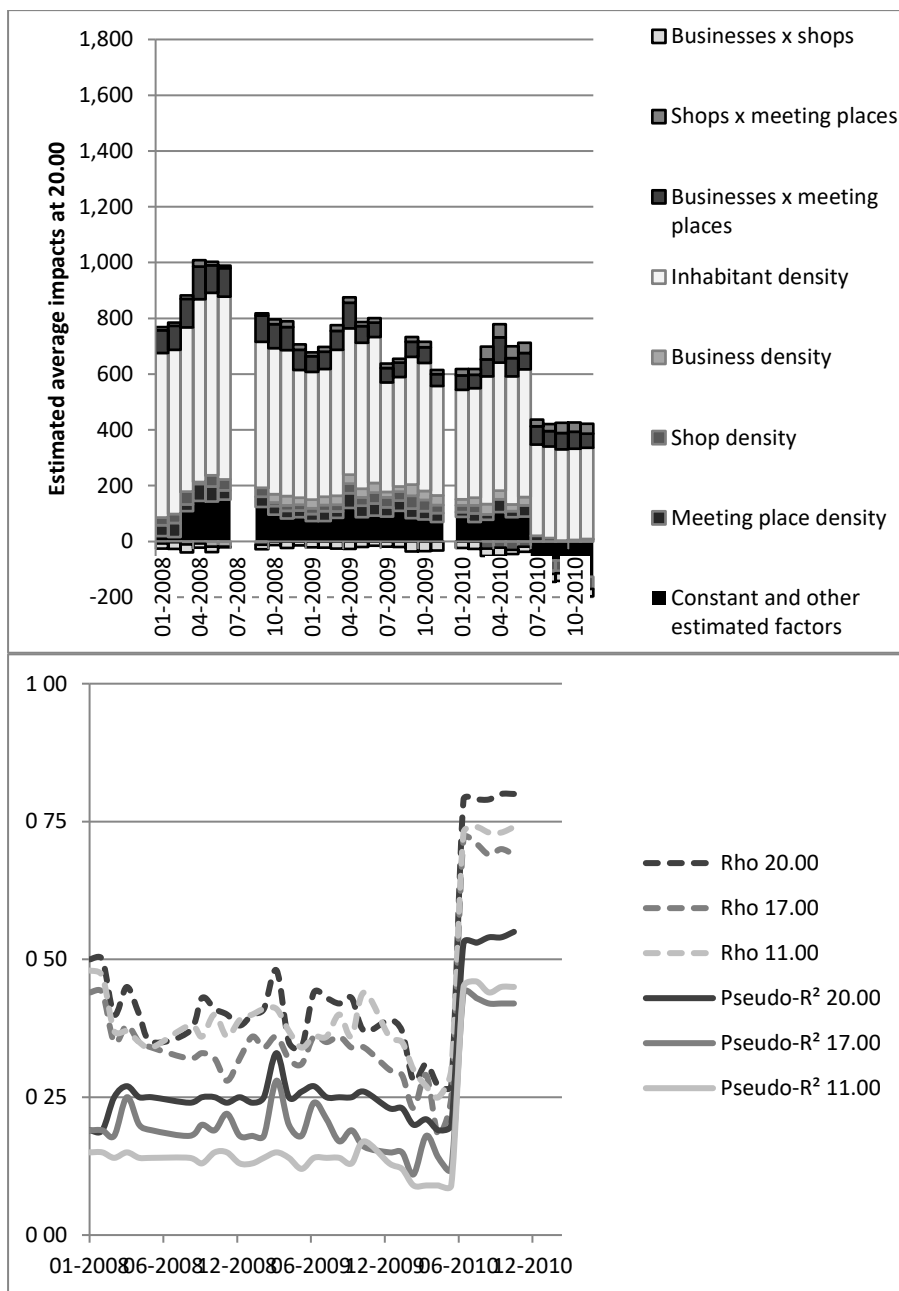


Fig. B.1. Results from fitting this paper's model on phone-usage data for separate monthly averages: estimated impacts of land-use densities on phone usage at different hours (first three graphs), levels of rho and pseudo-R² (last graph)

Appendix C: Streets considered very or less attractive and problematic districts

Table C.1. Classification of attractiveness of streets in Amsterdam, categorised according to data from Gadet et al (2006).

Streets considered attractive	Streets considered less attractive
Beethovenstraat	Admiraal de Ruyterweg
Eerste van der Helststraat	Johannes Verhulststraat
Frans Halsstraat	Kinkerstraat
Haarlemmerdijk	Lelylaan
Hoogte Kadijk	Oostelijke Handelskade
Prinsengracht	Postjesweg
Utrechtsestraat	Spaarndammerstraat
	Tweede van der Helststraat
	Van der Pekstraat
	Zuidplein

Table C.2. Neighbourhood list compiled by the Dutch Ministry for Housing, Neighbourhoods and Integration and published by Bicknese et al (2007).

Problematic neighbourhoods in Amsterdam	4-digit postcode
Nieuwendam Noord	1024
Volewijk	1031, 1032
Landlust	1055
Van Galenbuurt	1056
De Krommert	1057
Kolenkitbuurt	1061
Westlandgracht	1062
Slotermeer Noord-oost & Zuid-west	1063, 1064
Slotervaart	1065
Geuzenveld	1067
Osdorp Oost	1068
Osdorp Midden	1069
Transvaalbuurt	1092
Indische buurt West	1094
Bijlmer Oost	1103, 1104

Chapter 8. Accessibility and territorial cohesion in a case of transport infrastructure improvements with changing population distributions

Abstract: *In the last decade or so many studies have looked into the impacts of infrastructure improvements on decreasing territorial disparities. In those studies population levels are usually assumed static, although future population levels likely change in response to changing accessibility levels as well as to other factors. This study uses future population distributions simulated by the LUISA land-use model to assess the impacts of regional transport network investments on disparities in local accessibility levels. The results indicate that contrasting local urbanization patterns only modestly affect average national accessibility levels, but that those patterns may substantially affect regional inequality indicators. This shows the relevance of incorporating future population levels when assessing cohesion impacts of infrastructure investments.*

Key words: Accessibility, cohesion, land-use modelling.

This chapter originally appeared as Jacobs-Crisioni, C., Batista e Silva, F., Lavalle, C., Baranzelli, C., Barbosa, A., Perpiña-Castillo, C., 2016. Accessibility and cohesion in a case of infrastructure improvements with changing population distributions, *European Transport Research Review*, 8(1), pp. 1-16.

1 Introduction

Accessibility deals with the level of service provided by transport networks, given the spatial distribution of activities (Geurs & Van Wee 2004). Improving accessibility is an important means to increase social and economic opportunities (Halden 2002; Geurs & Van Wee 2004) and accessibility considerations are deemed an important component of sustainable development (Bertolini et al. 2005). In Europe, a substantial amount of public funding is dedicated to increase accessibility in peripheral and/or landlocked regions; in particular through the European Union's (EU) cohesion policy instruments (EC 2004). The territorial cohesion aim of those policies is usually interpreted as the aim to decrease disparities between European regions (López et al. 2008). To do so, the EU's cohesion policies provide funding for regionally tied projects in a wide range of sectors with the aim to "kick-start growth, employment, competitiveness, and development on a sustainable basis" (Brandsma et al. 2013, p. 13). The regional investment program includes a considerable amount of funding available for transport infrastructure

improvements; but funding is also available for other aims such as environmental protection, promoting tourism, and urban and rural regeneration.

To assess whether transport infrastructure improvements have the intended effect of decreasing disparities in accessibility among European regions, recent studies have employed sophisticated accessibility measures and inequality indicators (López et al. 2008; Martin et al. 2004; Stępniaak & Rosik 2013). The cohesion effects that those measures yield are varied, depending on the resolution and extent of analysis and on the analysed transport mode. Spiekermann and Wegener (2006) have shown for Europe that, while network investments in a certain country may reduce international disparities, it may increase disparities within the nation itself. In general, road link upgrades seem to increase territorial cohesion (Gutiérrez & Urbano 1996; Stępniaak & Rosik 2013), while in contrast high speed railway links accentuate differences in accessibility between regions (Martin et al. 2004; López et al. 2008). Most accessibility measures are based on two dimensions: on the one hand the traveltime or generalized travel-cost needed to overcome geographic distance making use of available transport options; and on the other hand the spatial distribution of activities (commonly using GDP or population counts as a proxy). As is the case in all previously mentioned case studies, the effects of transport infrastructure improvements on accessibility are usually taken into account by known reductions in traveltime or generalized cost, while spatial activity distributions are often presumed static. However, the spatial distribution of activities is surely not static, and in fact adjusts to changing accessibility levels over time (Xie & Levinson 2010; Levinson 2008; Koopmans et al. 2012). Thus, if spatial activity distributions adjust to changing accessibility levels, ex-ante evaluations of infrastructure studies may benefit from taking reciprocities with spatial activity distributions into account – for example to assess the robustness of found accessibility benefits with differing population growth scenarios, or to compose complementary spatial planning strategies that optimize the effectiveness of transport infrastructure investments.

Accessibility has received considerable attention in the literature. For example, the effect that accessibility improvements may have on activity distributions has been studied repeatedly (Xie & Levinson 2010; Levinson 2008; Koopmans et al. 2012; Hansen 1959; Meijers et al. 2012; Padeiro 2013). Other studies have researched spill-over effects of transport infrastructure improvements (Stępniaak & Rosik 2013; Condeço-Melhorado et al. 2014). The effect that spatial activity distributions may have on accessibility, as studied in this paper, has received less attention. Geurs and Van Wee (2006) compared the land resource, accessibility and transport

consumption impacts of the relatively compact post-war urban development in the Netherlands with the outcomes of alternate land-use planning policies. Their study shows slightly better aggregate accessibility levels as a result of compact development, mainly due to lower congestion levels. Wang et al. (2014) compare accessibility levels and associated social welfare effects in Madrid with different transport policy measures, while explicitly modelling changes in transport behaviour and land-use patterns. Other studies in the Netherlands have also explored land-use impacts on accessibility (Geurs et al. 2012; Geurs et al. 2006), which in general confirm that land-use policies may increase aggregate accessibility levels and that tailored spatial planning can increase the benefits of transport infrastructure investments.

All of the abovementioned studies focus on total or average accessibility changes, and it is still unclear to what degree the spatial redistribution of activities may affect disparities in accessibility, in particular in regions where general activity levels are decreasing. This article will add to the available literature by looking into how local population changes may affect found levels of territorial disparities in accessibility. Because of computational limitations the study at hand had to be limited to four countries. Austria, Czech Republic, Germany and Poland have been selected, because they make a spatially adjacent but mixed set of new and old member states that differ substantially in current levels of infrastructure endowment (with much larger endowments in Austria and Germany) and in levels of transport infrastructure investment funded by EU cohesion policies (with much more investment in Czech Republic and Poland). Results from four cases will be compared: a reference case that comprises the current road network and population distribution in Europe in 2006 (case I); a case in which population distributions are from 2006, but road network improvements are imposed that are assumed to gradually decrease travel times between 2006 and 2030 (case II); and two cases that consider the same road network improvements, as well as modelled future population distributions (Compact scenario: case III and Business As Usual or BAU scenario: case IV). The latter two cases assume identical regional population projections, but differ in assumed local spatial planning policies, and therefore have different intra-regional population patterns. The modelled future road networks and population distributions are mostly based on well-documented and empirically tested relations, but to some extent rely on expert judgement, which in turn may raise doubts concerning their validity; a common problem for scenario approaches (Dekkers & Koomen 2007). To provide some reference, this paper will compare the outcomes of relevant indicators with the same indicators computed

for changes in observed population levels and accessibility levels between 1971 and 2011. We must nevertheless stress that past changes are not necessarily indicative of future changes. Furthermore, the uncertainties surrounding future projections are not problematic as long as the simulation outcomes are used for what they are: maps showing potential future developments, given many scenario-related assumptions.

2 Methods

The here presented results were produced in a land-use modelling exercise that aimed to look into how EU cohesion policies and other EU policies with spatial relevance may affect land-use, accessibility and a range of environmental indicators. The mentioned study is comprehensively documented in Batista e Silva et al. (2013) . The study assumes a number of road network improvements funded by the EU's regional cohesion policy program for the years 2014 to 2020. A part of those improvements is known in advance, and a part consists of modelled upgrades given available funding at regional level. Population redistributions are modelled using the European Commission's platform for Land-Use-based Integrated Sustainability Assessment (LUISA) (Lavallo et al. 2011). In this section we will describe the used land-use modelling platform, the way by which cohesion policy impacts are modelled with it, and the applied methods to evaluate cohesion impacts of the modelled outcomes.

2.1 The LUISA platform

LUISA is a dynamic spatial modelling platform that simulates future land-use changes based on biophysical and socio-economic drivers and is specifically designed to assess land-use impacts of EU policies. Its core was initially based on the Land Use Scanner (Hilferink & Rietveld 1999; Koomen et al. 2011), CLUE and Dyna-CLUE land-use models (Veldkamp & Fresco 1996; Verburg et al. 2006; Verburg & Overmars 2009), but its current form is the result of a continuous development effort by the Joint Research Centre (Lavallo et al. 2011) that owes much to the highly flexible GeoDMS (ObjectVision 2014) modelling software in which LUISA is implemented. LUISA downscales regional projected future land use demands to a fine spatial resolution and thus models changes in population and land use with reference to CORINE land-use/land-cover maps (Büttner et al. 2004) and a fine resolution population distribution map (Filipe Batista e Silva et al. 2013). It allocates land uses and population per year on a 100 m spatial grid. It discerns a number of land-use types, which can roughly be separated in urban, industrial,

agricultural and natural land uses. The timeframe for which LUISA simulates land-use changes varies per study; for this study the model ran for the period from 2006 to 2030.

As can be seen in Figure 8-1, LUISA is structured in a demand module, a land-use allocation module and an indicator module. At the core of LUISA is a discrete allocation method that is doubly constrained by on the one hand projected regional land demands and on the other hand regional land supply. For an elaborate description of the land allocation method we refer to Hilferink and Rietveld (1999) and Koomen et al. (2011). The regional land demands are provided in the demand module by sector-specific economic models, such as the CAPRI model for agricultural land demands (Britz & Witzke 2008) and the GEM-E3 model for industrial land demands (EC 2013a). Within its constraints, the model attempts to achieve an optimal land-use distribution based on spatially varying local suitabilities for competing land uses. Those suitability values for given land uses, in turn, are derived from fitting biophysical, socio-economic and neighbourhood factors on spatial land-use patterns with a multinomial discrete choice method. LUISA is run for each country independently. Its outcomes are population distributions, spatial land-use patterns and accessibility values for each of the model's time steps. Those outcomes are used to inform local suitability values in the next time step and to compute policy-relevant indicators of the impacts of land-use change in the indicator module. A broad range of indicators is computed within LUISA, of which cohesion effects of policy scenarios are particularly relevant for this paper.

Two recent additions to LUISA set it apart from similar land-use models. The first addition considers the parallel endogenous allocation of number of people to the model's 100 m grid, which is described here briefly; for a detailed overview see Batista e Silva et al. (2013). In LUISA's people allocation method, in each time step a region's population is distributed over space. The distributed population and threshold rules are subsequently used to simulate the conversion to urban and abandoned urban land uses before all other simulated land-use types are allocated in the discrete land-use allocation method. Following observed land-use and population distributions, pixels become urban if their modelled population exceeds 6 inhabitants; conversely, urban pixels become 'abandoned' when their modelled population declines below 2 inhabitants. The distribution of population is foremost based on a 'population potential' function that describes likely population counts per grid unit. This is a linear function incorporating neighbourhood interdependencies, the log-linear distance to the closest road, current potential

accessibility, slope and current land uses; it is fitted on the observed 2006 population distribution by means of spatial econometric methods. For an overview of spatial econometric methods see Anselin (2001).

