THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Network-based urban growth

How centrality and accessibility shape land use

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ABSTRACT
The world is experiencing unprecedented and rapid urbanization. To be able to handle this transformation and guide the design of these cities in the way the inhabitants want to have them, it is necessary to understand the drivers and perform planning beforehand.

Cities are complex systems. That means that one cannot modify an isolated part and expect a precise result from that change. It is therefore necessary to understand and model cities as holistic adaptive systems, where all parts interact and create sometimes unexpected results.

Transport system (streets, roads, and rail) planning and land-use planning ("urban planning") are often seen as separate processes, depending on different levels of political decisions, and performed by different professions. What this thesis show, with support from earlier research, is that these two planning processes interact and affect each other to a large extent. It is maybe intuitive that urban land use that attracts visitors, workers, or inhabitants requires access to a sufficient transport system. What is less well known is that new transport infrastructure, by creating new opportunities for access to previously undeveloped land, can induce urban growth.

Urban research has often treated cities as continuous areas. But the accessibility given by the transport system is far from uniform, it rather forms a network that allows interaction between different land areas. This idea of cities as networks of interacting places has shown to be fruitful to understand how the transportation network, places, and their interaction form cities and induce urban growth. This thesis argues that this network of places can be modeled and understood by using a proposed novel model that incorporates these peculiarities.

Finally, the thesis claims that this way of understanding and modeling urban growth is useful not only to explain the current situation but also to understand the historical development and to calculate potential trajectories of future growth.

Included publications

This thesis is based on the work contained in the following papers:

Paper I. L. Nilsson and J. Gil
The signature of organic urban growth.
In L. D'Acci (Ed.), *The Mathematics of Urban Morphology* (1 ed.).
Contributions: LN conceived the presented idea and designed the study. LN wrote the manuscript together with JG. LN created maps. LN performed the statistical analysis. JG supervised the project.

Paper II. A. Hellervik, L. Nilsson, and C. Andersson. *Preferential centrality–A new measure unifying urban activity, attraction, and accessibility*, Environment and Planning B: Urban Analytics and City Science 46.7: 1331-1346 (2019).
Contributions: AH and LN conceived the presented idea. AH, LN and CA designed the study. AH performed theoretical modeling and simulation. AH and LN performed data analysis. LN performed the statistical analysis and created maps. CA supervised the project and contributed with conceptual input. All authors interpreted the results, wrote the manuscript, and approved the final version.

Paper III. A. Hellervik, L. Nilsson, and C. Andersson. *Preferential centrality as a multi-regional model for spatial interaction and urban agglomeration (2021)*
Under review: Journal of transport geography
Contributions: AH and LN conceived the presented idea and designed the study. AH performed theoretical modeling, simulation, and data analysis. AH wrote the manuscript in consultation with LN and CA. LN created maps. AH performed statistical analysis in consultation with LN. CA supervised the project. All authors interpreted the results and edited and approved the final version.

Paper IV. L. Nilsson, A Hellervik and J. Gil
*Does new transport infrastructure induce urban growth? (*2022)
Under review: Journal of transport and land-use
Contributions: LN conceived of the presented idea and designed the study. AH performed simulations. LN wrote the manuscript in consultation with AH and JG. LN created maps. LN performed the statistical analysis. JG supervised the project. All authors interpreted the results and edited and approved the final version.

Acknowledgments

A PhD thesis is not the solo work of a single person. It is a cooperation between many people with extra support from others.

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Gothenburg, October 2022

Leonard Nilsson

Table of contents

Glossary

Below is a glossary for abbreviations. All definitions and glossary are stipulative for this thesis unless otherwise noted or referenced.

- GIS – Geographical Information System. A system consisting of data capture, data storage, analysis, and presentation of geographical information.
- MAUP – The Modifiable Area Unit Problem (Openshaw & Taylor, 1979); Depending on the size and partitioning of area features in geographical analysis, the result can vary, or worse, using certain sizes and partitioning can be used to produce a wanted result.
- OSM – Open Street Map, a global open data and crowd-driven initiative to map all streets, roads, railways, paths, etc. in the world and keep them updated.
- LUTI model – Land-Use-Transportation-Interaction model. It is an umbrella term for many different models developed since the 1960s (Acheampong & Silva, 2015) that aim at predicting the results of the interaction between the transport system and land use (often including population and workplace density).
- BLUE - Best linear unbiased estimation. A requirement to trust a Pearson regression analysis is that BLUE is reached, which can be checked with various statistical tests.
- DID - Difference in difference, a counterfactual method to investigate whether an intervention causes a difference that deviates from the expected (without intervention) results.
- ITS - Interrupted time series analysis. This is a method to analyze time series, where a sudden intervention is hypothesized to change the time series after the intervention, compared to time series without intervention.
- IV - Instrumental variables. This is a very powerful research technique to afterward partition empirical data sets in a way that they resemble another kind of experiment; random, natural, or quasi.

1 Introduction

1.1 Background

The world is currently facing unprecedented rapid urbanization. This means that more and more people are living in dense areas of different sizes, and subsequently, the density and intensity of services, workplaces, land value, and other attributes of urban areas are steadily increasing compared to more rural areas.

To make cities sustainable, suitable for living, and well-functioning, it is necessary to understand the mechanisms driving urban growth and the resulting changes in land use. Urban growth can be both intensive (densification and transformation) as well as extensive (expansion and sprawl) (Batty, 2013).

This thesis is focused on the effects of large transport infrastructure projects on urban development. Today many road infrastructure projects are initiated to ease up congestion, make it simpler for passing intercity traffic, and increase the possibilities for commuting to workplaces. The main intentions are in most cases not to change any land use apart from the immediate area around the roads, but rather to give the inhabitants better access to workplaces and services (Levinson et al., 2005; Trafikverket, 2022).

However, research has shown that urban areas transform after new road infrastructure developments are introduced in their vicinity (Andersen et al., 2018; Baum-Snow, 2007; Gerritse & Arribas-Bel, 2017; Kasraian et al., 2016; Yudhistira et al., 2019). Unintended growth (or decline) of urban areas can therefore appear after the intended effects of the road infrastructure investment are fulfilled. They can often appear a long time after the investments since urban development is a slow process.

Large infrastructure projects today are often planned by a state road authority. Their focus and knowledge areas are not about urban design and planning but about transport systems. They often see the transport system as a service system for citizens, trade, and industry and do not always account for how new roads affect the land-use (Levinson et al., 2005).

Urban design and planning, both as a research field as well as in practice, are on the other hand primarily concerned with the planning of land use and the need for buildings. This is often done on a more local, although sometimes regional or municipality scale by architects or specialist urban designers and planners. Their focus has traditionally been on land-use planning and thus the need for buildings and public spaces.

This partitioning of the planning of the built environment into two professional categories is not that old, it started with the building of railways during the last part of the 1800s and was then a slowly growing process during modernism when the car-oriented society emerged (Sjöblom, 2011a, 2011b). Before modern roads and railroads, there were no countrywide centralized road or rail planning agencies.

But both these professions deal with a complex system, as cities are (Batty, 2013). The implications of this are that the effects of planning interventions (by either profession) are not straightforward. The aims of one plan will probably not only result in the intended effects, but also in unintended effects. These effects are often not accounted for from the infrastructure perspective and are sometimes unwanted. There are rarely any quantifications of the long-term effects on land use, although some attempts have been done to identify them (Trafikverket, 2022).

To understand these effects on urban areas caused by new infrastructure developments, it is necessary to take a cross-disciplinary view on urban design and planning, infrastructure development, and their interplay, not just researching the specific parts in the various professional categories as predominantly done today.

1.2 Aim

This thesis aims at understanding the effects of transportation network projects on urban growth and land use change by:

- Identifying and quantifying these (often ignored) effects.
- Trying to model these effects to be able to predict them.
- Using such a model and other research to understand the interplay between transportation projects creating access to places and how this altered accessibility influences the interaction between these places.

To comprehend these effects, it is necessary to find an approach that can increase the understanding of the complex interplay between these infrastructure interventions and land use in the urban growth process.

By investigating places and their interaction with each other, this thesis seeks to reveal the changes in land use that are claimed to follow changes in the accessibility pattern. It will focus on the different roles of built places and traffic networks in urban development and try to, through modelling using various data sets, contribute to new theory formation in this field in order to better explain this interplay.

Such model, prediction, and theoretical understanding could improve planning decisions by offering a better understanding of the consequences of such decisions. However, it does not aim to give recommendations or guidelines for ends. That is the purpose of political decisions.

1.2.1 Research questions

In extension of these aims, the thesis more specifically tries to address the following research questions

1. How do infrastructure network interventions cause urban growth?
2. In what way can we predict and understand this growth?
3. Which implications could knowledge of this growth have on the urban planning process?

The first question is addressed in a more descriptive manner in the paper I, while the causal relation is addressed in paper IV.
The second is addressed in papers II, III, and IV, and the question of how we can understand this growth is touched on in paper I and more thoroughly discussed in paper IV. Using the results from all papers the third question will be discussed and answered in the concluding chapter of the kappa.

1.3 Outline of the thesis

Due to the wide range of purposes and approaches of urban planning and design, a positioning of the thesis is made to set the scope. In chapter 2, the thesis is positioned regarding common ontological, epistemological, sustainability, disciplinary, and methodological approaches in urban planning and design.

To give a theoretical background as well as the chosen theorizing of this thesis, chapter 3 present both recent theories and current challenges within urban design and planning. It gives justifications for the chosen research approaches to urban growth.

The chosen approaches to answer the research questions require both models and data, which are presented in chapter 4. Besides presenting them, some paradigms and approaches in research design and data collection are discussed.

Then, the significance of the results of the included papers as well as other findings is discussed in chapter 5. This chapter is based on the results from the included papers, therefore a quick overview and short summary of the papers included in this thesis is added as an appendix. The chapter reports the main conclusions, both regarding scientific claims as well as possible implications of the results on the planning process. Finally, future research and possible future tools and methods for urban planning and design are suggested.

2 Positioning of this thesis

In urban design and planning, there are many ways of doing research with various purposes. Both quantitative and qualitative research is made, as well as descriptive, predictive, and causal conclusions. The field has also a wide spread of research aims ranging from cognitive to normative purposes. To navigate in this wide research field, the following chapter aims at positioning this thesis in these many dimensions.

2.1 Ontological positioning

2.1.1 Models of the universe

A model is a simplification of reality. It is always wrong in the sense that it is not the reality or a complete description of it. But since the reality is too complicated or large to grasp or use in research, models are necessary to understand and analyze it. Models are a method to simplify reality to serve as a useful tool for our understanding of reality. It can be used to strengthen a theory or a hypothesis as well as form the basis for various methods used for the test or analysis of theories. Another purpose that is also important is the use of models to visualize and/or explain some concept, information, or theory to others. A model is based, consciously or not, on a theory, an assumption, or a hypothesis. This thesis argues that it is, in this context of urban planning, better with a simple model with sufficient predictive power than a complicated one with excellent predictive power. This is due to the data, the number of parameters, and the knowledge needs of a complicated model.

However, a model always concerns specific aspects of the world which are highlighted in the model for clarification and to facilitate the stringent study of them. Hence, depending on what the model is intended to help the study of it can be constructed very differently, why models of the same object can look very different. It is therefore important to explicate the ontology of the model one is applying in research.

In this thesis, the intent is to build a model of urban areas and regions, but such models can take many shapes depending on the area of study. In this case, it more specifically concerns the relation between the distribution of land use and street networks creating accessibility between these places. Moreover, it should be constructed so that it is possible to measure and visualize effects on land use when changes in the street network and thereby the accessibility are introduced and the effect this has on the distribution of land use.

2.1.2 Descriptions of the world

In some research, the main goal is to do a quantitative description of the subject under study. That is done to describe a system or a context with the help of a model, which in turn gives a quantification that is useful for understanding the subject of study and its properties. Quantitative descriptions are often used as the first step in many quantitative research areas to give an early understanding of the characteristics of the subject of study. In paper I, descriptive statistics are used for understanding what kind of probability distributions of roads can be found in the geographical analysis of urban areas. The characteristics of a probability distribution can often give a good idea of which kind of process generated it. Knowledge about the properties of those processes can give an idea about how urban evolution seems to work and what kind of elements are governing the system.

2.1.3 What do we measure?

To be able to describe, predict and understand (possible) causes and effects of transportation infrastructure and land use, it is necessary to decide how to quantify the elements of research. Accessibility (El-Geneidy & Levinson, 2006; Hansen, 1959; Jiang et al., 1999; Marcus, 2008) does not have a suitable physical quantity, therefore different (re)developed measures will be used to capture and quantify accessibility.

Land use is sometimes merely a categorical descriptor, although there are continuous values for describing intensities in some of the uses (such as density, economic values, etc.). This thesis makes use of some of the quantitative measures as different proxies for urban activity and growth. Various polygonal land use measures were used in this empirical validation, such as land value used in paper II and III, and population density in paper V. Using land use or some other polygonal partitioning will suffer from MAUP, (Openshaw & Taylor, 1979), but this thesis tries to justify the choices made, by using similar data as were made in the data collection.

Transportation networks are often described as road or rail (or other modes of transport) networks. To be able to model cities as intended in this thesis, there is a need to describe and model transportation networks as topological networks, where distances or travel times are quantified as impedances situated on the vertices, while places are modeled as nodes. Networks are also used to describe many different processes in cities, such as how a city works, and how knowledge and material flow. In those cases, classical graph theory is often used (as invented by Euler when he solved the problem of the seven bridges of Königsberg).

2.1.4 Predictions of the world

Another goal of models can be to do predictions of phenomena. That often requires more complicated methods and better models of the world as well as often a need for capturing more empirical data. It is called inferential statistics. Often this kind of statistics is dealing with bivariate data sets, that can be regressed to understand how they covariate and how strong that covariation is (and to find the parameter values under which the covarions emerge).

This can be useful in urban planning and design since it can tell what kind of demands and possibilities are likely to occur in the future if nothing is changed as well as how changes will affect the system, and how we, in the end, can predict them. If this is related to certain aims and means in urban design and planning, we may more accurately predict the effects of certain means and evaluate them in relation to given aims.

A central aim of this research is to be able to predict future land use out of changes in the transportation system. A prediction of future road network growth would be interesting (Xie & Levinson, 2007), but is probably very complicated in a real geographical context, and is therefore out of scope in this study. Since road networks are centrally planned technical systems (Levinson et al., 2005; Sjöblom, 2011a) that tends to follow the plans, change slowly, and persist for a long time (Rómice et al., 2020), they are a good study object for predicting the much faster and often bottom-up initiated (Batty & Xie, 1998) changes in land use.

2.1.5 Do effects happen from a cause?

Predictions can be based on simple algorithms that reflect the underlying processes in a way that also can give a theoretical explanation of why things happen. The matter of cause and effect is debated, already by classical philosophers (Hume, 1999) who said that the fact that things happen in a certain order does not necessarily mean that the first thing causes the second. Even if one time series predicts another time series (Granger causality) (Granger, 1969) it does not prove that the first series causes what is seen in the second one, only that the second series follows the first one, called a lagged time series. If time went in reverse order, the second series would predict the first one.

Later research (Kahneman, 2011) has shown that our intuition tries to make sense of events so that everything that happens is initiated by an actor, with the purpose to achieve some end.
Recent research has often focused on the methodological design of studies so that a possible cause (or causal relation) can be revealed and understood, to confirm a plausible theory. In econometrics, this has been highly prioritized, and there have also been some statistical advances in study design that could reveal a causal relation (Imbens & Angrist, 1994; van de Coevering et al., 2015). Paper IV is using these recent ideas to design a study on the (sometimes sparse) empirical data that could be found on this topic.