Population allocation in LUISA is subsequently restricted by three factors. Regional urban land demands are accounted for, implying that minimum and maximum limits are imposed on the number of pixels that reach the urbanization threshold. Regional urban land demands are based on: 1) recent Europop 2010 population projections (EuroStat 2011); 2) an assumed Europe-wide convergence of average household sizes on the very long run (i.e., to 1.8 in all regions by 2100, so that in most regions a limited decrease in household size is modelled by 2030); and 3) extrapolated historical trends of regional urban land consumption per household. In each time step the population distribution method allocates the net regional population growth in a region, as projected by Eurostat, as well as 10% of the pre-existing population in order to take internal movements into account. The 10% internally moving population is a coarse estimate of internal movements that is used because projected internal migration numbers are unavailable. Lastly, the method is restricted by per-pixel housing supply, which is approximated in terms of inhabitant capacity in the model and is instrumental in imposing a larger degree of inertia on the model results. Approximated housing supply increases potential population if current population undershoots population capacity, and it penalizes population potential if population counts are higher than housing supply. Every five time steps it assumes the values from current modelled population counts to proxy structural changes in housing supply.

A second recent addition to LUISA is the inclusion of endogenous potential accessibility as a suitability factor for its land-use allocation and population distribution method. Here the model computes the following equation for each time step:

$$A_i = \sum_{j=1}^n \frac{P_j}{f(c_{ij} + c_j)},$$

in which accessibility levels A for each origin point i are computed using current population counts P in destination zones j , the results of a function of traveltime c between i and j , and a zone-specific internal traveltime c_j . The origin points are equally distributed throughout Europe with roughly 15 km intervals.

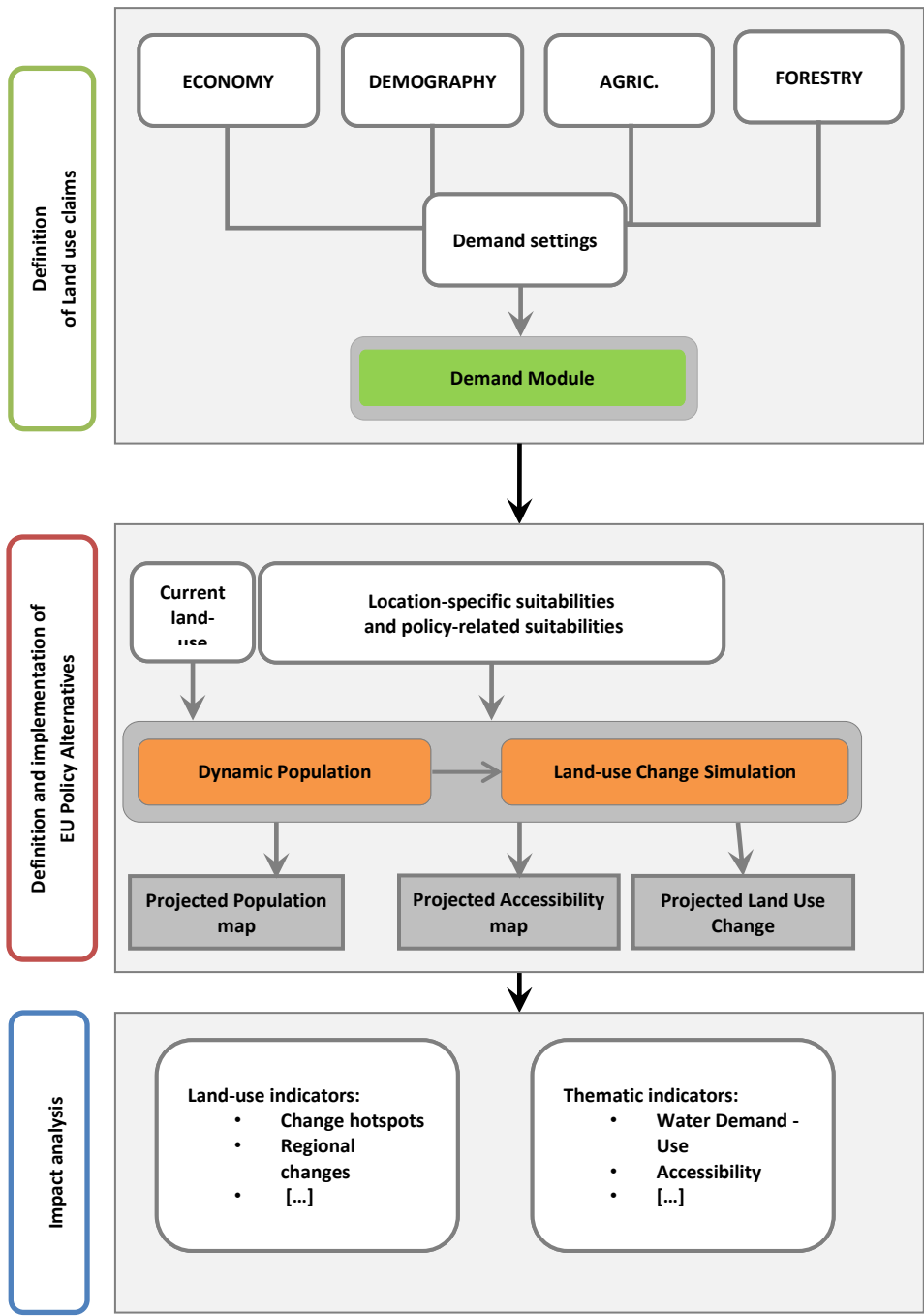


Fig. 8-1. Flow chart of the LUISA land-use model.

Within the model, the destination zones are hybrid sets that differ per modelled country and consist of municipalities within, and NUTS2 regions outside of the modelled countries. Although national borders impose substantial barriers on levels of spatial interaction and urban development near national borders (Redding & Sturm 2008; Brakman et al. 2012), no penalties on potential cross-border interactions are currently imposed on accessibility values. Population counts are aggregated from the model's previous time step's population distribution outcomes in the modelled country. Regional Europop2010 population projections are used for the remaining regions. Traveltimes are obtained from the TRANS-TOOLS road network (Rich et al. 2009) using a shortest path algorithm assuming free-flow traveltimes. For the purpose of this study, current and future traveltimes are distinguished (see the following section). To account for the unknown distribution of destinations within zones an additional traveltime is added that essentially depends on a destination zone's geographical area. It uses the Frost and Spence (1995) approach to approximate internal Euclidean distances; thus, internal distance d_j is assumed to be $d_j = 0.5\sqrt{AREA_j/\pi}$. Subsequently, internal travel times c_j are computed from d_j by means of a function in which effective travel speeds in km/h are obtained with the fitted function $10.66 + 13.04\ln(d_j)$, with a minimum of 5 km/h imposed on very small zones. For details on the fitted function, see Jacobs-Crisoni and Koomen (2014). Lastly the distance decay function $f(c_{ij})$ in the model is of the form $c_{ij}^{1.5}$. The form of the distance decay function was chosen among many tested in the population potential fitting exercise because, in terms of explained variance, it fitted best on observed population distributions.

The feedbacks between land-use and transport that are modelled in LUISA are characteristic of land-use/transport interaction models (LUTI). In LUISA, just as in most other LUTI (Geurs & van Wee 2004), accessibility is used as an important factor in the location decisions that cause land-use change, and as an indicator of socio-economic welfare. For an overview of LUTI models we refer to Wegener (1998). Compared to other recently applied LUTI, for example MARS (Pfaffenbichler et al. 2008; Wang et al. 2014) or TIGRIS XL (Zondag & De Jong 2005), LUISA has a larger geographic extent (all of the European Union), operates at a finer resolution (the 100 m pixel level), takes into account a broader set of land uses (including agricultural and forest land uses), and reports on a much more diverse set of environmental and economic indicators (including for example accessibility and land-use efficiency, but also ecosystem services, freshwater consumption and energy provision). However, currently LUISA does not take into account some of the characteristic strongpoints of other LUTI such as the

modelling of network use and congestion, the inclusion of multiple transport modes, and the incorporation of other human activities besides residence, such as employment. Future development plans for LUISA do include the estimation of transport network use and a further breakdown of human activity, if sufficiently detailed data becomes available on a Europe-wide scale. For the article at hand the model's shortcomings imply limitations to the breadth of the applied methods and drawn conclusions. Thus, for example the effects of transport investments that aim to alleviate congestion cannot be explored, and impacts related to job-market dynamics and job-market access cannot be presented.

2.2 Modelling cohesion policy impacts

LUISA allows multi-policy scenarios to be accommodated, so that several interacting and complementary dimensions of spatially relevant policies are represented. Often LUISA inherits policy provisions from other sector models. For example, the CAPRI model from which agricultural land demands are obtained takes the EU's Common Agricultural Policy on board, and the macro-economic models that project future industrial land demand pass through energy and economic policies (Lavalley et al. 2013; Batista e Silva et al. 2014). Other policies such as nature protection schemes and transport infrastructure improvements are modelled in LUISA through assumed impacts on local suitability factors.

To assess the territorial consequences of EU cohesion policies, a number of impacts are inherited from upstream models; the most important example here is that the impacts of cohesion policy on industrial land demand were obtained using forecasts of economic growth from the Rhomolo model (Brandsma et al. 2013). Regional population projections were assumed not to change as a result of the cohesion policies. At the local level suitability factors were adapted in order to assess the impacts of cohesion policies on the spatial distribution of people and land uses. Only aspects of the cohesion policy with a clear impact on land-use patterns were taken into account: investments in transport networks, investments in urban regeneration, investment in research and technological development infrastructure, investment in social infrastructure and investments in improving existing ports and airports. In this article we elaborate on how road network improvements were modelled; for an overview of the other modelled cohesion policy impacts we refer to Batista e Silva et al. (2013) . We will furthermore elaborate on the two contrasting urban development scenarios that were taken into account in the cohesion policy assessments.

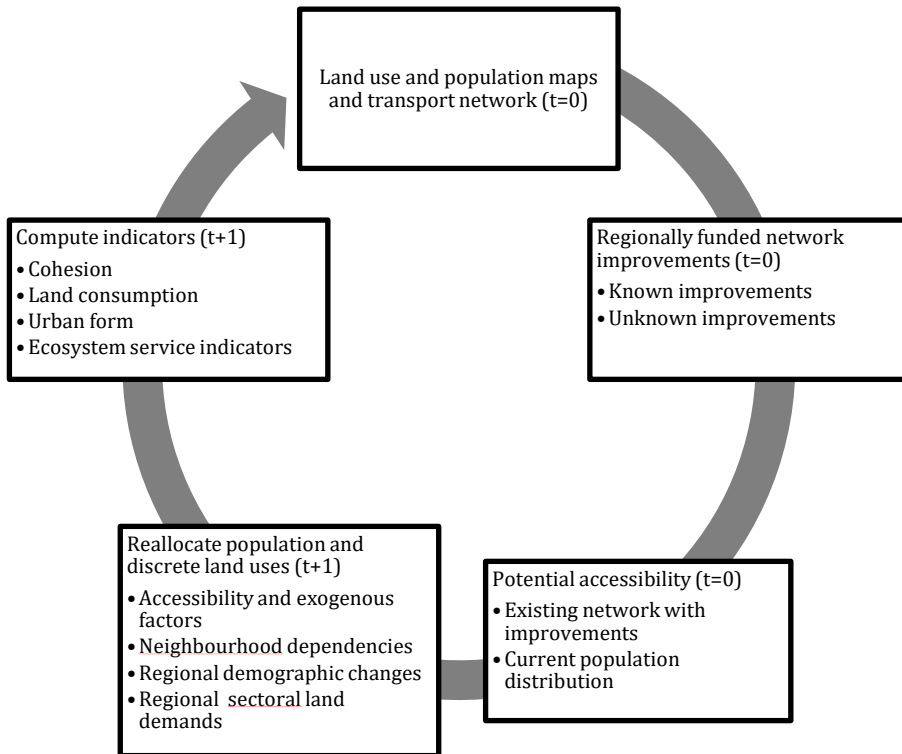


Fig. 8-2. Endogenous accessibility and population computations in LUISA

Taking into account road network funding

The effects of future funding for motorways and local, regional and national roads have been modelled explicitly by taking into account future changes in travel times and their subsequent effects on potential accessibility. The way that road upgrades were incorporated in LUISA is shown schematically in Figure 8-2. Because the true distribution of funding in the cohesion policy was not yet known at the time the research was conducted, the funds were assumed to be the same as in the 2007 to 2013 programme. Those funds are destined to three distinct road types, namely motorways, national roads and local roads. All modelled road network improvements were assumed to lead to travel time improvements, either by new links identified in the used TRANS-TOOLS data, or by upgrades to the existing road network. The costs of upgrading one kilometre of lane were averaged from a European database of road construction projects that have successfully been

implemented with cohesion policy funding; see EC (2013b). For the purpose of this paper the total EU investments cited for those projects are divided by the length of the built road and the number of constructed lanes. Subsequently total road construction costs were estimated for the three road types based on an assumed amount of lanes per type. All cost assumptions are given in Table 8-1. We must acknowledge that the costs quoted here are very rough estimates that do not take into account terrain conditions, nationally varying pricing structures or complex civil engineering works. These estimates have nonetheless been used because more accurate information on road construction costs was unavailable. Finally, please note that the recorded projects are only co-funded by the EU so that only a part of the entire project costs are taken into account. The accounted partial costs are consistent with the modelling approach in which the effects of future EU subsidies on road network development are modelled.

Table 8-1. Characteristics of road types as used in the upgrade funding allocation method and assumed amount of available funding.

Type of road	Assumed max. speed	Number lanes	Est. cost per km	Cohesion policy investment categories (assumed total EU funding)
Local road	80 km/h	2	3M Euro	Regional and local roads (9.8 Bn)
National road	100 km/h	2	4.2M Euro	National roads (7.7 Bn)
Motorway	130 km/h	4	10M Euro	Motorways (5.2 Bn) TEN motorways (17.5 Bn)

Table note: these are the costs for road projects incurred by the European Commission in projects that are only co-funded by the European Commission. Total construction costs may be much higher.

Given the costs of constructing a kilometre of a certain road type, the costs of road network improvements that are known a-priori were computed first. In many regions a substantial amount of funding was not depleted by those already known infrastructure developments. In such regions the remainder funding was allocated to road segments that, according to some simple rules, are likely candidates for upgrades. In that way all regional funding was allocated to road network improvements. The selected road segments had to meet the following criteria: they 1) were not known to be upgraded; 2) had slower recorded maximum speeds than typical for the destination road type; and 3) had the highest transport demand according to a simple transport modelling exercise. That transport modelling exercise is based on a straightforward spatial interaction model of the

form $T_{ij} = P_i P_j c_{ij}^{-2}$, with demand for flows T between municipalities i and j , population counts P and traveltimes c . The demands T were allocated to the shortest path between i and j , yielding estimated flows per road segment. With the set criteria, first upgrades to motorway level were allocated, and subsequently upgrades to regional and local roads. This was done until no more road segments could be upgraded because funds were depleted or because no more segments that meet the criteria were available in a region. This method assumes that network investment decisions follow an ad-hoc rationale of catering for transport demand where this is needed the most. We believe this is a fair assumption as long as strategic network investment plans are unknown for the regions that receive funding. We must acknowledge that the used transport demand figures are obtained from a rather coarse method that for example does not take into account spatially varying car ownership or the lessening effects that national borders have on transport flows (Rietveld 2001). We expect that this method is nonetheless useful here to demonstrate the effects that potential infrastructure investments may have on accessibility levels. Finally, the network improvements were assumed to be completed by 2030, with linearly improving traveltimes between 2006 and 2030 that fed into the LUISA accessibility computations.