2.2 Epistemological positioning

Urban planning and design theory has sometimes been criticized regarding its scientific value (Marshall, 2012). One phenomenon often questioned in such theory and research is that it has a normative foundation, in the sense that it is trying to prove already reached preferences. In extension, what passes as a theory in urban design and planning is argued to often rest on weak empirical evidence. Typical examples are the anecdotal argumentation of Jane Jacobs (Jacobs, 1961) or the limited statistical underpinning for Kevin Lynch's work (Lynch, 1960). However, at times this critique is misguided since a lot of theory in urban design and planning has never claimed to be scientific but rather to be generative or explorative. Hence, very little of this literature is useful for the purposes of this thesis.

To position the thesis within the research field, the thesis uses an, in the research area of urban morphology, useful classification scheme by Gauthier and Gilliland (Gauthier & Gilliland, 2006), which suggests that research on urban development can be sorted into two axes, on one hand on a scale from normative to cognitive and on the other on a scale from internalistic to externalistic, which helps describe the position of this thesis relative to other research in urban planning and design. These axes are described in more detail in the next paragraphs. Research in urban planning and design can be positioned according to other characteristics, but this model is easy to understand and places this thesis in relation to other important research/researchers.

2.2.1 Normative or cognitive research?

The research in this thesis is aimed at being cognitive and serving as a decision basis for planners by articulating the means to the planners rather than formulating the ends as in normative research.

There are several reasons behind this decision. One reason is that in urban planning and design, this is important because decisions on the ends of infrastructure and land use are made by politicians based on popular will (in democratic systems), whereas the means for achieving those ends are offered by specialists in urban planning and design. The aim of such a system is that the aims for urban development projects ultimately are the outcome of the will of the voters but materialized by urban designers and planners. Another reason for cognitive research is to be able to produce knowledge that can, in a neutral way, describe the probable effects of political decisions. In extension, this helps make such decisions more transparent and thereby supports a more informed critique and public debate.

Therefore, the goal of the research is to be cognitive contrary to normative, with the aim to produce knowledge on the means in urban design and planning that is broadly accepted by the scientific community and potentially integrated and applied in practice according to professional standards. Having a cognitive basis for the results, enables the results to be used for both descriptive, predictive, and inferential purposes. However, such cognitive knowledge can and will of course be applied by professional planners and designers in normative contexts defined by politics.

This study uses many widespread terms, that often are considered normative. If we look at these three pairs of words, most people will intuitively think that the property to the left in these dichotomies is desirable.

- Natural vs artificial
- Organic vs Synthetic
- Self-organization vs planning

Unfortunately, there are no other words that can describe these properties in a dichotomic and adequate, but non-normative way. Therefore, these words are used throughout the whole thesis, due to their descriptive power and historical use, but the debate of whether these properties are desirable is left for another discussion.

2.2.2 Externalistic or internalistic?

There have been many attempts at cognitive research on cities that have introduced a great variety of properties and measures, why another axis for sorting research on urban development is to distinguish between externalistic and internalistic approaches to such research (Gauthier & Gilliland, 2006).

The internalist and externalist models are of course complementary to a large extent, although the choice of viewpoint will reveal different types of properties of cities and their development.

Here, the main approach is internalistic, since a fundamental hypothesis in this thesis is that urban growth can be understood by studying the interplay between internal spatial structures consisting of on one hand road and street networks and on the other land-use distribution. Studying externalistic changes, such as legal regulations and economic situations will affect urban development, but since that often affects cities in a similar way for whole countries and all their urban areas, this thesis does not mainly concern them. This research aims to control for some of those external factors from the ones resulting from internal factors. New road infrastructure can be seen as an external force, but it is still interlinked with the existing urban fabric. To some extent, this thesis will claim that such external factors can be seen and are a response or adaptation to the internal factors (i.e. investment in new/improved roads can be a political/economical/legal response to congestion or more general demands for better connections).

To summarize this analysis, using the classification scheme of Gauthier and Gilliland in Figure 1 (Gauthier & Gilliland, 2006), this thesis will be placed in the internalist/cognitive quadrant. The aim is to understand the city development based on the existing internal logic of roads and land use and give cognitive answers.

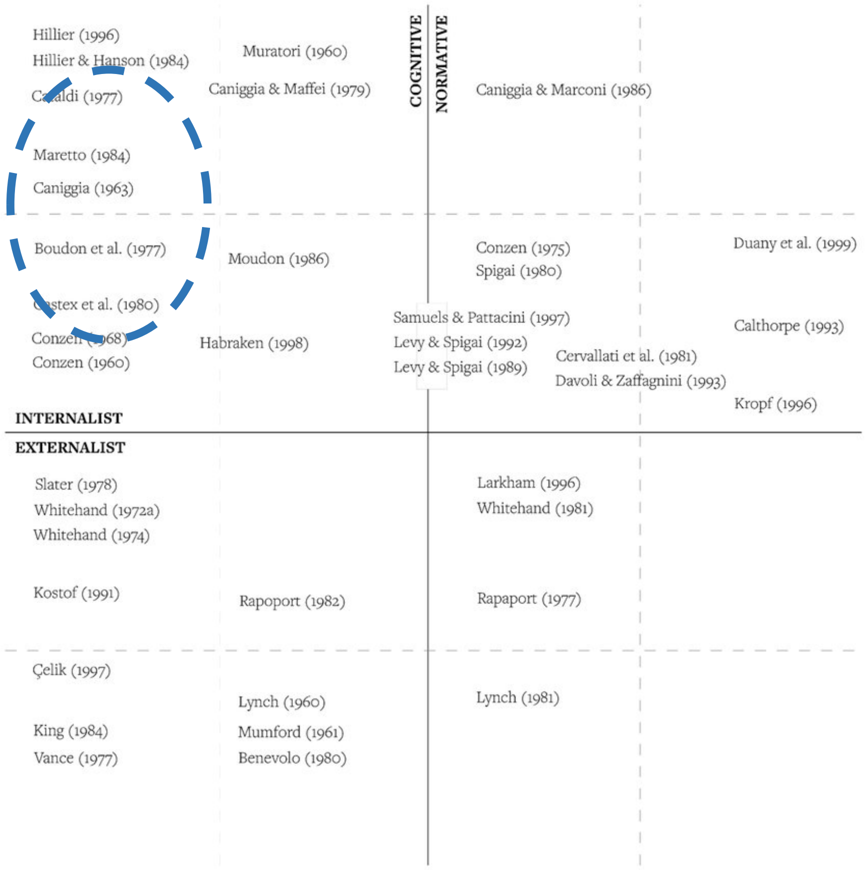

Figure 1 The diagram from Gautier and Gilliland, with this thesis' approximate position within the dashed blue line.

2.3 Disciplinary context

To fully comprehend and model urban growth, it is necessary to look further than the often-used influential urban design and planning literature, i.e. (Alexander, 1965; Jacobs, 1961; Kostof & Tobias, 1991; Lynch, 1960) since the concepts and methods found in this literature are not well enough suited to capture the typical complexity of urban systems. However, there are a lot of interesting questions raised in this literature (among them, complexity and network problems), but the methods and models are not sufficient for the aim of this thesis (since they were not invented at that time). Instead, this study makes an outlook on research in various other fields that can be (and are) used to understand urban land use and growth in the way this thesis aims at doing. One can select methods, models, and theories from many research fields, but here, five (sometimes seemingly unrelated) research fields have emerged as the main contributors to this thesis's cross-disciplinary approach.

2.3.1 Physics – Urban models

During the last twenty years, a lot of urban research has been performed by physicists (Barthelemy, 2011; Goh et al., 2016). This research is often focused on modeling urban growth and patterns, by applying models from typical research areas in physics to questions about urban growth and development. Such adapted models can provide valuable insights into urban development theories as well as providing models that can be used to predict urban growth. A new model proposal inspired by a physicist approach is used in papers II and paper III in this thesis, since these kinds of urban models proposed in physics follow the modelling intentions of this thesis of being minimal and simple to use.