Two contrasting scenarios of urban development

Unfortunately, local urban planning policies and regulations are not included in LUISA, even though their effect on future local land-use patterns is presumably profound. Such local policies are excluded because consistent Europe-wide data related to urban plans are yet unavailable. To sketch the potential impacts of cohesion policies with different local planning policies, those impacts have been computed with two contrasting, stylised spatial planning regimes. The choice of planning regimes reflects the contradiction between sprawled and compact urban development that is often addressed in spatial planning evaluation (Geurs & Van Wee 2006; Ritsema van Eck & Koomen 2008). In the Compact scenario (case III), urban development is restricted to the immediate surroundings of existing urban areas, thus leading to densification and expansion of existing urban perimeters, while limiting scattered and uncontrolled development. Because of the restricted availability of land near urban areas, this scenario additionally yields a more evenly spread urban development within regions. In the BAU scenario of urban development (case IV), urban areas are allowed to develop freely, are attracted to the areas with the highest gravitational attraction, and there form relatively scattered patterns that generally follow the main transport axes.

2.3 Measuring cohesion effects on accessibility

To study the effects of transport network improvements on accessibility a number of accessibility measures need to be selected from the many accessibility measures that are available in the existing literature; see for example Geurs and Van Wee (2004). We used the same set of accessibility measures as López et al. (2008). These measures are location accessibility, relative network efficiency, potential accessibility and daily accessibility, which can be loosely linked to specific policy objectives: location accessibility measures to the degree in which locations are linked (Gutiérrez & Urbano 1996); network efficiency measures the effectiveness of transport networks (López et al. 2008); potential accessibility measures economic opportunity (López et al. 2008; Stępnik & Rosik 2013); and daily accessibility can perhaps indicate aspects of quality of life objectives, as it measures the opportunities that people may enjoy on a daily basis.

Table 8-2. Accessibility measures used in this study and their definition.

Indicator	Definition	Remarks
Location access	$L_i = \sum_{j=1}^n c_{ij} P_j S_j / \sum_{j=1}^n P_j S_j$	$S_j = \begin{cases} 1 & \text{if } j \text{ is in a capital or large city} \\ 0 & \text{if not} \end{cases}$ <p>For this study only national capitals, Düsseldorf, Hamburg and Munich are selected through S.</p>
Network efficiency	$E_i = \sum_{j=1}^n \frac{c_{ij}}{\hat{c}_{ij}} P_j / \sum_{j=1}^n P_j$	Ideal traveltimes \hat{c}_{ij} are based on Euclidean distances between i and j and the fastest maximum speed (130 km/h) recorded in the road network data
Potential accessibility	$Pot_i = \sum_{j=1}^n P_j f(c_{ij})$	$f(c_{ij}) = c_{ij}^{-1.5}$
Daily accessibility	$D_i = \sum_{j=1}^n P_j \hat{c}_{ij}$	$\hat{c}_{ij} = \begin{cases} 1 & \text{if } c_{ij} \leq 240 \text{ min.} \\ 0 & \text{if } c_{ij} > 240 \text{ min.} \end{cases}$

All accessibility indicators use shortest traveltimes (c_{ij}) between i and j and population at the destination (P_j). The list of used indicators is shown in Table 8-2. In all cases, the regularly distributed points described in Section 2.1 were used as origins, and municipalities were used as destinations. The road network data used

to obtain traveltimes describes the current (2006) road network in case I, and describes the expected future (2030) network in cases II to IV. The latter takes into account the expected network improvements enabled by cohesion policy funding. For municipal populations the current (2006) population levels were used in cases I and II, while in cases III and IV future (2030) population levels modelled by LUISA were applied. All accessibility measures were computed for the roughly 22,000 municipalities in the study area. We must acknowledge that the selected accessibility indicators do not provide a comprehensive overview of socially relevant accessibility effects. As Geurs (2006) and Wang et al. (2014) show, accessibility indicators that include competition effects at the destination may add relevant information considering access to resources with limited capacity, such as jobs or public facilities. Because such resources are not yet modelled in LUISA, competition effects cannot be taken into account in this exercise.

Subsequently, a number of indicators were computed that measure the territorial cohesion of the various accessibility indicators. The diversity indicators that have been proposed for measuring cohesion effects by López et al. (2008) were used here. These indicators are the coefficient of variation and the Gini, Atkinson and Theil indices. All indicators capture the degree to which endowments are inequally distributed over areal units, but differ in the emphasis put on the distribution of high and low values. In all cases, lower values of the indicator signify greater equality of endowments and thus increased territorial cohesion.

2.4 Historical data for reference

To provide some reference to the modelling results, the same set of variables and indicators will be computed using historical data that has very recently become available. One used data-source describes municipal population counts in 1971 and 2011 in all municipalities in the selected countries (Gløersen & Lürer 2013). The other used data describe the European road network in 1970 and 2012 (Stelder et al. 2013) in a level of detail that is roughly comparable with the TRANS-TOOLS data used in the LUISA modelling effort. Thus, for the sake of comparison, historical trends regarding the cohesion effects of population and network changes are computed in the four selected countries.

3 Results

In this section, first the results of allocating available funding to currently unknown future network improvements will be demonstrated along with the modelled

population changes. Subsequently potential impacts of the cohesion policy on population distribution and accessibility levels will be discussed. Results from 2006 will be compared with results from 2030. Results from 1971 to 2011 are used to provide an historical reference. Please note that, because of the assumed linearly changing traveltime improvements, the impacts of intermediate years will fall roughly between the 2006 and 2030 results.

3.1 Allocated infrastructure improvements and population changes

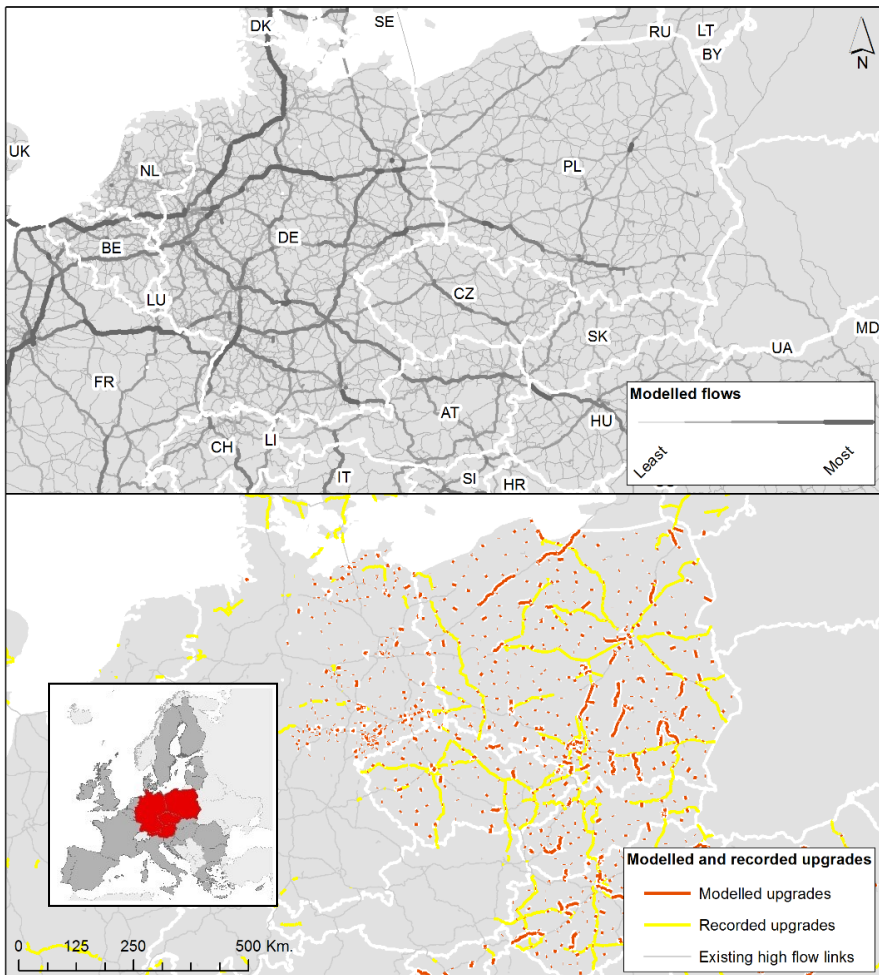


Fig. 8-3. Above: modelled flows using 2006 population and road network data. Below: the road upgrades that are assumed to be in place in 2030 that are based on the modelled flows.

According to the available data, roughly 16.000 kilometres of road are known to be upgraded or constructed as motorways with cohesion policy funding. Not all funding is depleted with those upgrades. The previously outlined upgrade allocation method yields that an additional 700 kilometres of road in Europe are upgraded to motorways.

This method furthermore yields that 3600 kilometres of road are upgraded to national roads and 6500 kilometres of local roads are upgraded to the maximum speeds of the local / regional road level. The transport modelling results and the distribution of new links is shown in Figure 8-3. From the assumed funding distribution follows that new EU member states such as Poland and Czech Republic will receive the most substantial funding for upgrades to the road network. This result is not surprising, given the speed at which road networks are expanding in the EU's new member states (Stępniaak & Rosik 2013).

Table 8-3. Inequality indicators of average road speeds in the historical network and in the network used for modelling.

Regional speeds distribution	Network 1971 (r)	Network 2012		Network 2006 (I)	Network 2030 (II – IV)	
			% dif			% dif
Coeff. of variation	0.106	0.080	-24.43	0.233	0.193	-17.32
Gini index	0.057	0.042	-27.26	0.124	0.105	-15.29
Theil (0)	0.006	0.003	-42.75	0.031	0.020	-36.02
Atkinson (0.5)	0.003	0.002	-42.70	0.017	0.011	-39.01

Note: case numbers (I to IV) are given between parentheses. Case r serves as a reference for the relative differences in the historical trends; case I serves as a reference for the relative differences in the modelling results.

To understand how the modelling network compares with historical road data, road speeds for 1971 and 2012 (historical network) as well as for 2006 and 2030 (modelling network) have been averaged for all European regions. Those averages are weighted by segment length so that longer links have a greater weight in the network average. When comparing average regional speeds, the historical network and the modelling network are considerably different. In the modelling network, regional inequalities are much more profound even when compared to the 1971 network; see Table 8-3. Thus the modelling network potentially overestimates disparities in accessibility. By 2030, speeds on Europe's road networks are expected to be more equally distributed. However, the modelled pace of inequality reduction does not keep up with historical trends. This is no doubt because only

EU-funded network upgrades are foreseen in this analysis, so that many future network upgrades are likely not accounted for. To tackle that potential hiatus in knowledge, an effort to comprehensively project road network improvements in the EU is necessary, but such an exercise is outside the scope of this paper.

Next to infrastructure improvements, population changes affect the analysed accessibility levels. In this modelling exercise, all future population levels are based on the 'Europop2010' regional population projections for 2030. Those projections assume a general 7% population growth in all of Europe between 2006 and 2030, but a 3% population decrease in the study area (see Table 8-4).

Table 8-4. Population projections used in the population modelling exercise aggregated per country. Source: Europop2010 (EuroStat 2011).

Country	Population 2006	Population 2030	% dif
Austria	8,254,298	8,849,533	7%
Czech Republic	10,251,079	10,839,979	6%
Germany	82,437,995	77,871,677	-6%
Poland	38,157,055	37,564,976	-2%
Total	139,100,427	135,126,165	-3%

In Figure 8-4 the projected regional population changes are shown as well as the differences in the municipal population distribution as modelled by LUISA in the Compact and BAU scenarios. In both scenarios, regional migration flows modelled in the Europop2010 population projections cause that population levels will have increasingly unequal distributions in the study area. In fact, a quick check shows that the Europop2010 projections cause a 3% to 5% increase in population concentration. At the local level the modelled level of population concentration is even more pronounced, with up to 53% increases in population inequality indicators.

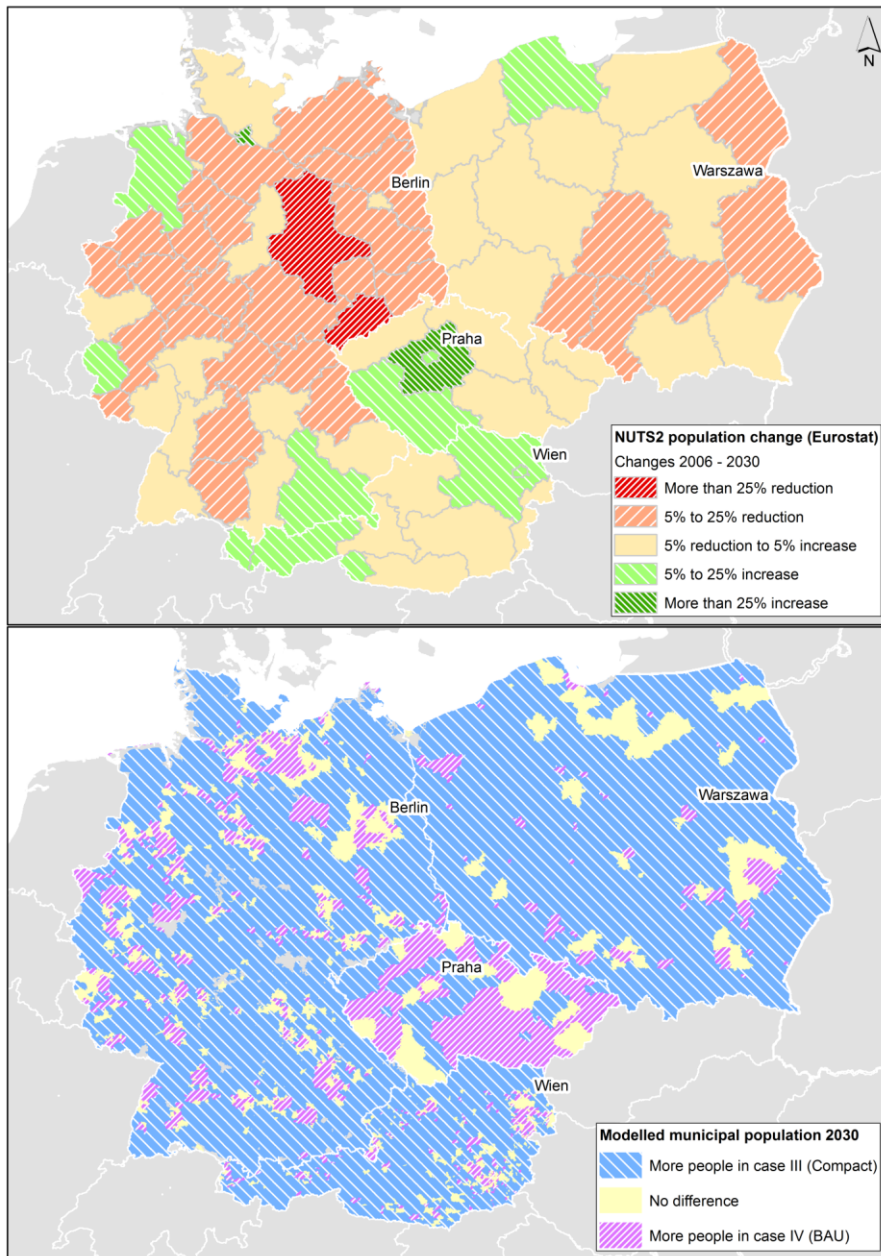


Fig. 8-4. Above: projected population changes per NUTS2 region from 2006 to 2030 (EuroStat 2011). Below: the differences in modelled municipal population between cases III (Compact scenario) and IV (BAU scenario).

Table 8-5. Inequality indicators of observed population distributions in 1971 and 2011, and in 2006 and 2030 according to the LUISA's Compact and BAU scenarios.