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2.3.2 Complex systems approach – models, tools, and theories

Complex systems research is a quite novel area of research (compared to urban planning). It is cross-disciplinary (as opposed to the physicist approach) in the sense that complex systems are found in many areas of the natural sciences as well as in many studies of societal phenomena. Therefore, it can offer new models and theories in general, sometimes stemming from completely different research areas, but can be applied to other research areas. The approach is moreover often closely related to physics and mathematics. Theories, some tools, and statistical methods developed in this kind of research are used in this thesis, due to its fundamental claim that cities must be understood as complex systems.

2.3.3 Economics – statistics and basic theories

Certain areas of economics, not least econometrics, have developed many statistical methods over the last thirty years, some of them focusing on spatial aspects. The latter can contribute to the understanding of the effects of aggregated human behavior for such things as attractivity and price for a location depending on its place in the accessibility pattern. Many of the statistical methods used in this thesis as well as some assumptions on aggregated human behavior come from economics and more specifically econometrics. Since this thesis aims at comparing modeled data with empirical data, it is necessary to use some of the methods for understanding spatial phenomena that have emerged in economics during the last forty years.

2.3.4 Geography and spatial analysis – models and explanations

Geography is a very broad field that can support the understanding of urban development in many ways. For the current thesis, it is especially the quantitative approaches in spatial analysis that contribute relevant insights, theories, and modeling techniques of urban growth and development. Some of the models used in this thesis quite directly come from geographical research.

2.3.5 Network science - methods, models, and descriptions

Parallel to the research on complex systems, another field of research with much broader implications has rapidly evolved since the end of the 1990s, which is the network science (Watts, 2004). Network science specifically commits to the study of relations between entities rather than the entities themselves, which has proven an extraordinarily generic and useful type of modeling of broad scientific use. As computers have become more powerful, new methods have appeared for calculating network properties also in very large networks, such as small-world network properties, and scale-free properties (Andersson et al., 2005; Barabasi & Albert, 1999; Barthelemy, 2002; Crucitti et al., 2006b; Newman, 2003; Telesford et al., 2011; Watts, 2004; Watts & Strogatz, 1998), based on new theories and methods.

After this brief outlook, this thesis claims that borrowing methods, models, and concepts from these above-mentioned four scientific disciplines are necessary to comprehend the aims and answer the questions raised in the introduction. These methods, models, and concepts will be further elaborated on in chapter 3.

2.4 Methodological positioning

Space can be conceptualized in very many ways where no one is more right or wrong in a general meaning. The most fundamental way of thinking about space is as the geographical surface of the earth or our position in the universe. This is in geography understood to represent an *absolute* conception of space. But one problem with this view is highlighted by Tobler’s law (Tobler, 1979), which states that spatial properties are autocorrelated. That means that all positions in space are related to each other. This demands an alternative conception of space as *relative*.

If we moreover look at space from a human perspective, the space that we use is a small subset of all space, that is, the (mostly) humanly created places or spaces that we use in everyday life. A particular space in this subset can by a human only be reached by moving through other spaces in this subset, why the study of human use of space predominantly concerns a relative conception of space.

However, such studies can be conducted on different scales, where it is common to study cities as a partitioning of the urban areas into polygons, often defined by administrative limits, for example, city districts. Studies of relative space in cities then concern the relation between urban places. Curiously, these kinds of relations between spaces have (in parallel) been studied in transportation and land-use research, but under the umbrella term accessibility (El-Geneidy & Levinson, 2006).

The morphology of urban areas has been studied as an academic discipline for a long time (Whitehand, 2007) but it has often taken the form of qualitative studies based on perceived patterns of built-up areas, elements, and places (Kostof &

Tobias, 1991; Lynch, 1960). What we look for here, however, are ways where the *relation* between such places on the morphological scale can be captured and measured. Such modeling was raised by the research direction space syntax (Hillier, 1996) about forty years ago and has been further enhanced by the rapid advance of computer power and accessibility to data in the recent decade. In parallel, other quantitative research initiatives were taken in the 1990s, aiming to analyze cities through growth simulations, often using cellular automata (Batty & Xie, 1998).

Network analysis has been applied to cities for some time, but generally on the aggregated scale of relations between urban areas or major traffic arteries. The original contribution from space syntax research was to apply such analysis to the fine-scale morphological level of cities related to human perception and cognition. When the results from a space syntax analysis on a larger urban area are analyzed as a complex system or complex network, it can reveal interesting properties (Jiang, 2007; Jiang 2015; Porta et al., 2006b) As such it presents a fruitful way of modeling this thesis, as presented in paper I.

2.5 Sustainability positioning

Since this thesis is aimed at understanding the consequences of various planning decisions, it does in principle not in itself have any consequences for policies or effects regarding sustainable development. Connecting to the beginning of this chapter, sustainability is of course a normative aim that as such also has been debated. But this central theme in current society is also in need of cognitive (or descriptive) knowledge. Since the research in this thesis aims at predicting the long-term consequences of urban planning and design decisions, the results can be highly interesting for decisions or policies aiming at sustainable development. In urban planning and design, several factors can have effects on sustainable development. Today this discussion is often dominated by greenhouse gas emissions from motorized traffic, something that will not be discussed in this thesis.

However, there is also another problem with cars and traffic apart from greenhouse emissions; that is the fact that roads take up valuable space that could be utilized for other land uses. Many kinds of pollution and noise are also local, which decreases the possible land uses in the vicinity of the roads. The consequences can also be barrier effects that shape the urban landscape in an unintended way.

This is in the long run affecting accessibility since it means that the urban landscape will have to grow extensively due to a lack of space. Moreover, increasing numbers of cars will create congestion, which in turn often leads to political decisions for even more roads or capacity increases of existing ones (Duranton & Turner, 2011). As argued in this thesis, this will in turn lead to often unexpected land-use redistributions. This redistribution of land-use have implications for cities' sustainability, although that topic is too big for this thesis and therefore not explicitly discussed. The role of cars in our cities, therefore, complicates the issue of sustainability in many ways. This thesis claims that besides the fact that car traffic is using extensive portions of urban land, urban traffic systems also redistribute land use by changing the accessibility to land.

3 Theory

The research questions and aims posed in chapter one, are like all research questions part of a more or less expressed theory. It is therefore important to explicate these theoretical contexts, which also is fundamental for the methodological choices made to answer these questions.

Cities are complex systems, probably the most complex creation in human civilization. The complexity means that they are inherently hard to predict since one often-seen characteristic of a complex system is that small changes in the input parameters can have large unforeseen effects on the outcome. To try to understand cities, this thesis claims that it is necessary to model them as complex systems and develop adequate measures for the descriptions, predictions, and causal claims. More generally, this thesis is based on an understanding of cities as complex adaptive systems, which reflects a rather recent paradigmatic shift in how cities are scientifically studied (Batty 2013). This in turn leads to the formulation of specific theories and hypotheses when it comes to the types of questions asked in this thesis about infrastructure-induced urban growth.

3.1 Complex systems

How do birds manage to navigate in a flock? And how do ants build their ant-heaps? These are examples of questions that have been thought of for a long time but have not been possible to understand and study until recently. Earlier it was thought that flocks of birds had leaders, but nowadays we know that this is not the case, rather these flocks can be best described as complex systems (Hildenbrandt et al., 2010). Complex systems denote systems that, apart from containing many elements, are self-organizing systems. The elements in the system can be for example agents, and they can communicate with each other and the environment in some way. In nature, many good examples of complex systems can be found. Complex systems are not to be confused with complicated systems. Complicated systems are systems consisting of many parts but without any self-organizing principle, For example, top-down designed systems such as an airplane.

At the beginning of the 2000s, the search for models of complex systems resulted in the use of power-law distributions as a signature for having a complex system (Clauset, 2007; Clauset et al., 2009), since power-law distributions have scale-free properties, which is one often seen characteristic of complex systems. Several calculations and tests on whether a distribution is a power-law have been developed and used in the research field of cities (Andersson et al., 2005; Batty & Xie, 1998; Jiang, 2007; Porta et al., 2006b). The problem with sticking to power laws as a signature of complexity is that the criteria for something to follow (with a certain probability) a power law or not, are very strict. Because of this dichotomic interpretation of the results, some complex processes cannot satisfactorily be defined by using power laws as a signature.

In this thesis, power-law distributions are used as indicators of complex systems in urban evolution. The fact that cities are complex (adaptive) systems is deducted from the findings that many of the different patterns of empirical data exhibit a power-law distribution, along with earlier research. (Clauset, 2007; Clauset et al., 2009; Crucitti et al., 2006a; Farmer & Geanakoplos, 2008; Mohajeri et al., 2013; Newman, 2005) There are few processes that can generate power-law distributions, often it is the multiplicative growth that results from the principle of preferential attachment. That can be described in simple terms as "The rich get richer" or the "Mathew effect" (from Mathew 13:11-12) (Perc, 2014). Such a process is typical for certain classes of complex systems, such as growing preferential attachment systems (Barabasi & Albert, 1999; Perc, 2014) .

An example of power law distribution is wealth among people, where we can see that the distribution follows a certain pattern. For example, the 20% richest persons own 80% of the wealth. This simple principle is called the Pareto principle. A special property of these kinds of distributions is that they are scale-free, or scale-independent. This means that if we look at the 20% richest people, 20% of them will own 80% of the wealth in that group. This pattern will show up at all scales, hence the name scale-free. This scale-free distribution appears in a lot of different fields such as biology, physics, social sciences, etc.

3.1.1 What is a complex adaptive system?

Complex systems are chaotic in the way that they cannot be predicted and described by a simple equation or formula. Complex adaptive systems (second-order complex systems), are systems where predictions (to the extent possible) will affect the system, hence the name second order, or adaptive. The weather does not change due to us predicting it, but land valuing, labor markets, stock market, and many other human systems will respond to predictions. Cities are adaptive complex systems since they respond to predictions (i.e., future land values, population forecasting) and expectations. That means that cities (as well as other complex adaptive systems) are hard to predict since the predictions in themselves alter the future state of the system.

3.1.2 Complex networks

The last decades have not only brought up complex systems as an object for study but also complex networks and network science as a means for such study (Barabási & Albert, 2000; Watts, 1999, 2004). It is shown that these properties are valid for a lot of network types, for example, social networks, power grids, websites etc.

Since all cities contain a transport system that facilitates internal interactions between places in cities, an increasingly common approach has been to model urban growth by using complex networks (Andersson et al., 2005; Andersson et al., 2003; Batty, 2013).

3.2 Cities as complex systems

3.2.1 Why have cities formed complex systems?

How can complexity emerge in an urban system? To make one illustration of how complex system behavior can form, we can, for example in analogy with (Korotayev, 2016; Zuckerman, 1996), investigate the attraction cities have on people, which is one foundation of urbanization. We can do a simple model of the city size and the labor market in the city, as illustrated in **Figure 3**. The more inhabitants a city has, the more diversified the labor market becomes. This results in an increase in productivity which results in higher wages. Specialized and higher-paid jobs will attract people to move to a city, with the result in an increase in inhabitants. The increase in inhabitants will result in an even more diversified and specialized labor market with higher wages, and so on. This phenomenon is called a positive feedback loop and it is known to be an unstable process. The result of such an unstable process is often a complex system.

(Altszyler et al., 2017; Zeigler et al., 2000) Of course, this process will not immediately result in one big city containing all the population on the earth. There will probably emerge some negative feedback factors over time, such as congestion in the transport system. Then there is a time component and adaptation effects that will affect the system. But still, we have not seen any limit to how big a city can become.

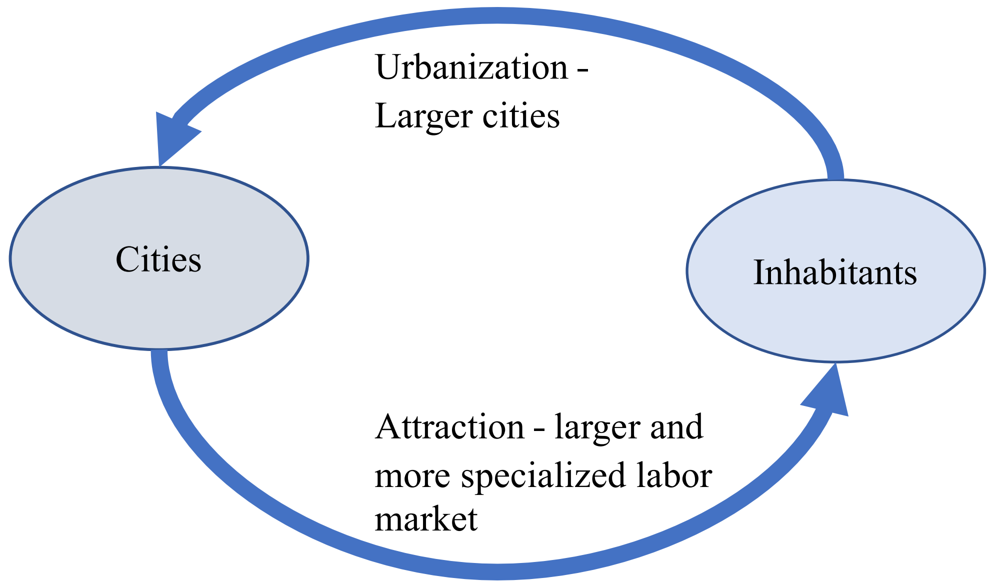

Figure 2 An illustration of a positive feedback loop resulting in a complex system

To be able to contribute to the understanding of urban growth, which is one of the central aims of this thesis, it is necessary to take a dynamic complex systems approach to the modeling and understanding of this process.
The focus in this research field of spatial analysis has traditionally been on Euclidian geometry, normal distributions, and gravitational models, a classical case is the models on the organization between different cities and the resulting pattern (Christaller, 1933), which is insufficient for studies of cities as complex systems. It is necessary to instead use new dynamic models, to understand scale-free distributions, as well as network science, and more, to be able to understand, perhaps predict, and hopefully understand at least parts of urban dynamics.

To help understand complexity, several theories and tools have been developed during the last decades. The first mathematical understanding of a complex system is the discovery of fractals. Fractals are a special kind of function in mathematics with a chaotic behavior (in the sense that they are exceptionally sensitive to input changes). They also demonstrate self-similarity on many scales, which is the definition of a scale-free or scale-independent phenomenon. It is claimed that many phenomena in nature are fractal (Mandelbrot, 1983). In the research field of urbanization, cities are often claimed to have a fractal pattern (Batty & Longley, 1994), which means that certain measures have scale-free properties. That also implies that the processes causing urban growth are of a kind that is likely to generate fractal results. All the papers in this thesis use various complex system methods, from descriptive to predictive purposes.

What these ways of addressing complexity have in common is that they are parts of a new paradigm (Batty, 2013). Complex systems internal structures are not possible to capture with traditional cause-effect analysis. They are without any intelligible central organization, rather they are bottom-up systems governed by the rules of the parts that constitute the system. Their organization emerges without any external organizing or coordinating factor. These new ways of thinking and analyzing are of such a fundamental kind that they amount not only to new theories but a new paradigm for theorizing. The key to understanding chaos and complexity is to model how the parts interact and results in a complex system, not dividing into and analyzing parts one by one. Since this thesis claims that cities must be understood as complex systems, this new paradigm is essential to understanding and answering the questions raised.

3.3 Understanding bottom-up and top-down forces in urban development

In line with the exploration of self-organization and complex systems described in the chapter before, many claims that cities are created 'Bottom-up', which means that they are self-organized and not so much a result of the central planning (Batty, 2013; Batty & Xie, 1998; Jiang et al., 2008).'Top-down' planning refers to more centralized governmental planning. To answer the questions stated about whether infrastructure induces urban growth, one must have a brief understanding of the different forces that drive urban growth.