Population distribution	Population 1971 (r)	Population 2011 % dif			
Variation coeff.	6.695	6.482	-3.17		
Gini index	0.778	0.783	0.54		
Atkinson (0.5)	0.536	0.541	0.89		
Theil (0)	1.775	1.743	-1.81		
Population distribution	Population 2006 (I and II)	Compact scenario (III) % dif		BAU scenario (IV) % dif	
Variation coeff.	6.355	8.334	31.13	9.462	48.89
Gini index	0.782	0.858	9.72	0.883	12.83
Atkinson (0.5)	0.541	0.668	23.51	0.711	31.59
Theil (0)	1.733	2.354	35.83	2.658	53.35

Note: case numbers (I to IV) are given between parentheses. Case r serves as a reference for the relative differences in the historical trends; case I serves as a reference for the relative differences in the modelling results.

When comparing the results from modelled population distributions with historical trends, it is immediately clear that the concentration tendencies in the modelling results are more conspicuous than in the historical trends. This can to some degree be explained by the increased concentration according to the used Europop2010 projections. Nevertheless, although we must repeat here that past trends are not indicative of future changes, the contradictory results may still signal a bias in the modelling results towards more concentrated population distributions. To verify the validity of modelling results, the team involved in developing the LUISA model is therefore using historical population data to explore whether variables that are relevant for population distributions are missing in the current approach. Notwithstanding whether the future will resemble the modelled trends, useful information can be extracted from a comparison of the modelled scenarios of land-use developments. Table 8-5 shows that in case III the regional inequality of population levels is much less compared with case IV. As Figure 8-4 shows, in case III urban development is less substantial in the environs of the largest urban areas; this is due to the more restricted supply of land there in that scenario. Instead, in that case urban development is more evenly distributed near the edges of the

various smaller and larger urban areas within the modelled regions. Thus, within the frame of overall population trends, the level of land-use development can have a substantial impact on population distribution outcomes.

3.2 Territorial cohesion impacts of accessibility

We proceed to discuss the territorial cohesion effects of the modelled accessibility changes. Here we take into account accessibility levels with the reference 2006 population and network (case I); with the 2006 populations but with network improvements in place (case II), so that the separate effects of infrastructure improvements and population changes can be observed; and lastly with 2030 population levels according to the Compact and BAU scenarios of local urban development (respectively cases III and IV). Reference accessibility levels and the relative effect of the assumed road network improvements on accessibility measures are plotted in Figure 8-5. For all scenarios the averaged accessibility changes per country are furthermore given in Table 8-6. In both the mentioned figure and table, population levels are held static. The results show that, in relative terms, the assumed road network improvements have a profound effect on accessibility levels in particular in the easternmost regions of Poland and Czech Republic. In contrast, western Germany is hardly affected by the EU funded infrastructure improvements. These results confirm that EU road investments are the largest in more peripheral regions (Stępniaak & Rosik 2013; Gutiérrez & Urbano 1996). Nevertheless, the infrastructure improvements do not affect the ranking of countries in terms of accessibility levels, and in absolute terms, the changes are modest. That the absolute accessibility effects of the infrastructure investments are so modest is without doubt caused by the fact that accessibility levels in the studied countries were already reasonably high in 2006.

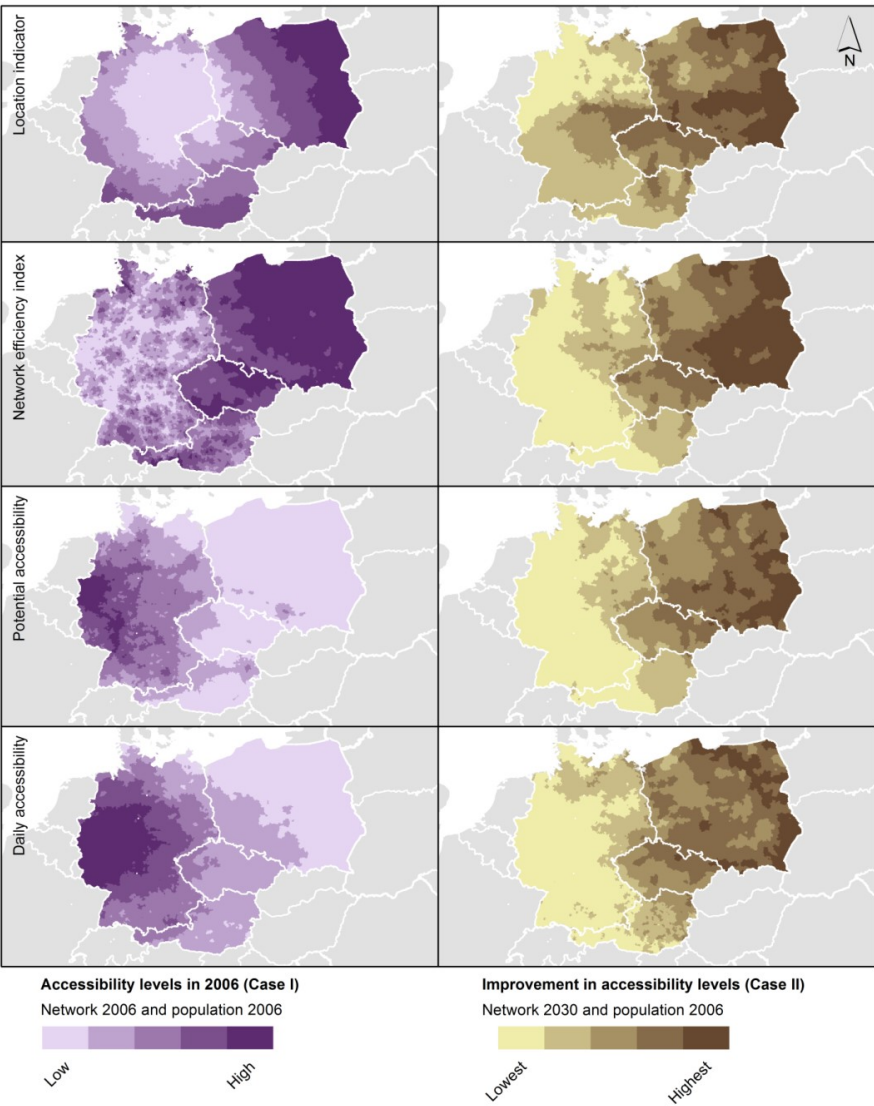


Fig. 8-5. Left: spatial distribution of accessibility levels with 2006 data (case I). Right: improvements in accessibility levels when taking only network changes into account (case II). The class breaks represent a Jenk's natural break distribution. Cases III and IV are deliberately excluded here to save space; when mapped the changes brought forth by those cases appear very similar to the results of case II.

Table 8-6. Averaged accessibility levels per country given current and expected future road networks and the Compact and BAU scenarios of population change.

Network	2006	2030					
Population	2006 (I)	2006 (II)		Compact scenario (III)		BAU scenario (IV)	
<i>Austria</i>		% dif		% dif		% dif	
Location	352	345	-1.99	352	-0.11	354	0.35
Network eff.	1.50	1.47	-1.94	1.47	-2.14	1.47	-2.20
Potential	59,199	60,431	2.08	63,187	6.74	63,184	6.73
Daily	43.79	45.64	4.23	47.78	9.11	47.76	9.07
<i>Czech Rep.</i>							
Location	295	285	-3.41	298	0.95	303	2.63
Network eff.	1.56	1.51	-3.27	1.50	-3.73	1.50	-3.80
Potential	57,380	60,674	5.74	62,571	9.05	62,573	9.05
Daily	43.50	48.42	11.30	48.32	11.07	48.44	11.35
<i>Germany</i>							
Location	273	269	-1.62	268	-1.80	272	-0.52
Network eff.	1.47	1.44	-1.81	1.44	-2.03	1.43	-2.10
Potential	81,560	82,702	1.40	84,733	3.89	85,316	4.60
Daily	71.99	73.21	1.70	72.68	0.97	73.12	1.58
<i>Poland</i>							
Location	404	384	-4.98	396	-1.85	399	-1.29
Network eff.	1.60	1.52	-4.55	1.52	-4.96	1.52	-5.02
Potential	42,215	45,736	8.34	46,853	10.99	47,265	11.96
Daily	25.75	29.74	15.47	29.56	14.77	29.81	15.77

Note: all relative differences are computed with case I as reference. Case numbers (I to IV) are given between parentheses.

The redistribution of population as modelled in LUISA substantially impacts accessibility levels. In general, the change in the location indicator is much smaller with future population levels, network efficiency is slightly increased and potential accessibility is much larger; while the effects on daily accessibility are mixed. The significant increase in potential accessibility in Germany, despite the overall population decline, is surprising. The observed increase of potential accessibility occurs in both cases III and IV and must therefore be due to regional population trends. This shows that such regional population distributions can have a substantial impact on potential accessibility levels. While cases III and IV yield

consistently better average accessibility levels than the scenarios that ignore population changes (I and II), the results of cases III and IV do not differ much between themselves. This shows that, when considering average accessibility levels, regional population projections surely matter, but the aggregate effect of differing local urbanization patterns is rather limited.

Table 8-7. Inequality indicators of accessibility levels given current and expected future road networks and the Compact and BAU scenarios of population change.

Data source	Observed				
Network	1970	2012			
Population	1971 (r)	1971	2011		
<i>Coefficient of variation</i>			% dif		% dif
Location	0.074	0.046	-37.6	0.041	-44.0
Network efficiency	0.143	0.051	-64.2	0.052	-63.4
Potential	0.432	0.332	-23.2	0.336	-22.3
Daily	0.596	0.423	-29.0	0.426	-28.5
<i>Gini index</i>					
Location	0.042	0.026	-38.2	0.023	-44.5
Network efficiency	0.066	0.025	-62.2	0.025	-61.7
Potential	0.235	0.181	-22.9	0.183	-22.1
Daily	0.325	0.237	-27.0	0.236	-27.4
<i>Theil (0)</i>					
Location	0.003	0.001	-62.0	0.001	-69.3
Network efficiency	0.009	0.001	-86.2	0.001	-85.6
Potential	0.091	0.055	-39.9	0.055	-39.1
Daily	0.168	0.089	-46.8	0.089	-47.1
<i>Atkinson (0.5)</i>					
Location	0.001	0.001	-62.4	0.000	-69.7
Network efficiency	0.004	0.001	-85.7	0.001	-85.2
Potential	0.046	0.028	-40.1	0.028	-39.5
Daily	0.084	0.046	-45.8	0.045	-46.8

Table 8-7 (continued)

Data source	Modelled						
Network	2006	2030					
Population	2006 (I)	2006 (II)	Compact scenario (III)		BAU scenario (IV)		
<i>Coefficient of var.</i>			% dif		% dif		% dif
Location	0.191	0.182	-4.5	0.184	-3.5	0.179	-6.2
Network efficiency	0.041	0.033	-18.7	0.033	-20.7	0.033	-20.7
Potential	0.285	0.266	-6.7	0.269	-5.8	0.273	-4.3
Daily	0.430	0.391	-9.1	0.393	-8.7	0.394	-8.4
<i>Gini index</i>							
Location	0.099	0.097	-2.4	0.097	-2.1	0.094	-4.8
Network efficiency	0.023	0.019	-19.3	0.018	-21.4	0.018	-21.4
Potential	0.158	0.147	-7.0	0.148	-6.7	0.149	-5.5
Daily	0.240	0.219	-9.0	0.219	-8.9	0.220	-8.6
<i>Theil (0)</i>							
Location	0.017	0.016	-7.4	0.016	-6.1	0.015	-11.3
Network efficiency	0.001	0.001	-33.9	0.001	-37.1	0.001	-37.2
Potential	0.040	0.035	-13.1	0.035	-11.8	0.036	-9.5
Daily	0.092	0.076	-17.0	0.076	-16.6	0.077	-16.2
<i>Atkinson (0.5)</i>							
Location	0.008	0.008	-6.8	0.008	-5.9	0.007	-11.0
Network efficiency	0.000	0.000	-33.9	0.000	-37.1	0.000	-37.1
Potential	0.020	0.017	-13.2	0.017	-12.1	0.018	-9.9
Daily	0.046	0.039	-17.0	0.039	-16.7	0.039	-16.4

Note: all relative differences in the observed data are computed with case r as reference; all relative differences in the modelled data are computed with case I as reference. Case numbers (I to IV) are given between parentheses.

In contrast to average accessibility levels, territorial cohesion indicators can change considerably with different local urbanization patterns. Table 8-7 shows cohesion effects of the outcomes of accessibility indicators in cases I to IV. Comparing cohesion indicators when only the network improvements are in place yields that the infrastructure improvements considerably increase cohesion: here, in all cases the inequality indices are lower when the 2030 network is taken into account. This is consistent with the findings of López et al. (2008). However, when projected

population changes are taken into account, the cohesion impacts of infrastructure improvements are much smaller. With most inequality indicators, potential and daily accessibility have a smaller but still positive impact on cohesion. Only the cohesion effects of network efficiency seem to consistently improve with the modelled population changes, while in particular the cohesion effects of potential accessibility levels suffer from the modelled population changes. Differences in local urban development patterns have a substantial impact on the used cohesion indicators, with differences in cohesion indicator values of over 20% in the case of potential accessibility. Comparing the results between cases III and IV, we find that more compact urban development decreases disparities in potential and daily accessibility, but increases disparities in location accessibility. Location accessibility, in fact, seems to profit considerably from the urban patterns modelled in the BAU scenario (case III).

All in all, cohesion indicators of accessibility are very sensitive for local population levels. This is again emphasized when looking at the results from historical data. Those data show much more profound impacts on cohesion indicators, which is no doubt caused by the substantial network improvements observed between 1970 and 2012 and the relatively small changes in inequality of population distributions. All in all, the historical data show a remarkable decline in accessibility disparities that are in many cases even augmented by changes in population distributions over time. Thus, from the historical trends and the modelled results we extract that investments in the road network may have a considerable impact on disparities in accessibility levels, and that land-use development policies may be used to restrict the potentially unwanted effects of population distributions on those disparities.

4 Conclusions

This article explores the cohesion effects of accessibility changes induced by road infrastructure upgrades, given ongoing population changes. Accessibility levels have been obtained using partially provisional road network improvements and future population distributions that are modelled on a fine spatial resolution. The aforementioned population distributions have been modelled to readjust to intermediately changing accessibility levels, regional demographic trends and various other factors. Two scenarios of urban development have been assessed here: a Business-As-Usual scenario with unrestricted urbanization patterns and, as a consequence, considerable relocation to each region's prime centres of attraction; and a Compact scenario with more restricted urbanization patterns, and ultimately more evenly spread population growth in a region. The used methods to

model future population projections and their accessibility impacts provide a useful first insight into potential future outcomes. It is however important to note that the presented framework only supports the evaluation of general accessibility impacts and may be unable to evaluate specific aims of network investments. For example, accessibility impacts may differ across population groups with diverging activity patterns and transport mode availability (Kwan 1998), and network investments may be necessary to improve access to specific activity places (such as hospitals or schools) or to support large recurrent transport flows (for example for tourism or international commuting). A comparison with results from observed historical changes in population levels and the road network show that the LUISA model seems to overestimate the level of concentration in future population levels. This emphasizes the importance of empirical model validation exercises that are currently underway.

Some more general findings can be extracted from the found results by comparing accessibility results with different population distribution assumptions. Average accessibility levels are improved substantially by population changes in both cases that take future population projections into account. This shows that average accessibility levels depend substantially on future regional population levels. The effect of local population distributions on average national accessibility levels is fairly limited. However, variance in local urbanization patterns can have a drastic effect on the impact that infrastructural investments have on territorial cohesion; in some cases migration to main urban areas can substantially alter the decrease in disparities that infrastructure investments aim at. The results further show that the cohesion effects of transport network investments, such as for example reported by López et al. (2008) and Stępniaś & Rosik (2013), can differ substantially when population changes are taken into account. All in all, if policy makers aim at reducing disparities between regions by means of infrastructure investments, they will do well to take future urbanization patterns and spatial planning policies into account when evaluating their plans. This may be necessary to ensure that network investments are effective and robust to possible population changes.

We cannot easily discern a good and a bad scenario of urban growth here, even when the only goal would be to preserve or increase territorial cohesion. Some accessibility measures yield better territorial cohesion in one scenario of urban growth, while other measures score better cohesion marks in the other scenario. The essential question here is which sort of accessibility needs to be optimized? If the emphasis is on more evenly spread economic opportunity, cohesion results of potential accessibility indicate that policies that incite more evenly spread urban

development over different cities in a region have better cohesion effects. However, the effectiveness of such policies and the net welfare effects of inciting such urban development is unclear; furthermore, infrastructure developments may aim at optimizing very different accessibility measures.

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Part V: Conclusions and summary

Chapter 9. Conclusions

In this dissertation several questions related to interdependencies between land-use patterns, short and long distance interactions are investigated. The dissertation consists of three separate sections. In the first section, spatial data analyses are presented that are instrumental to understand the relationship between interaction opportunities and spatial organization. In the second part, the driving forces behind transport network formation are investigated to better understand how the infrastructure for long-distance interaction comes into existence. The third section offers a study of how the reciprocity between land-use patterns, local and long-distance interactions affects current spatial planning dilemmas. The included studies provide a number of conclusions that are relevant for the establishment of land-use and infrastructure policies and for the evaluation of those policies. The first three sections of this chapter summarise the main findings of the three parts that comprise this thesis. Based on these findings some policy recommendations are proposed. Finally, some general conclusions and suggestions for further research are discussed that are relevant for the practice of ex-ante policy evaluation and the understanding of spatial processes.

1 Understanding the relationship between interaction opportunities and spatial organization

The first part of this dissertation is dedicated to various aspects of the relationship between interaction opportunities and urban land use. To facilitate land-use analyses and land-use modelling on a fine resolution, a potential accessibility measure has been downscaled to that resolution using the method outlined in Chapter 2. The influence of the scale and shape of areal units on the outcome of explanatory analyses is investigated in Chapter 3. The main conclusions from the mentioned chapters will be expanded in the following sections.

1.1 Downscaling potential accessibility levels to the local scale

Chapter 2 demonstrates a method to compute potential accessibility at a very fine spatial resolution by means of spatial interpolation of accessibility levels between sample points. This is a necessary heuristic in cases where it is not possible to compute accessibility directly at the desired resolution because of technical or data limitations. Using this method enables the inclusion of potential accessibility measures in fine resolution spatial analyses and land-use modelling efforts. The

interpolation method yields more accurate accessibility estimates than when imposing a zone's accessibility level to all space that is part of that zone; the zonal method is shown to be particularly less accurate farther away from the centroid of a zone.

1.2 The impact of spatial aggregation on urban development analyses

Chapter 3 reiterates the findings of, amongst others, Gehlke and Biehl (1934), Openshaw (1984) and Arbia (1989) that urban development analyses are hindered by the fact that the results of statistical analyses of spatial data depend on the scale and shape of the areal units in which the analysed data are obtained. Scale effects are as persistent as shape effects and both can partially be mitigated by means of methodological improvements. In this dissertation, spatial econometric methods are applied to capture the large amount of otherwise unexplained local variance with fine resolution data, and area weighting techniques are applied to reduce the effect that unevenly sized areal units may have on the results of explanatory analysis. The results of an explanatory analysis underpin that variables with relatively little local variance, such as potential accessibility, do affect the geographic distribution of urban land uses even at the very local level; but in addition many other factors come into play at this scale level as well. Proximity to motorway exits for example only is relevant at very fine resolutions. Furthermore, Chapter 3 confirms that the effects of neighbourhood observations have a more important effect on observed values in the case of fine resolution data.

In addition to having methodological implications the results are also relevant for policy evaluation. The differences between the results from regularly latticed and administrative units show that, in the case of data at the administrative unit level, the obtained, unweighted impacts of spatial policies on urban development may be overestimated. In this case, the found policy effects are not necessarily the spatial consequence of an implemented policy, but they may well be an idiosyncratic result of the analysis, caused by the fact that the evaluated policies are bound to the same spatial units in which the effects of the policy are evaluated. This brings forth a more conceptual problem for policy makers and the evaluators of policy effects: are policy makers attempting to optimize distributions over space or distributions for particular administrative units?

2 Understanding overland transport network expansion

From the results of the previous sections it must be clear that the development of transport networks has affected the spatial distribution of urban growth. But what is the logic of transport network development? Why do some places get connected and others not? The second part of this dissertation is dedicated to improve understanding of what drives the ongoing geographic expansion of transport networks. The chapters in this section are dedicated to the development of the Dutch railway network between 1839 and 1930. The determinants of network development that have driven accessibility changes are investigated in Chapter 4, as well as the role of the Dutch state in that process. There has been a clear logic in the construction of the Dutch railway network and that various investor types have followed different objectives. This leads to the conclusion that different institutional involvement or a different playing field of investors would have yielded a different final network outcome. To be able to evaluate the effect of policies and investor involvement on network expansion, Chapter 5 introduces Transport Link Scanner, a model that simulates transport network expansion.

2.1 The driving forces of railway network expansion

Infrastructure investments are often taken as exogenous to land-use and economic developments, but they clearly are not. The geographic expansion of infrastructure networks is tied to the spatial distribution of people, to the physical layout of the land and water bodies that need to be overcome by the railroad network, by the preferences of investors and by contemporary market conditions. In Chapter 4 I demonstrate that the often observed stagnating growth of transport networks in their mature stage (Levinson 2005; Nakicenovic 1995) is in fact coupled with the declining return on investment of new links, as the transport market becomes saturated. The saturation of markets is conditioned by the speed improvements that are offered by the transport investments: in case of network improvements that allow for faster travel speeds, the transport market is saturated earlier. Thus there is a clear link between transport speeds and end-state network density.

Chapter 4 furthermore shows the potential risk of excessive public involvement in potentially profitable transport network developments. Here, the Dutch state backed one competitor on the Dutch passenger railway market with, according to the literature, the objective to increase the pace of railway network expansion in the country. Unfortunately, the heated competition caused a much higher level of investments in transport supply than the country had demand; this contributed to the bankruptcy of many private enterprises and a too high railway network density.

2.2 Simulating geographic transport network expansion

From Chapter 4 follows that infrastructure investments have a clear rationale. Chapter 5 introduces a model to reproduce the expansion of an overland transport network. In the presented model, single lines are added to the growing network in every simulation round. To do so, a most attractive combination of investor and line is repeatedly selected from a limited sample of likely investments. The selection process consists of three steps. In the first step, presumably attractive links between two terminating municipalities are selected based on the expected flow on the line between those two municipalities and the lowest cumulative construction costs to connect the municipalities. Subsequently, most plausible routes that include detours are obtained, using a solution from the corridor location problem literature (Goodchild 1977; Scaparra et al. 2014). Finally all decision criteria for investment attractiveness are evaluated, and a conditional logit model is used to determine which investor-link combination is added to the network in the iteration at hand. Different types of investors evaluate attractiveness according to different criteria and the expected benefits depend on the already built network.

As an evaluation of its practical use, the model was applied to reproduce the development of the Dutch railway network, and its results have been compared with the results from a much simpler model suggested by Bruinsma and Rietveld (1998). The results from this simulation exercise are promising, and show that the development of the Dutch railway network can be reproduced with reasonable accuracy. Compare with the Bruinsma and Rietveld model, accuracy gains are relatively small. However, the addition of investor variation and additional attractiveness criteria do allow the modelled network to grow after commercially viable investment options are exhausted, while the Rietveld and Bruinsma model would stop there. The introduced model thus allows for the reproduction of a larger part of the constructed railway network. Multiple scenarios were run that vary in the relative speed improvement offered by the railway network; in the level of price-elasticity of transport consumption; in the set of investors that partake in network construction; and in the level of cooperation between competitive investors. All in all, this chapter demonstrates that institutional settings and the investor playing field may have a crucial impact on final network outcomes. This underlines the potential usefulness of the introduced model for evaluating the network and accessibility impacts of policies that aim at improved connectivity, such as the European Union's cohesion policies (EC 2004).

3 How interactions between land-use patterns, local and long-distance interactions affect current spatial planning dilemmas

The previous parts of this dissertation have shown that land-use patterns and transport infrastructure development are reciprocal: high accessibility levels affect land-use densities, while land-use densities affect transport network development. Furthermore it is clear that local interactions affect land-use patterns through neighbourhood effects; in the aforementioned sections often tackled as an auto-correlated error term. The third part of this dissertation focuses on analyses in which the reciprocity between land-use patterns, local and long-distance interactions are an important factor for current spatial planning dilemmas. In Chapter 6, the expected social benefits of dense and mixed urban land-use patterns are analysed. The role of domestic and cross-border accessibility on historical municipal growth is analysed in Chapter 7. In Chapter 8, the effect of infrastructure investments on accessibility distributions is analysed in a case in which population distributions respond to accessibility levels. The main conclusions from those three chapters is elaborated upon in the next sections.

3.1 Exploring social benefits of dense and mixed urban land-use patterns

Dense and mixed urban land-use patterns are expected to instigate prolonged and more intense activity patterns in urban areas, which in turn are expected to make a safer and more attractive urban environment (Jacobs 1962). In Chapter 6 I demonstrate that such land-use patterns are indeed associated with prolonged and more intense activity patterns. A further analysis shows that urban areas that experts deem attractive coincide with relatively high densities and a large share of non-residential activities, while urban areas that have abundant socio-economic problems coincide with areas with medium densities and a limited share of non-residential activities. Thus, land-use configurations are clearly associated with activity patterns, and high-density, mixed land-use urban areas may indeed foster more attractive social environments. Developing new urban areas that have adequate land-use configuration has proven to be a costly affair; but existing urban areas that do have the wanted characteristics do need to be protected from the sort of developments that sap shopping and meeting activities from residential areas. All in all, failing to protect existing lively urban areas may come with higher social costs than are commonly understood.

3.2 The impact of national borders on population growth

Chapters 3 and 7 show that interaction opportunities are an important determinant for the geographical distribution of urbanization. However, national borders reduce the amount of interaction that one would expect, given geographical separation and the amount of cross-border interaction opportunities. Increased costs and contract enforcement risks associated with cross-border spatial interactions are often quoted as the main reasons for such border effects. The existence of border effects is clearly reflected in urbanization patterns in Western Europe. Despite the fact that Western Europe is the region with the greatest degree of international economic integration in the world (McCormick 1999), Chapter 7 shows that cross-border accessibility still has a very limited impact on urbanization patterns compared with accessibility to domestic interaction opportunities. This dissertation, furthermore, shows that border regions partially lag behind because cross-border opportunities that drive urbanization are underused. This is a relevant finding for policymakers as a typical reaction to enhance cross-border activity would be to improve infrastructure to decrease the costs of reaching interaction opportunities across borders. However, the results from Chapter 7 show that cross-border infrastructure improvements are likely to have a very limited effect as it is not lack of international interaction opportunities that cause that cross-border activity is limited.

3.3 Accessibility and cohesion in a case of infrastructure improvements with endogenous population distributions

When assessing the impact of infrastructure improvements on accessibility indicators, population distributions are usually held static, even though it is well-known that activity distributions respond to the proposed infrastructure improvements as well as to a wide range of more general demographic and economic trends. In Chapter 8 I use a land-use model to project future population distributions in two scenarios of land-use change while taking into account likely future infrastructure improvements. Summed accessibility indicators as well as changes in accessibility disparities were subsequently computed to quantify the accessibility effects of infrastructure improvements.

The results of this exercise show that changing population distributions may have a substantial impact on accessibility indicators, to the extent that demographics and migration may even negate attempts to increase the level of equality in interaction opportunities through infrastructure investments. Conclusively, either spatial planning efforts to optimize the effect of transport infrastructure improvements, or

reconsideration of those transport infrastructure improvements may be necessary. The results furthermore underpin that assessing the effects of infrastructure investments on accessibility equality is rather pointless if future scenarios of population distributions are not taken into account, especially where population levels are expected to change substantially due to processes of migration and ageing.

4 Recommendations for land-use and transportation policies

This dissertation deals with the relationships between land use and short and long-distance interaction opportunities. The presented findings are especially relevant for policies that deal with the spatial implications of growth. A first relevant conclusion to be made from this dissertation is that the development of transport networks and the spatial allocation of economic activity are interlinked. Chapters 2 and 7 have shown that spatial patterns of growth depend largely on accessibility levels; and Chapters 4 and 5 have shown that, at least in case commercial interests are present, the development of transport networks depends on the spatial distribution of transport demand.

Despite the clear link between the transport and urban land-use sectors, these sectors are commonly managed by separate authorities (Bertolini et al. 2005). That separation brings forth the risk of different strategic priorities and lack of coordination. Given the clear linkages between transport and land use it is surely advisable to at least ensure close alignment of sectorial objectives. Ideally, transport and land-use related interventions are used to enforce each other. For example, the results of this dissertation suggest that travel demand and spatial disparities in accessibility levels may partially be managed through land-use planning interventions; while nature protection schemes may benefit greatly when the connectivity of protected areas is reduced. All in all, the cross-dependence of land use and transport has a wide range of policy implications. Several of these implications are discussed in the remainder of this section.

4.1 Be cautious when intervening in ongoing transport network development processes

Chapters 4 and 5 of this dissertation show that, after the introduction of a new transport technology, the necessary transport infrastructure may develop autonomously without government intervention. This is in line with other studies on network formation (Levinson et al. 2012; Bala & Goyal 2000). In fact, Chapter 4

shows that in the development of the Dutch railway network, involvement of the Dutch state caused excessive competition on the transport market, resulting in an overly dense railway network, the decline of many operators on that network, and finally the necessity to nationalize the entire network. In the Dutch case, government action to achieve a dense railway network caused substantial extra costs for building and maintaining the railway network, while a sufficient network density possibly could have been achieved with more limited intervention. Chapter 4 in this dissertation confirms that the agents in network formation act in self-interest. The implication is that some level of coordination is needed to drive the outcomes of network formation processes towards a social optimum (Youn et al. 2007; Anshelevich & Dasgupta 2003; Li et al. 2010). Thus, surely, there is an important role for policy makers in network expansion; but policy makers should be careful not to intervene more than necessary.

4.2 Transport network development may spur excessive urban expansion

It is clear from Chapter 7 that places with more long-distance domestic interaction opportunities have historically grown more. That chapter furthermore shows that growth happens mostly in municipalities with more interaction opportunities and relatively low population densities. The conclusion is that higher interaction opportunities may favour growth in low density areas; with the potential outcome of excessive urban expansion and a loss of densities in urban areas, as has been the reality for many cities in the last 50 years or so (Halleux et al. 2012; Glaeser & Kahn 2004).

If increasing interaction opportunities causes excessive urban expansion, investments in transport infrastructure may have a number of unwanted indirect effects on other policy objectives. One key spatial policy objective in Europe is the preservation of attractive and lively cities. From Chapter 6 it is clear that local interactions and activity patterns are necessary for the liveliness deemed necessary in cities, and that at least in Amsterdam livelier urban areas coincide with areas that are deemed more attractive. Thus, it may well be that improvements in transport infrastructure reduce the local interactions that are so crucial for neighbourhood attractiveness. In that light, loss of urban densities can have a detrimental effect on the quality of Europe's cities.