3.3.1 Bottom-up forces

Bottom-up forces are economically driven, small-scale actors that make use of the existing road network to develop both new connecting roads (to existing highly connected ones, i.e. preferential attachment) (Barabasi et al., 1999) and develop the land adjacent to these roads (due to the increased accessibility that creates an increased potential for urban growth). It is these forces one must understand in order to simulate bottom-up urban development. The hypothesis is that all actors act in their self-interest (Levinson & Huang, 2012), which characterizes bottom-up forces.

The result of the actions of these bottom-up forces is dense land usage (the ratio between buildings to roads is high) since roads are costly, not useable for building purposes, and sometimes require more coordinated planning. The road network often becomes more organic. Another consequence of this efficient resource use is unfortunately congestion and lack of redundancy in the road network (Albert et al., 2000). This congestion and lack of redundancy often motivate the other kind of the two major forces, top-down interventions.

3.3.2 Top-down forces

Opposed to the small-scale and long-time bottom-up forces are the top-down forces; They consist mainly of societal planning of new roads and highways to avoid congestion and make the network less sensitive and more resilient. A typical example of a top-down intervention is Hausmann's reorganization and rebuilding of Paris' Street network. A historical analysis of the Paris street networks' properties from medieval organic pattern to Hausmann's intervention, that supports this hypothesis is made in paper I.

3.3.3 Is this a true dichotomy?

This categorization is according to this thesis, as well as in (Kostof & Tobias, 1991), not a distinct dichotomy, but rather a question of more or less planning interventions (or more or less self-organization). Due to its simplicity, the dichotomic description is still often used as a predominant description of city development.

This thesis rather presents the hypothesis that urban development is a balance between those two kinds of forces or drivers, bottom-up forces, and top-down forces. A city can over time move on the scale between top-down and bottom-up

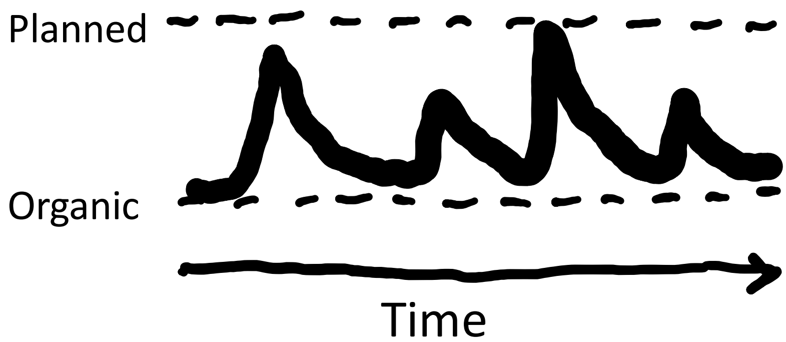

Figure 3 Cities are continuously altering between planned and organic morphology

development depending on time and other external factors, which is illustrated in Figure 3. As presented above, top-down interventions are a reaction to the results of the bottom-up self-organization, while such self-organization happens after all changes or interventions. This seesawing between those forces results in different patterns in different areas (Levinson & Huang, 2012) which is discussed in Paper I.

What happens after a top-down intervention is that this planning creates new potential for bottom-up forces in the form of new or better accessibility to new land parcels and new highly connected roads that are attractive to connect to. This potential could maybe be described as spatial capital (Marcus, 2008). In this cyclic way, the development goes on forth and reverse between these kinds of forces, creating the urban development seen. To investigate whether a city is more shaped by bottom-up or top-down forces the study in paper I investigates the pattern in streets and roads. It is claimed that the bottom-up process creates emerging scale-free properties seen in the road network (Jiang & Yin, 2014), which means that organic cities might by analogy be called fractal.

Therefore, this thesis claims that cities shaped mostly by bottom-up forces are usually seen as “organic” while cities shaped mostly or most recently by top-down forces are often seen as “planned”. A peculiar aspect is that organic patterns have been seen as desirable in cities, and therefore efforts to mimic them have often been used in planning. The discussion of what kind of urban patterns are beautiful, and desirable is a huge research topic (mainly in aesthetics) as well as a big political debate, at least in Sweden. Therefore, this thesis will not take any position on that topic.

Despite research on the topic, there are still few consistent ways of quantitatively classifying and describing the properties and characteristics of morphologic patterns regarding the level of planning. Since cities are such an important study object and this dichotomy's categorization – organic versus planned - is often used as a fundamental explanation, it is problematic that there are still few consistent ways to quantify it.

In paper I, the hypothesis is that the bottom-up forces in cities strive to reach an optimal state between road area and built area. That is the most economical way of organizing a city, given that roads are a shared cost. This is also supported in other research (Levinson & Huang, 2012)

Maybe this way of seeing urban development as driven by infrastructure development can be subsumed into an ecological approach to urban development (Holling, 1973; Marcus, 2014; Rómice et al., 2020). A suggestion for how this could look is presented in figure 2.

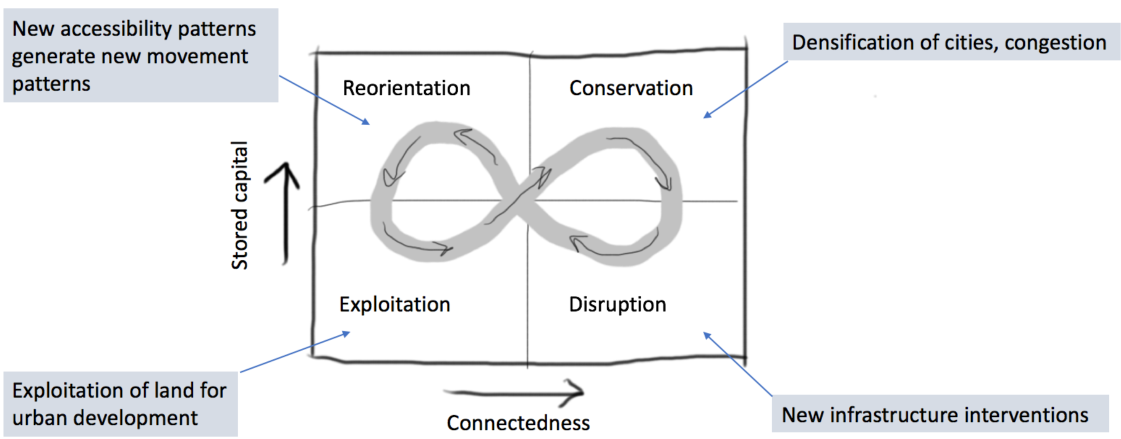

Figure 4 An ecological approach to urban development based on infrastructure development.

3.3.4 Rates of change for different elements in cities

All the elements that constitute a city, from large roads to the businesses that reside inside the buildings consociate with each other and change themselves regularly. However, the rate of change is very different for the different parts. Roads and streets tend to be in place for a very long time, from hundreds up to thousands of years. Parcels, plots, and blocks also tend to stay the same for a long time, but here the change rate can be counted in hundreds of years and sometimes shorter. Buildings can indeed stand for hundreds of years as well, but the turnover rate tends to, on average, be shorter than for plots, often less than one hundred years. Apart from interiors, which are not of interest in this case, inhabitants and businesses have the fastest turnover rate in cities (Wegener, 2004). Often their change can happen in a few years. These different rates of change are often correlated with the scale of the elements (roads and blocks are large, houses are smaller, etc.) (Rómice et al., 2020).

This has important implications for the study of cities. First, it means that one must be aware of which elements are modeled and which empirical data is studied, especially in longitudinal studies. Secondly, and more important for the theories proposed in this thesis, is that the faster changing elements tend to be reconfigured and structured among the slower elements (Rómice et al., 2020). This can seem obvious in one sense, but it implies that the interactions between land use and transport system happen at very different rates (Wegener & Fürst, 2004). Therefore, changes in the transportation system will have a long-lasting impact on land use.