Chapter 7 shows that in the last 50 years, preferences for low-density areas with high car accessibility have been the norm. On the other hand, some authors

mention an urban renaissance (Stead & Hoppenbrouwer 2004) in which cities are regaining their attractiveness as places to live and work in. In fact, Dutch cities have increased in density in the last decade (Broitman & Koomen 2015). The renewed attraction of the city is paired with a decline in car usage among young Dutch (Jorritsma et al. 2014). Thus, the last decade may be the sign of a trend change that might make it easier to limit urban expansion and might reduce the need for additional network development.

4.3 Local land-use planning policies may affect the effectiveness of network investments

Chapter 5 has shown that reducing disparities in interaction opportunity was a key driver of public investment in railway networks in the 19th century. The same aim to reduce territorial disparities is at the heart of, for example, current European Union cohesion policies, which amongst others provide funding for transport network investments. Chapter 8, however, shows that the effectiveness of these policies depends to some degree on the path of urban development in the targeted areas. In all presented cases the expected population decline and relocation to larger cities greatly limit the potential for decreasing disparities. Within that context, land-use planning does matter. Results from a land-use modelling exercise show that the level of decrease in disparities for different accessibility measures changes if supply for urban land is limited through political intervention.

Arguments for the integration of land-use and transport policies have been voiced before (Bertolini et al. 2005; Geerlings & Stead 2003; Wegener & Fürst 1999). The findings of Chapter 8 again underpin the importance of coordination between land-use planning and transport network investment.

4.4 Transport investments have a limited effect on growth in peripheral areas

The improvement of transport networks is often seen as a method to incite growth in peripheral areas. However, the results of this dissertation cast some doubt on the effectiveness of transport investments in order to incite growth in the periphery. Such peripheral areas typically have low population densities and low levels of economic activity. Given the results from Chapter 4 and 5, investors are more likely to construct transport links in central regions. Chapter 4 shows that, even if construction of links is more costly in central areas, the much larger transport demand in high density areas makes it more cost-effective to construct in those areas. Thus, it is no doubt more costly to incite network development in the periphery.

The results from Chapter 7 confirm others (Koopmans et al. 2012; Vickerman et al. 1999; Hansen 1959) that growth is partially driven by interaction potential, which besides access to transport infrastructure also requires activities at the destination. Chapter 8 shows that substantial investments in transport infrastructure in peripheral regions cause a limited reduction in potential accessibility disparities; and those effects may even be smaller in the future, if population redistribution is taken into account. Thus, sizeable investments cannot offset the advantageous position that central cities enjoy. The scale and extent of analysis is again important here. Spiekermann and Wegener (2006) have in fact shown before that infrastructure improvements that reduce disparities between countries may in fact increase disparities at the local level within countries. All in all, infrastructural improvements set to incite growth in countries that lag behind may worsen the situation for regions that are already lagging behind.

If growth is indeed driven by interaction potential, better connecting regions that are far away from more productive or more populated places will not have the desired effect, as the effect on interaction potential will be limited. Chapter 7 furthermore shows that access to economic activity across national borders is a poor substitute for access to domestic economic activity. Even in member states of the European Union, which may be expected to have relatively high levels of international economic integration (McCormick 1999), I have not found any effect of cross-border accessibility improvements on growth. All in all, the pessimistic conclusion may well be that transport investments are a poor instrument for bettering the situation of regions that lag behind.

5 Discussion and outlook

This dissertation has presented a number of investigations into processes of land-use development, transport network expansion, and spatial interaction; in all cases using observed or modelled spatial data with sizeable observation counts, and using or (in the case of Chapter 5) introducing state-of-the-art methods. This section reflects on some of the general conclusions that can be drawn from the presented investigation, with emphasis on lessons learned for the practice of ex-ante policy evaluation and the understanding of spatial processes.

The key research question posed in this dissertation is:

“How do long-distance interaction opportunity and local interactions affect land-use patterns and the management of those patterns?”

Although this question is too broad to be answered completely within the constraints of a dissertation, all chapters have covered aspects of this question. In Chapter 3 it is established that long-distance interaction opportunities matter for urban land-use patterns; and that, particularly when studying at a fine resolution, local interactions (proxied using spatial econometric techniques) have an important role in the studied land-use patterns. Chapter 4 and 5 show that, at least in the case of railway infrastructure, the distribution of people is an important determinant of the choices that have driven transport network expansion. On the other hand, in Chapter 7 I find that long-distance interaction opportunity, in this case supported by road infrastructure, has played only a modest role in population changes in Western Europe in the last 60 years; while negative crowding effects have had a consistent and highly significant damping effect on population changes. The negative crowding effects found in that chapter hide the result that many of Europe's large cities have had a lasting attractiveness on people, which in the analyses are captured as fixed effects. Those fixed effects underline that local interaction opportunities are beneficial for urban growth. Benefits of local interaction opportunity may come into play through externalities related with agglomeration (Krugman, 1998), diversity (Jacobs, 1969) or competition (Porter, 1990). For an overview of research into those externalities, see De Groot et al. (2016). Finally, Chapter 6 gives an example of how local diversity externalities cause behaviour changes, and coincide with urban areas that are considered attractive.

All in all, I conclude that both long-distance and local interaction opportunities are important determinants of urban growth. Surely, long-distance interaction opportunities play an important part in highly aggregate processes!; but, given the lasting importance of local level indicators in Chapters 2 and 7, those long-distance interaction opportunities are by no means acting as a complete substitute for local interaction externalities.

5.1 Models of land-use/transport interactions

The central theme of this dissertation is the importance of spatial interaction for urban land use; with the underlying assumption that the potential to interact is a fundamental organizing force in models of spatial organization, such as those presented by Christaller (1934), Von Thünen (1826) and Alonso (1964). A potential accessibility measure, which explicitly includes the performance of transport systems as well as notions of centrality with regard to other people or activities, is repeatedly used in the dissertation as an operationalization of the potential to

interact. The link between potential accessibility and urbanization has been explored repeatedly before (see, for example, Koopmans et al. 2012; Hansen 1959), but several aspects related to potential accessibility measures have so far hindered the inclusion of those measures in fine-resolution land-use models.

A number of issues related to the practical usefulness of potential accessibility measures in land-use models are addressed in this dissertation. A first issue is related to the fact that potential accessibility measures are by necessity obtained from a two-dimensional matrix of travel times between origins and destinations, which implies that every doubling of the spatial resolution of origins and destinations causes a squaring of computation demand. To make implementation in 1km and 100m land-use modelling frameworks feasible, Chapter 2 offers a spatially asymmetric, spatial interpolation-based method to include potential accessibility as a factor in fine spatial resolution land-use models that does not excessively increase demand for computation power.

Another issue is the complex relation between potential accessibility, which has relatively little spatial variance between small neighbouring units, and the choice behaviour behind land-use changes. Here, potential accessibility seems to be important for regions, but the limited local variance begs the question if this factor is even relevant at the local scale? Other studies have found that, when controlling for amongst others distance to jobs, interaction opportunities are not relevant in the choice behaviour of people that change residence (Zondag & Pieters 2005). However, Chapter 3 demonstrates that even at a very fine spatial resolution, potential accessibility measures retain their explanatory power in analyses of land-use patterns if individual measures; at least when individual distances to jobs cannot be controlled for.

Lastly, it has been noted that accessibility to foreign destinations can be an important element in total interaction opportunity levels (Stępnik & Rosik 2013). This may signify that national borders need to be included when modelling the effects of potential accessibility on urban growth. This is further supported by the finding in Chapter 3 that, when only including domestic accessibility levels to explain shares of urban land-use in the Netherlands, national border proximity has an invariably positive effect. On the other hand, it is well-known that national borders and the cultural, linguistic and institutional differences that they signify, substantially reduce spatial interaction (Brakman et al. 2012; McCallum 1995). This raises the question whether cross-border accessibility needs to be included in land-use models? Chapter 7 shows the enduring relevance of potential accessibility in

historic processes of population growth in Western Europe, and demonstrates that accessibility to cross-border destinations hardly plays a role in population growth. One implication is that the importance of national border proximity established in Chapter 3 applies only to the analysed static land-use patterns and not to land-use changes. I speculate that in the Netherlands, other factors such as historic border changes or the presence of coal fields possibly have been the reason that the country has relatively high urban land-use shares close to the border.

The work presented in Chapters 2, 3 and 7 has supported the adoption of a potential accessibility measure in the European Commission's LUISA land function modelling platform, as is shown in Chapter 8. A number of issues pertaining to the study of potential accessibility measures and their effect on growth deserves further study. This relates foremost to the presence of endogeneity in the studied processes, which is likely to bias the found effects (Percoco 2015). Chapter 7 shows that municipal population change depends on accessibility levels, while Chapters 4 and 5 demonstrate that network improvements depend on population levels. The reciprocity between population changes and accessibility changes is obvious. In the mentioned chapters, the studied dependent variables are consistently modelled to depend on past accessibility or population levels. I assume this removes a lot of the endogeneity in the modelled process. Nevertheless a more satisfactory solution is needed. Hopefully, the driving factors analysis proposed in Chapter 4 and the transport network expansion model proposed in Chapter 5 may be used to good effect here in the future, by offering assessments of the probability of the transport infrastructure investments that have caused accessibility growth.

A second issue that needs to be dealt with in the future relates to the use of aggregate car-based accessibility measures used in this dissertation. The assumption here is that the applied aggregate measures determine preferences for a given location. In reality, access to specific transport means and the desire to live or work in locations with specific accessibility characteristics may depend greatly on personal preferences and socio-economic status. Hägerstrand (1970) already emphasized the importance of taking individual-level constraints into account; and to do so, individual accessibility measures are available in the literature (Dijst 1995; Kwan 1998). Unfortunately, lack of consistent data on transport means, preferences and moving behaviour has prevented the adoption of such methods in this research.

Lastly, in this dissertation I have ignored the effect that congestion on transport networks may have on growth. Such effects may cause travel-time decreases and

thus accessibility reductions, and are often central in transportation policies. Some models are available to understand the impacts of congestion on land-use changes. For example in the Tigris XL model (Zondag & De Jong 2005), accessibility effects are computed as individual utilities of potential dwelling locations, so that any congestion effect affects the attractiveness of potential dwellings for the modelled individuals. On an aggregate level, the link between congestion and economic growth certainly is not clear. To some degree, congestion can be seen as an indicator of economic success, as it results from a demand for the offered transport service. Because congestion in most cases only affects transport networks during very specific times of day, changing travel schedules or increasing density of vehicle use can be effective strategies to avoid travel time losses. In fact, recent research on cities in the United States shows that congestion decreases job growth only in cases of consistently severe traffic, while travel time losses are not found to have had any significant effect on jobs growth (Sweet 2014). Any negative land-use effects of congestion-induced travel time losses are clearly hard to prove empirically. Furthermore, in cases of consistently troublesome congestion, transport network managers may be expected to increase capacity to meet demand. All in all, the link between congestion and consequences for growth is not straightforward, and merits further study.

5.2 Models of transport network expansion

Two chapters in this dissertation deal with the expansion of the Dutch railway network between 1839 and 1930. With the exception of contributions in the 1960s and 1970s (Taaffe et al. 1963; Kolars & Malin 1970; Warntz 1966; Morrill 1970; Fogel 1964), transport network additions have generally been studied individually or with a small subset of additions in a limited timeframe. The long-term process of network development has only very recently regained attention (Anshelevich & Dasgupta 2003; Youn et al. 2007; Xie & Levinson 2009). Chapter 4 and 5 add to the body of knowledge by analysing and reproducing the investment decisions made in the transport network development process. These chapters confirm the expectation voiced by Rietveld and Bruinsma (1998) that railway network formation is largely driven by the cost-benefit considerations of investors. The findings in this dissertation add that other considerations played an important role in that process as well, especially for publicly funded investors. Another novel finding is that, in transport network formation, the initial stage of network formation as defined by Taaffe et al. (1963) coincides with increases in network diameter, while additions in later stages mostly add to the network's densities; and

that mostly the network additions that contributed to the network's diameter yielded positive network externalities.

All in all, these chapters show that transport network expansion can – to some extent – be predicted. Moreover, they highlight that the economic and political context in which the network develops can have an important impact on network formation even when the investment decisions are taken by relatively autonomous actors. The Transport Link Scanner model introduced in Chapter 5 is set up to explore the potential effects that these contexts may have on the long-term outcome of network formation processes. The first results are quite promising and show that network expansion models may become a useful addition to the toolbox of transport policy evaluators.

The results of Chapters 4 and 5 enable the investigation of a number of relevant follow-up questions. Some pertain to the link between the development of the Dutch railway network and its found effects on municipal growth (Koopmans et al. 2012). In the study published by Koopmans et al., accessibility improvements only start to become effective after 1880. The findings in Chapter 4 indicate that the onset of accessibility effects on municipal growth coincides with the maturity of the railway network and the related decline of benefits of additional links. This coincidence is consistent with an interpretation in which the growth effects of travel times from a transport technology are late, because actors are cautious for the new technology. In any case this finding begs the question whether transport network lock-in has been relevant for the found effect of accessibility improvements on municipal population growth. Another question here deals with path dependence. If municipal population growth depended to some degree on the development of transport networks, how much would different transport network formation rules have affected the final municipal population distribution in the country?

Additional questions may be tackled with the methods introduced in Chapter 4 and 5 as well. From this research follows that the interventions of the Dutch state may have been counterproductive. A full cost-benefit analysis of the state actions is still necessary to judge those interventions. Lastly, Chapter 4 shows the importance of network economics in the formation of transport networks; and Chapter 5 shows how differing playing fields can affect that process as well. At the moment of writing, available transport systems (motorways, airways and high speed railways) are mature or on their way to maturity. Marchetti (1994) argues that the world economy will be driven by ever faster transport networks. The methods presented

in Chapters 4 and 5 may assist in ex-ante evaluations of the formation of these networks. The introduced methods could be helpful when further exploring the role of network economics in network formation (see Economides 1996), and when investigating how policy interventions may bring the Nash equilibria in multiple-investor network formation processes towards a social optimum (a question also tackled in Youn et al. 2007; Li et al. 2010; Anshelevich & Dasgupta 2003). These researches can provide important insights in the network formation process and may indicate potentially effective policy interventions.

5.3 Understanding spatial processes

With the exception of two chapters on transport network expansion, all chapters in this work essentially obtain conclusions by inducing spatial process mechanics from aggregate spatial data. Spatial processes generally have at least one important feature that sets them apart from non-spatial processes: namely, the fact that nearby processes are commonly interdependent. The existence of this interdependence, most elegantly formulated in Tobler's First Law of Geography (1970), causes the existence of so-called spatial autocorrelation. In this dissertation, spatial econometric methods (Anselin 2001; LeSage 1997; Griffith 2000) have been applied in a number of chapters to control for the existence of spatial autocorrelation. Chapter 3 shows that spatial autocorrelation can be considered a proxy for otherwise unobserved local interactions, and that it is particularly important when dealing with data on a high spatial resolution.

In the continuum between truly inductive and truly deductive methods (Overmars, De Groot, et al. 2007), the approaches taken in this thesis are closest to theory-guided inductive methods. Those methods have been very useful to prove the existence of expected relations in available data, such as (in Chapter 7) whether cross-border interaction opportunities have been important for municipal growth in Europe, or (in Chapter 6) whether mixed land-use patterns affect temporal activity patterns in a city. However, the possibly complex processes, interactions and considerations that underlie these changes cannot be identified with the used data and methods.

The methods introduced in Chapters 4 and 5 take into account that spatial processes involve multiple actors that may have different objectives, and that the outcomes of these processes depend on the interactions in between those agents and between those agents and geography. These more deductive, agent-based approaches are inherently more suitable to reproduce the rationale that drives

spatial processes and to pinpoint adequate policy interventions. Recent additions to the land-use modelling literature have explored agent-based (Zondag & De Jong 2005; Irwin & Bockstael 2002) and deductive (Koomen et al. 2015; Overmars, Verburg, et al. 2007) approaches to model land-use change. Clearly, more deductive research is needed to, for example, model the linkages between changes in accessibility, inhabitant preferences and investor behaviour. Although such an approach would require substantial additional data that is not generally available, this would provide a useful addition to existing land-use models.

5.4 Data availability

During the years that this dissertation was in preparation a seemingly gradual change took place from data scarcity to data abundance in the social sciences. There are many causes for the growing availability of data. Authorities, for example, are more willing to share their data on so-called open data platforms such as the European Commission's upcoming Urban Data Platform or the open data platform of the United Kingdom's government. But also citizens are increasingly involved in the generation of data, creating so-called crowd-sourced data. This citizen involvement may be by volunteered information sharing (Goodchild 2007). Examples of citizens that volunteer data are users contributing to data platforms such as 'OpenStreetMap'; or citizens that use appliances such as wrist watches and mobile phones that record spatial data, and share their recorded data on websites such as 'Garmin Connect'. Of course, the involvement of citizens in the data generation process may also be entirely involuntarily, when the activity of their mobile phones, credit cards or electronic public transport passes is being recorded.

The increasing availability of data allows the validation of hypotheses that have long remained untested, such as the expectations from Jane Jacobs that have been assessed in Chapter 6. Yet, many restrictions remain in place on the many novel and detailed data sources that can potentially enrich scientific research (Janssen et al. 2012). Some data remain the exclusive property of the companies and organisations that collect them, while other data sets – due to privacy or other considerations - are only available in aggregate or otherwise restricted form. In our case, for example, the data mobile phone activity could not be linked to the individuals that made those phone calls. While this has not hampered the analysis and conclusions presented in Chapter 6, it would have been interesting to understand where the observed callers were from. With that information it would have been possible to verify if specific land use types attract visitors to an area, or

instead entice the area's inhabitants to participate in activities outside the house; and it would have allowed some understanding of whether the found relations were representative for the entire country or just for the study area. Another example of the restrictions that remain on data availability can be found in Chapters 7 and 8, where distance decay functions could not be obtained from observations because sufficiently fine-resolution Europe-wide spatial interaction data on passenger flows is currently unavailable. For these chapters a sensitivity analyses had to be executed to verify that the conclusions are not too sensitive for the selection of one particular distance decay function.

Given the increasing emphasis on open data as a means to increase wealth and assist in democratic processes (Janssen et al. 2012), it may be expected that availability of government and crowd-sourced data will further increase in the near future, bringing new challenges to the table. For example, just as with the mobile phone data used in this dissertation, discussions of the representativeness of data are likely to remain a recurring theme in many future studies, and the sometimes difficult compromise between detail, privacy interests and the need for reproducible results will certainly complicate matters. All in all, the coming years will become an exciting period for the spatial analysis community.

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Summary in English

The last centuries have seen major improvements in transport technology that in turn have provided ever faster and cheaper ways to travel. To repeat a metaphor offered by Waldo Tobler, those transport technology changes have caused not only that the Earth's surface has shrunk, by ever reducing travel times between places; they have also caused that the Earth's surface has shriveled, by ever increasing the disparities between places with low and high access. Indeed, some places have profited immensely from the reduced transport costs that new transport infrastructure has brought; while other places are lagging behind ever more. This has raised a number of politically relevant questions; for instance, what are the consequences of the availability of ever faster transport and ever greater transport disparities on the spatial organization of society?

Central to this dissertation is the idea that opportunity for human interaction – regardless of the type of interaction – is the chief determinant of the spatial organization of society. Transport systems affect that organization by making long-distance destinations reachable, and thus providing additional opportunities to interact. When improvements in a transport system allow that more people, more customers or more jobs can be reached from a certain location, this likely translates into an increase of attractiveness of that particular location. Long-distance interaction opportunity can therefore be expected to be ever more closely related to where economic growth occurs. However, long distance transport can be costly from a user's, societal and environmental point of view, so that long distance interaction opportunities are probably not a perfect substitute for interaction opportunities in the close environment. Presumably, there is some tension between long-distance and local interaction opportunities, which affects the way land is used and managed in modern societies.

The core question posed in this dissertation is “how do long-distance interaction opportunity and local interactions affect land-use patterns and the management of those patterns?” There are a great number of questions and consequences attached to that question. For example, does interaction opportunity really affect the spatial patterns of urban land use - even at a local level? How is the measurement of the effects of both concepts on land-use patterns affected by scale and spatial resolution? Is the availability of fast transport itself not dictated by the spatial organization of society? How beneficial are local interactions for existing urban areas? How are border areas affected by increasing interaction

opportunity? And can investment policies help reduce territorial disparities in terms of interaction opportunities? These questions have been studied in this dissertation, always using state-of-the art geographic methods and data. In the remainder of this summary, the results of those studies will be treated.

Interaction opportunity and geographical scale

The first part of this dissertation is dedicated to measuring interaction opportunity as a variable, and how the spatial resolution of analyzed data relates to any potentially established effects of interaction opportunity. To measure interaction opportunity, a so-called potential accessibility measure is used. That measure essentially indicates the opportunities to interact with resources that are distributed over space. It takes into account the spatial distribution of resources (often, population or jobs) and the willingness to travel a certain amount of time or distance; while not taking into account competition for limited resources at the destination, or the fact that people have a limited capacity for interaction.

Potential accessibility is a computationally complex measure in which the computational task increases exponentially with the number of points for which accessibility is computed. This is problematic when an analyst wants to compute potential accessibility measures on very high resolutions, such as is necessary for high resolution spatial data analyses of urban land use. Chapter 2 in this paper shows that reasonably accurate estimates of potential accessibility can be achieved on very high spatial resolutions using the spatially interpolated results of an asymmetric accessibility computation method, introduced in that chapter.

Another issue that becomes evident when computing potential accessibility is that it typically varies very little locally. This begs the question whether the measure is very useful when trying to explain the presence of urban land use, which is often much more distinctive spatially. Chapter 3 studies this in the wider context of the so-called 'Modifiable Areal Unit Problem', a persistent issue in geography that causes that the results of commonplace quantitative analysis methods depend on the shapes and scale of the spatial units of analysis. This chapter concludes that potential accessibility plays an important role on every geographical scale of analysis; that variables important in a local context have additive explanatory power when analyzing at a finer resolution, but lose their relevance at higher scales; and that the effects of the Modifiable Areal Unit Problem can be limited by using particular weighting schemes, and ensuring that the set of used explanatory variables include factors at all potentially important geographic scales.

Understanding transport network expansion

The second part of this dissertation is dedicated to understanding and modelling the expansion of transport networks. The key question here is, whether the availability of fast transport itself is not dictated by the spatial organization of society? The two chapters in this part focus on the expansion of the Dutch railway network in the 19th century. The two chapters present a method to generate a choice set with which the driving factors in network expansion can be analysed, and a model in which the expansion of a transport network can be simulated with varying economic contexts or public interventions. One finding to be extracted from these chapters is the important role that existing population distributions have had on the development of the Dutch railway network. Especially in the earliest stage of network development, investors consistently preferred to invest in links that maximized additional passenger mileage, as modelled in a spatial interaction modelling approach. A logical consequence is that, despite higher construction costs due to weak soils, railway network development was to set off first in the densely populated West of the Netherlands. That same result has been repeated in all different scenarios ran in the Transport Link Scanner model introduced in this dissertation – in all simulated alternative scenarios, railway network expansion initiated in the same densely populated region.

Additional questions that have been researched in this part of the dissertation concern in general the role of network economics in transport network expansion processes, and in specific the role of public interventions in Dutch railway network development. According to results in Chapter 4, different stages of development of the Dutch railway network coincided with variations in the relative importance of direct and network benefits of added links. Those results also shows that those direct and network benefits broadly coincide with links that increase either network density or network diameter. Lastly, Chapter 4 suggests that the Dutch railway network grew much longer than what seems sensible economically. This prolonged growth may have been spurred on by heated competition between private investors and the Dutch state, where also the latter acted as a competing operator.

Exploring the role of long-distance and local interaction opportunities in current policy dilemmas

The third part of this dissertation is dedicated to currently politically relevant questions in which the interplay between long-distance transport, local

interactions and urban land use plays a role. In Chapter 6 the importance of local interactions for cities is studied. In that chapter, proof is sought for a hypothesis first offered by Jane Jacobs in her influential book “The death and life of great American cities”. Jane Jacobs suggested that cities needed suitably high activity densities and a fine-grained mixture of land uses to enable a vibrant life on city streets. To test Jacobs’s ideas, the potential effects of local land-use interactions on activity patterns were sought. Mobile phone data recorded in Amsterdam have been used as a proxy for spatiotemporally varying activity patterns. The results confirm that indeed, the colocation of different land uses may cause that a city’s residents and visitors change their activity patterns and add to liveliness in city areas. Subsequently, coincidences between activity patterns and specific indicators of neighbourhood success are researched. The results show that neighbourhoods that are deemed attractive coincide with areas with higher activity densities, with a larger share of those higher activity densities consisting of non-home-based activities. The results furthermore show that home-based activities are substantially overrepresented in the activity structures of Amsterdam’s most problematic neighbourhoods. The evidence in this chapter confirm the role that mixed-use urban environments play in city life, as was supposed by Jane Jacobs. This indicates that such environments may produce unmeasured social benefits. It may be necessary to take the potential social benefits of such environments into account - for example, when evaluating the merits of development initiatives that promote land-use segregation and the movement of human activity to the urban periphery.

Chapter 7 presents the results of a study into cross-border accessibility growth and the relevance of cross-border accessibility for municipal population growth in countries that are in the majority members of the European Union. The study focused on the period from 1961 to 2011 in multiple West-European countries. The results show that, compared with base domestic and foreign interaction opportunities, in all studied countries the European network of main roads and motorways has contributed relatively more to foreign than to domestic interaction opportunities. EU accession often coincided with high growth in cross-border accessibility; the most striking example is found in the 1986 accession countries Portugal and Spain. Despite substantial progress in cross-border accessibility and the removal of many barriers that hindered cross-border interactions within the EU, cross-border accessibility has in the majority of cases not had a significant impact on municipal population growth. I find that only domestic accessibility contributed to municipal population growth in the studied municipalities, and

compared to for example the effects of municipal population densities, the effect of accessibility has been modest. All in all, under usage of cross-border interaction opportunities is most likely one of the reasons why in particular border regions of Western European countries lag behind.

Lastly, Chapter 8 presents a modelling effort in which the accessibility disparity effects of road network investments are analyzed in four EU member states, given that population distributions change partially in response to current and future road accessibility levels. This work has been executed using the LUISA model that is developed by the European Commission's Joint Research Centre. For this study, modelling results have been computed given the current state; a case in which roads are improved but population is static; a case in which also population distributions change, without substantial political limitations on residential location; and a case in which potential residential locations are limited by a fictive spatial policy. In all cases, population redistribution as modelled by the LUISA model cause that a part of the disparity-reducing effects of network investment will be offset by people moving to main urban areas in the study area. However, the degree in which disparity effects are undone will depend on land-use policies: if those land-use policies manage to more evenly spread population redistribution, the unwanted effect of population movements on accessibility disparities may be limited. This underpins, above all, the importance of aligning spatial and transport investment policies. This chapter therefore argues that spatial planning matters for transport network investment effectivity, and that sound evaluations of transport investments do well to take likely population movement patterns into account.

Discussion

All in all, this dissertation offers a number of studies into the relation between urban land-use patterns, long-distance and local interaction opportunities. Much of the work provides policy advice, and has in some cases already led to improvements of current policy evaluation methods (notably, the previously discussed LUISA model). However, many issues are still open for future research. A select number of issues are flagged in this summary. First of all, the effects of congestion and congestion-alleviating measures are not included in the accessibility measures that are repeatedly used in this dissertation, even when congestion often takes center stage in discussions on transport policy. The role of congestion in shaping cities and urban growth certainly deserves more attention in future studies. Furthermore, this dissertation has repeatedly focused on aggregate car-based accessibility measures. Although cars are by far the dominant means of

transport in most of the world, current trends show that attitudes towards car ownership and transport means are changing - in particular in urban areas. This would require, amongst others, for a reconsideration of the focus on car-based accessibility in land-use/transport interaction models such as LUISA. Lastly, this dissertation presents the novel Transport Link Scanner model with which the effects of different economic contexts and political interventions on final network outcome can be simulated. This model allows studying a number of relevant questions, regarding for example the necessity of political intervention in transport network expansion, and the degree in which long-run population distributions depended on early decisions in the network expansion process.

Samenvatting in het Nederlands

De laatste eeuwen hebben grote verbeteringen in transporttechniek gebracht, die op hun beurt reizen steeds sneller en goedkoper hebben gemaakt. Om een metafoor van Waldo Tobler te herhalen, die technologische verbeteringen hebben er door steeds kortere reistijden niet alleen voor gezorgd dat de Aarde als het ware is gekrompen - maar ook dat zij is verrimpeld, door toenemende ongelijkheden tussen goed en slecht bereikbare plekken. Sommige plekken hebben immens geprofiteerd van de verminderde transport kosten die nieuwe transport infrastructuur heeft gebracht; terwijl andere plekken steeds verder achter blijven. Dit roept een aantal beleidsrelevante vragen op; bijvoorbeeld, wat zijn de gevolgen van de beschikbaarheid van steeds sneller vervoer, en steeds grotere verschillen in vervoersbeschikbaarheid, op de ruimtelijke ordening van onze maatschappij?

Centraal in dit proefschrift staat het idee dat de mogelijkheid tot menselijke uitwisseling – ongeacht het soort uitwisseling - de belangrijkste drijfveer is van de ruimtelijke ordening van een maatschappij. Transport systemen beïnvloeden die ordening door bestemmingen over grotere afstanden bereikbaar te maken, en zo het aantal interactiemogelijkheden te verhogen. Als verbeteringen in een transport systeem het mogelijk maken dat vanuit een bepaalde plek meer mensen, klanten of banen kunnen worden bereikt, dan vertaald dat zich waarschijnlijk in een toenemende aantrekkelijkheid van die plek. Het is daarom te verwachten dat lange-afstands interactiemogelijkheden steeds nauwer verweven zijn met economische groei. Aan de andere kant, lange-afstands verkeer kan kostbaar zijn vanuit het perspectief van de gebruiker, de maatschappij of de omgeving, en daardoor zijn die lange-afstands interactiemogelijkheden waarschijnlijk geen perfect substituut voor interactiemogelijkheden in de nabije omgeving. Er bestaat een zekere spanning tussen lange-afstands en plaatselijke interactiemogelijkheden, terwijl beiden invloed uitoefenen op de ruimtelijke ordening van moderne maatschappijen.

De kernvraag die wordt gesteld in dit proefschrift is “hoe beïnvloeden lange-afstands interactiemogelijkheden en lokale interacties de verdeling van landgebruik en het beheer van dat landgebruik?” Er zijn een groot aantal vragen en gevolgen verbonden aan die kernvraag. Bijvoorbeeld, beïnvloeden interactiemogelijkheden echt lokale stadsvormen? Hoe wordt enige meting van de effecten van interactiemogelijkheden op landgebruikspatronen beïnvloedt door schaal en ruimtelijke resolutie? Is de beschikbaarheid van snelle

transportverbindingen niet zelf gedicteerd door de ruimtelijke organisatie van de maatschappij? Hoe nuttig zijn lokale interacties voor het bestaand stedelijk gebied? Hoe worden grensgebieden beïnvloedt door groter wordende interactiemogelijkheden? En kunnen publieke investeringen helpen met het verminderen van de ruimtelijke verschillen in interactiemogelijkheid? Deze vragen zijn bestudeerd in dit proefschrift met behulp van moderne data en geografische methodes. In de rest van deze samenvatting worden de resultaten van die afzonderlijke studies belicht.