3.4 Lack of theories for integrated models

Spatial modeling has a rich history but still suffers from the lack of integrated theories where the word 'integrated' denotes theories that integrate several of the systems in urban areas. Von Thünen's idea of the monocentric distribution of land value (Thünen, 1826) would be correct in principle if a city center is a point (or circle) and distance is as the crow flies. This approach requires pointing out a city center á priori, which can be questioned in modern conglomerate urban landscapes. Hansen made an important piece of work (Hansen, 1959) (How accessibility shapes land-use), which claims that it is the accessibility (travel time) that determines attractivity and willingness to pay, therefore determining different land use. The problem with this theory is that the destinations and attractions must be defined á priori.

Both these theories require a way of transportation (implicit in Von Thünen's case) and places with different (land) use that can be reached by traveling between them. Urban areas can therefore in a very simplified way be described as consisting of two entities: A transportation network, whose purpose is to create possibilities for people to interact with each other, and places, which is where the interaction happens. Urban places can be both origins and destinations depending on the usage. This interaction system between transport networks and urban places can be described mathematically as a bipartite graph (Batty, 2013).

The transportation network consists, in its simplest representation, of linear features that are connected with nodes (that represent origins and destinations and contain topological information). The modeling of the transportation network is based on travel time contained in the linear features between the nodes in the network. Methods for finding optimal ways between origins and destinations in transportation networks have been around for a long time (Dijkstra, 1959), but lack of software (and/or computational power) has been limiting usage and research until the 1990s. The origins and destinations in an accessibility or transportation model are the places where human interaction and economic activity take place, often in buildings. The land use in these places is often represented as polygons (or cells). Analyzing land use is, therefore often more problematic than transportation networks both because of the MAUP (Openshaw & Taylor, 1979) and because of the abundance of measures and definitions that often differ in time and place due to legal regulations that often differ between countries as well as varying information models. It is necessary to understand both these spatial entities to be able to model urban growth.

Modern spatial predictive models, such as LUTI models, often make use of the transportation network in combination with socio-economic and demographic data. These models can be good at prediction under certain circumstances since they are primarily built for that purpose. However, that comes at a cost; first, they need a vast amount of detailed socioeconomic and transportation data on a local level, as well as parameter tuning. Secondly, the lack of a theoretical model foundation that unites transport networks and land use makes them of less use in the research to understand urban growth. Many attempts have been made since the 1960s but they all still suffer from a lack of an elegant theoretical underpinning (Acheampong & Silva, 2015; Iacono et al., 2008). Another shortcoming is that agglomeration effects are not given enough consideration (Iacono et al., 2008).

Because the urban system consists of both places and an interaction network between them there is a need for a coherent theory that can comprehend both these entities and the interaction between them. Since this thesis aims to be able to understand and predict the effects on land use out of changes in the transportation network, a good theory on this interaction is needed both to formulate a hypothesis as well as to interpret the result of the studies. In 1979 Batty argued that a model must be evaluated both regarding its contribution to science and design (Batty, 1979; Iacono et al., 2008).

3.5 The search for new theories and models

3.5.1 The need for minimal models

Urban economics can give a decent understanding and prediction of urban development. However, the results have suffered from limited predictive power and low spatial granularity (Barthelemy, 2016; Iacono et al., 2008). The reason behind the limited predictive power can be that the focus has been on a sound theoretical framework, not just predictive power as in LUTI models (Acheampong & Silva, 2015; Iacono et al., 2008).

Agent-based models focus on predicting urban development by looking into human behavior. For example, some models are calibrated based on travel surveys. The benefit of this
approach is the increased predictive power of these models, but the demand for many parameters, choice of many assumptions as well as large amounts of data makes them less geographically generic, even though their predictive power can be good (Eliasson & Mattsson, 2000). Since this thesis aim at exploring generalized theories and having a wide geographical usage, another approach is needed.

Due to these mentioned problems, another approach is needed for future urban modelling. To address these challenges, Barthelemy (Barthelemy, 2016) proposes a new category of models that could combine simplicity and good theory basis from urban economics with the predictive capabilities of the agent-based simulations. This thesis takes that suggestion as a starting point for theory and modelling. A rough diagram of the different kinds of models is shown in figure 6.

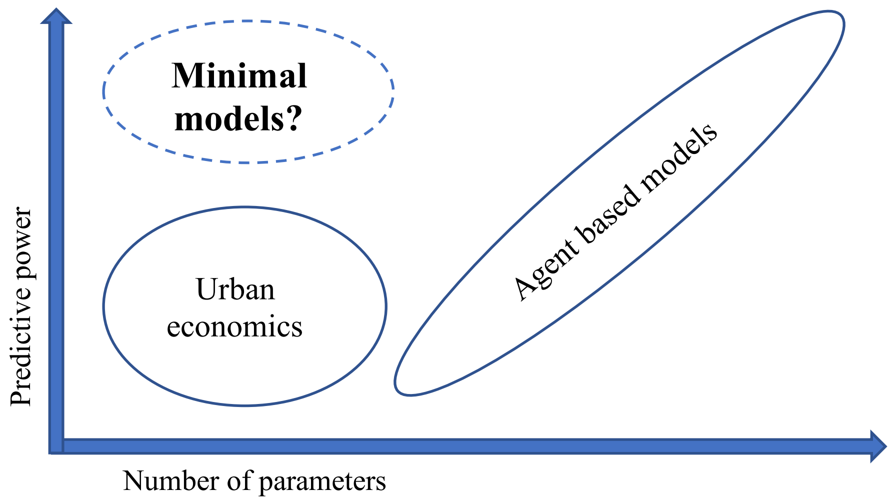

Figure 5 A suggestion for a new category of models. Adapted from Barthelemy (2016)

3.5.2 Space syntax as an example of a minimal model for urban research

Around the 1980s, Space syntax was developed to achieve a quantitative analysis of city street structures (Hillier, 1996; Hillier & Hanson, 1984). It focuses on the configuration of spaces, places, and streets, and the patterns that emerge from those relations. It is a good example of a minimal model whose results have many interesting correlations with urban phenomena. The theories are often based on ideas of human behavior in urban areas (Hillier & Iida, 2005) although that is disputed (Jiang & Jia, 2011; Omer & Jiang, 2015).

What is special about space syntax analysis of the road network is that the streets are connected over intersections and form the nodes, while the intersections are the edges, connecting the roads or spaces. This transforms the road geometry into a topological network. It is contrary to the traditional transport analysis (Porta et al., 2006a). When the transformation from geometry to topology is made with streets as nodes and intersections as edges (the dual graph), a scale-free pattern sometimes occurs (Porta et al., 2006b).

One good use of space syntax is that one can look at the probability distributions of degree (or some other network properties) for all the streets that are subject to the analysis. There are far fewer well-connected streets than less-connected ones. There are far more streets with less betweenness than streets with high betweenness. Based on this progress in space syntax and complex network analysis in general, new theories and methods for describing and understanding road and street network patterns have been developed within the research field (Batty, 2004; Jiang, 2007; Jiang 2015; Jiang & Claramunt, 2004; Jiang et al., 1999; Jiang & Jia, 2011; Jiang & Liu, 2009; Jiang et al., 2008; Lämmer et al., 2006; Omer & Jiang, 2015) (as well as Paper I in this thesis) which focus on understanding the road systems as a whole, not to study single roads in relation to their context. These analyses use the results from a space syntax analysis and thereafter analyze various properties, both individual measures, and statistical distributions.

4 Methods, models, and data sources used in this thesis

This chapter is listing the different methods, models, and data sources that are used in this thesis to address the research questions on how we can understand, predict, and prove that infrastructure interventions have an impact on urban land use.