Interactiemogelijkheid en geografische schaal

Het eerste deel van dit proefschrift behandelt het meten van interactiemogelijkheid als een variabele, en hoe de ruimtelijke resolutie van geanalyseerde data zich verhoudt tot mogelijk gevonden effecten van interactiemogelijkheid. Om interactiemogelijkheid te meten is een zogenaamde potentiële bereikbaarheidsmaat gebruikt. Die maat geeft in essentie aan hoeveel mogelijkheden er zijn tot interactie met ruimtelijk verspreide bronnen. De ruimtelijke spreiding van bronnen (vaak geoperationaliseerd als inwoners of banen) en de bereidheid om een zekere tijd of afstand te reizen zijn wel in deze maat verwerkt; terwijl concurrentie om de beperkte bronnen op een bestemming, of het feit dat mensen beperkt uit kunnen wisselen niet in de maat zijn verwerkt.

Potentiele bereikbaarheid is een rekenkundig complexe maat, waarin de rekentaak exponentieel groeit met het aantal punten waarvoor de maat wordt berekend. Dit is problematisch als potentiële bereikbaarheid moet worden berekend op een zeer hoge resolutie, zoals nodig is voor ruimtelijke analyses van stedelijk landgebruik. Hoofdstuk 2 toont dat redelijk accurate schattingen van potentiële bereikbaarheid kunnen worden gehaald op zeer hoge ruimtelijke resoluties door gebruik te maken van de ruimtelijke geïnterpoleerde resultaten van een asymmetrische bereikbaarheidsberekening, die is geïntroduceerd in dat hoofdstuk.

Een ander vraagstuk dat boven water komt bij het gebruiken van een potentiële bereikbaarheidsmaat om de ruimtelijke patronen van landgebruik te verklaren is dat het typisch weinig lokale variatie kent. Dat roept de vraag op of deze maat wel nuttig is bij het proberen verklaren van de aanwezigheid van stedelijk landgebruik, dat vaak een veel specifiekere ruimtelijk patroon kent. Hoofdstuk 3 onderzoekt dit vraagstuk in de bredere context van het zogenaamde 'Modifiable Areal Unit Problem', een koppig probleem in de geografie dat er voor zorgt dat de resultaten van gangbare kwantitatieve analyse methodes in het algemeen variëren als de

geanalyseerde ruimtelijke eenheden een verschillende schaal of vorm hebben. Dit hoofdstuk concludeert dat potentiële bereikbaarheid een belangrijke rol speelt in stedelijke vorm ongeacht de geografische schaal waarmee de analyse is gedaan; dat variabelen die een belangrijke rol spelen in een lokale context additionele verklarende waarde hebben op een lokale schaal, maar hun relevantie voor stadsvorm verliezen op hogere schaalniveaus; en dat de effecten van het Modifiable Areal Unit Problem kunnen worden beperkt door gebruik van specifieke methoden om observaties te wegen, en door er voor te zorgen dat de groep verklarende variabelen bestaat uit factoren op alle potentieel relevante schaalniveaus.

Het begrijpen van transport netwerk uitbreiding

Het tweede deel van dit proefschrift is gericht op het begrijpen en modelleren van de uitbreiding van transportnetwerken. De sleutelvraag hier is of de beschikbaarheid van snel transport zelf niet wordt gedicteerd door de ruimtelijke ordening van de maatschappij? De twee hoofdstukken in dit deel concentreren zich op de uitbreiding van het Nederlandse spoorwegnetwerk in de 19^e eeuw. Deze hoofdstukken presenteren een methode om een keuzeset te genereren waarmee de drijvende krachten in netwerkuitbreiding geanalyseerd kunnen worden; en een model waarmee de uitbreiding van een transport netwerk kan worden gesimuleerd met verschillende economische uitgaansposities of verschillende publieke interventies. Een vinding die uit deze hoofdstukken gehaald kan worden betreft de belangrijke rol die historische bevolkingsdistributies hebben gehad op de ontwikkeling van het Nederlandse spoorwegnetwerk. In het bijzonder in de vroegste fase van netwerk ontwikkeling hadden investeerders een consistente voorkeur voor investeringen in lijnen die, volgens een ruimtelijke interactie modelleringsbenadering, de additionele vervoersprestatie maximaliseerden. Een logisch gevolg daarvan is dat, ondanks hogere bouwkosten vanwege zwakke grond, de ontwikkeling van het spoorwegnetwerk is begonnen in het dichtstbevolkte westen van Nederland. Hetzelfde resultaat is steeds herhaald in alle scenario's die zijn doorgerekend met het Transpor Link Scanner model dat is geïntroduceerd in dit proefschrift: in alle gesimuleerde alternatieve scenario's begint de uitbreiding van het spoorwegnetwerk in dezelfde dichtbevolkte regio.

Een aantal aanvullende vragen met betrekking tot de ontwikkeling van spoorwegnetwerken zijn ook onderzocht in dit deel van de dissertatie. Deze vragen betrekken zich op de algemene rol van netwerkeconomie in de uitbreiding van transportnetwerken, en in het bijzonder op de rol van publieke interventies in de

ontwikkeling van het Nederlandse spoorwegnetwerk. Volgens de resultaten in Hoofdstuk 4 vielen de verschillende fases van de ontwikkeling van het Nederlandse spoorwegnet samen met wisselingen in de relatieve belangrijkheid van directe baten en netwerkbaten van toegevoegde lijnen. Deze resultaten laten ook zien dat directe baten en netwerk baten ruwweg samenvielen met aan de ene kant lijnen die de dichtheid van het netwerk vergrootten, en aan de andere kant lijnen die de diameter van het netwerk vergrootten. Hoofdstuk 4 suggereert bovendien dat het Nederlandse spoorwegnetwerk veel langer door is gegroeid dan wat economisch gezien verstandig lijkt. De lange doorgroei van het spoorwegnetwerk is waarschijnlijk aangespoord door verhitte concurrentie tussen private exploitanten en de Nederlandse staat, waarbij ook de laatstgenoemde partij zich gedroeg als een competitieve spoorwegexploitant.

Een verkenning van de rol van lange-afstands en lokale interactiemogelijkheden in huidige beleidsdilemma's

Het derde deel van dit proefschrift behandelt huidige beleidsrelevante vraagstukken waarin het spel tussen lange-afstands transport, lokale interacties en stedelijk landgebruik een rol speelt. In Hoofdstuk 6 wordt het belang van lokale interacties voor steden onderzocht. In dat hoofdstuk wordt bewijs gezocht voor een hypothese die eerst is gesteld door Jane Jacobs in haar invloedrijke boek "The death and life of great American cities". Jane Jacobs stelde voor dat steden passend hoge activiteitsdichtheden en een fijnmazige mengeling van landgebruiken nodig hebben om afdoende reuring op straat te krijgen. Om haar ideeën te testen zijn de mogelijke effecten van lokale uitwisselingen tussen verschillende landgebruiken onderzocht. Mobiele telefoondata, opgenomen in Amsterdam, zijn gebruikt als een indicatie van activiteitspatronen, variërend in ruimte en tijd. De resultaten bevestigen dat de nabijheid van verschillende landgebruiken er voor kunnen zorgen dat de inwoners en bezoekers van een stad een ander activiteitspatroon aannemen en bijdragen aan levendigheid in het stedelijk gebied. Vervolgens zijn overlappen tussen activiteitspatronen en specifieke indicatoren van buurtsucces onderzocht. De resultaten van deze exercitie laten zien dat aantrekkelijk bevonden buurten samenvallen met gebieden met hogere activiteitsdichtheden, waarbij die hogere activiteitsdichtheden bovendien voor een groter deel bestaan uit activiteiten buitenshuis. De resultaten laten ook zien dat thuisgebonden activiteiten overmatig aanwezig zijn in Amsterdams meest problematische buurten. De vondsten in dit hoofdstuk bevestigen de rol die stedelijke omgevingen met gemengd landgebruik spelen in het stadsleven, zoals is verondersteld door Jane Jacobs. Dit geeft aan dat zulke

omgevingen ongemeten sociale baten produceren. Het zou nodig kunnen zijn om rekening te houden met de potentiële sociale baten van dat soort stedelijke omgevingen – bijvoorbeeld bij het evalueren van de merites van ontwikkelingsinitiatieven die bijdragen aan segregatie van landgebruik en het verplaatsen van activiteiten naar de stadsrand.

Hoofdstuk 7 presenteert de resultaten van een onderzoek naar groei in grensoverschrijdende bereikbaarheid, en de relevantie van bereikbaarheid naar bestemmingen over de grens voor gemeentelijke bevolkingsgroei.. Het onderzoek concentreerde zich op de periode 1961 tot 2011 in een aantal West-Europese landen die in de meerderheid deel uitmaken van de Europese Unie. De resultaten van dit hoofdstuk tonen aan dat, vergeleken met alleen door bevolkingsspreiding gedreven binnen- en buitenlandse interactiemogelijkheden, in alle bestudeerde landen het Europese netwerk van hoofdwegen en snelwegen relatief meer bijdraagt aan buitenlandse dan aan binnenlandse interactiemogelijkheden. Toetreding tot de EU viel vaak samen met relatief grote groei in de bijdrage van het hoofdwegenet aan grensoverschrijdende bereikbaarheid. Het meest opvallende voorbeeld van sterke groei in grensoverschrijdende bereikbaarheid is te vinden in Spanje en Portugal, na hun toetreding tot de EU in 1986. Ondanks de sterke vooruitgang in grensoverschrijdende bereikbaarheid en het slechten van veel barrières die grensoverschrijdende interacties bezwaarden, laten verdere resultaten in dit hoofdstuk zien dat interactiemogelijkheden over de grens veelal geen significante invloed hebben gehad op gemeentelijke bevolkingsgroei. Er valt te concluderen dat onderbenutting van interactiemogelijkheden over de grens waarschijnlijk heeft bijgedragen aan het feit dat veel grensregio's van West-Europese landen achterblijven. Volgens de getoonde resultaten heeft historisch gezien alleen bereikbaarheid naar binnenlandse bestemmingen bijgedragen aan gemeentelijke groei. Vergeleken met bijvoorbeeld het effect van gemeentelijke bevolkingsdichtheden heeft binnenlandse bereikbaarheid maar een bescheiden rol gespeeld in die groei.

Hoofdstuk 8 toont de resultaten van een modelstudie waarin, voor vier lidstaten van de Europese Unie, de effecten van investeringen in het wegnetwerken op ongelijkheden in bereikbaarheid zijn onderzocht. Daarbij is aangenomen dat de bevolking van de bestudeerde landen zich zal verplaatsen, deels als reactie op huidige en toekomstige niveaus van bereikbaarheid. Om mogelijke toekomstige bevolkingsverplaatsingen in kaart te brengen is dit werk uitgevoerd met behulp van het LUISA model dat is ontwikkeld door het Joint Research Centre van de Europese Commissie. Voor dit onderzoek zijn model resultaten berekend gegeven de huidige

staat; een situatie waarin wegen worden verbeterd maar de bevolking statisch is; een situatie waarin ook de bevolking veranderd en zich zonder veel beleidsmatige beperkingen kan vestigen; en een situatie waarin potentiële vestigingsplekken zijn beperkt door gefingeerd ruimtelijk beleid. In alle gevallen zorgt herverdeling van bevolking als gemodelleerd door het LUISA model ervoor dat een deel van de ongelijkheidsverminderende effecten van netwerk investeringen teniet worden gedaan door mensen die zich verplaatsen naar de belangrijkste stedelijke gebieden in het studiegebied. Desalniettemin hangt de mate waarin ongelijkheidsverminderingen teniet worden gedaan af van ruimtelijk beleid: als dat ruimtelijk beleid er in slaagt de verplaatsende bevolking gelijkjer te verdelen, kan dat de schade voor het nut van investeringen in wegen beperken. De resultaten van deze exercitie tonen, boven alles, het belang van coördinatie tussen ruimtelijk beleid en transport investeringen. Dit hoofdstuk beargumenteerd daarom dat ruimtelijke planning er toe doet voor de effectiviteit van transport investeringen, en dat een doorwrochte evaluatie van die investeringen er goed aan doet om rekening te houden met waarschijnlijke bevolkingsverplaatsingen.

Discussie

Al met al biedt deze dissertatie een aantal onderzoeken naar de verhoudingen tussen stedelijk landgebruik, lange-afstands en lokale interactiemogelijkheden. Veel van het gedane werk leidt tot beleidsadviezen en heeft in sommige gevallen al geleid tot de verbetering van huidige beleidsevaluatie methodes; voornamelijk in het eerder besproken LUISA model. Desalniettemin laat dit proefschrift nog veel vragen open voor toekomstig onderzoek. Een selectief aantal vraagstukken wordt aangemerkt in deze samenvatting. Ten eerste, de effecten van congestie en congestie-verminderende maatregelen zijn buiten beschouwing gelaten in de bereikbaarheidsmaten die herhaaldelijk zijn gebruikt in dit proefschrift, terwijl congestie vaak veel aandacht opeist in discussies omtrent transportbeleid. De rol van congestie in het vormen van steden en stedelijke groei verdient beslist meer aandacht in toekomstige studies. Een ander aandachtspunt is dat de studies in dit proefschrift zich herhaaldelijk hebben geconcentreerd op geaggregeerde auto-georiënteerde bereikbaarheidsmaten. Alhoewel de personenwagen verreweg het belangrijkste vervoersmiddel is in een groot deel van de wereld, laten huidige trends zien dat houdingen jegens autobezit en vervoersmiddelgebruik aan het veranderen zijn; in het bijzonder in steden. Dat zou kunnen leiden tot een herwaardering van de nadruk op auto-gebaseerde bereikbaarheid in modellen zoals LUISA. Het laatste discussiepunt benoemd in deze samenvatting betreft het nieuwe Transport Link Scanner model, waarmee de effecten van verschillende

economische uitgangsposities en beleidsinterventies op uiteindelijke netwerkvorm kunnen worden gesimuleerd. Dat model maakt het mogelijk een aantal relevante vragen te bestuderen, zoals bijvoorbeeld de noodzaak van specifieke beleidsinterventies in de uitbreiding van transport netwerken, en de mate waarin ruimtelijke ordening op de lange termijn afhangt van vroege keuzes in het proces van netwerk uitbreiding.



SPATIAL DATA ANALYSES OF URBAN LAND USE AND ACCESSIBILITY

The opportunity to interact is a strong organizing element in human activity patterns. In this Ph.D. thesis the author attempts to uncover aspects of the relation between interaction opportunities over long distances, local interactions and human activity patterns, using state-of-the-art methods and often newly available geographic data.

The studies forming this thesis revolve around:

1. Methodological aspects of the relationship between long-distance interaction opportunities, local interactions and urban land-use patterns.
2. The driving forces and rationale behind the geographic expansion of overland transport networks.
3. The role that land-use patterns, local and/or long-distance interaction opportunities play in current spatial planning dilemmas.

The chapters in this thesis offer insights into the effects of the so-called Modifiable Areal Unit Problem; the expansion of the Dutch railway network in the 19th century; the effects of land-use density and mixing on human activity patterns; the effects of national borders on municipal population growth; and on evaluating the effectiveness of future road network investments when people are assumed to move.

About the author

Chris Jacobs-Crisioni graduated in spatial planning in 2007. Since his graduation he has developed a special interest in large dataset handling, quantitative analysis techniques and mapping, and he has developed GIS applications, transport and land-use models. He has worked as a GIS consultant in the transport sector and as a researcher at the VU University Amsterdam's SPINlab and the European Commission's Joint Research Centre. He is currently working as an independent researcher with his own company, Bureau Jacobs-Crisioni.