A point of departure in this research is that urban development to a large extent is understood by studying the spatial structures of cities. New road infrastructure is an external force, but it is based on the existing urban fabric. So, to understand urban development and its driving forces according to this thesis, it is necessary to have a model of spatial urban form including a theoretical foundation, along with adequate methods to capture the complexity of urban systems. The general hypothesis of network-based urban growth is illustrated in Figure 6

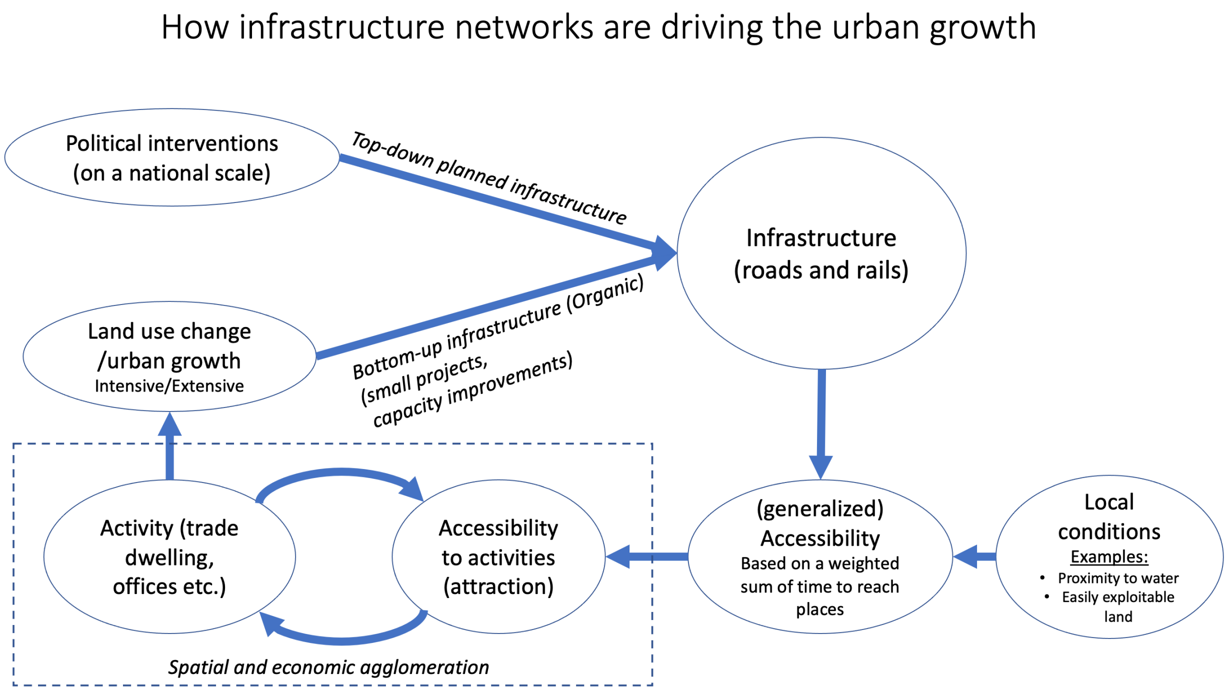

Figure 6 A suggestion for how the urban development process between transport infrastructure and land use, (inspired by Wegener)

4.1 Space syntax as a minimal model for complex systems approach on urban transportation network

Space syntax is a useful minimal model, which in this thesis is used to understand historical urban development. It is used in a less common way, in that from the space syntax analysis of all streets, the resulting probability distribution from all streets is analyzed and compared with other cities and other points in time.

These measures that are used in Paper I is a first attempt to understand the slow urban growth process, both organic bottom-up growth as well as growth stemming from top-down interventions

By using these elaborations in the space syntax research field, thanks to the network science and complex systems field in general, this thesis suggests a new way of quantifying some measures of urban growth.
Paper I claims that the pattern shown in the space syntax analysis can indicate where in the urban growth process the area (city) under analysis is. That could enable even further analysis of urban growth throughout history but are out of scope for this thesis.

4.2 Spatial and economic phenomena to explain land-use

To understand various land use and intensification of land use resulting from changes in infrastructure networks, there is a need to understand the concept of accessibility as well as agglomeration and the interplay between them.

4.2.1 Accessibility

In this thesis, unless specified elsewhere, accessibility is used in a generalized form as the sum of access from one place to all other places in the network. Accessibility is a multifaceted word. It means access to something, often an attraction (El-Geneidy & Levinson, 2006; Jiang et al., 1999; Levinson et al., 2005). It was brought into the context of urban planning by Hansen (Hansen, 1959) who investigated the impacts of accessibility on land use, where he defined origins and destinations a priori. However, to make a realistic approach on today's complex urban landscape this thesis takes the whole transportation system (in entire regions, as demonstrated in paper III and IV) into account. This thesis agrees with Hansen's statement that accessibility shapes land use, but unlike Hansen, accessibility does not only mean single distances to certain destinations but a (weighted) summary for each place in an interaction network, to all other places in that network.

4.2.2 Agglomeration

Agglomeration is a phenomenon in cities that was already investigated in the 1920s (Marshall, 1920) but later brought back into focus by the 'new economic geography' paradigm (Fujita et al., 1999; Krugman, 1996). As indicated by that research, it plays an important part in urban economy and growth, and therefore needs to be included in a model of urban growth. It is a phenomenon that consists both of economies of scale as well as network effects. This thesis claims that agglomeration is tightly bound to a spatial context, which also has support in earlier research (Duranton & Puga, 2004).

In Paper II and III, agglomeration effects are studied by varying an agglomeration parameter and comparing the outcome with empirical data. The results show that agglomeration effects are necessary to include in such a minimal model to reach a satisfying degree of covariance with the empirical data.

4.2.3 Intertwined phenomenon?

A central argument in Paper II, III and IV is that the accessibility provided by the transport system together with agglomeration shapes urban land use. By testing a model of accessibility and agglomeration against empirical data, it is investigated to which extent these two entities can explain land use. This thesis also claims that it is (with today's models) not possible to disentangle the effects of agglomeration and accessibility, they are intertwined in the urban development process.

4.3 Study designs

Cross-sectional studies in the field of urban research are easy to do, just as they often are in other research fields. What is problematic is the single point of time for all data, which makes it hard to determine causality. It is also often hard to find confounding variables. The papers I, II, and III are made with cross-sectional analysis, although a part of paper I is a small study on some temporal data of street networks. However, a necessary criterion to claim causality is to do longitudinal analysis (Anselin, 1988).

Geographical data and studies very rarely have the possibility to do randomized controlled trials, (which is the golden standard for inferential statistics and a powerful tool to find confounders), due to the difficulties of setting up experiments that are isolated from the rest of the world (van de Coevering et al., 2015). Therefore, we must use other methods to infer causal relations.

One attempt at achieving knowledge is to set up a model of how a certain thing would evolve, without any interference. And then to find cases of interferences and interruptions, which can be used as the do operator in do-calculus (Pearl & Press, 2000), thus testing if the counterfactual reasoning holds. Common methods for this are DID, ITS, and IV among others. Unfortunately, a useful instrument could not be found in any of these studies.

In Paper IV the methods of DID and ITS are used to try to prove a causal relation. It can therefore give stronger support to the theories of urban growth presented in this thesis. Paper IV uses a kind of longitudinal study, an interrupted time series analysis. That is looking into some phenomena before and after a quick and crucial change in something (accessibility, in this case, caused by replacing a ferry with a fixed link).

4.4 A suggestion for a new model with a coherent theoretical underpinning

A solution to the shortcomings presented in 3.5.1 could be to find a new minimal model with retained scientific value. One attempt to develop a minimal model is presented and tested in papers II and III, and then tested in an empirical longitudinal study in paper IV

The model can simply be expressed as a recursive algorithm that aims to predict urban economic activity:

$$a_j = \left(a_j + \alpha R_j\right) \sum_i \frac{a_i f(c_{ij})}{\sum_k (a_k + \alpha R_k) f(c_{ik})}$$

Where a_j is the urban activity, α is the agglomeration parameter, R_j is the local characteristics of a location and $f\left(c_{ij}\right)$ is a function representing the decay of interaction dependent on the generalized transportation cost c_{ij}A convergence criterion is set to reach a steady state of the distribution of activity.

It is derived from a similar theoretical foundation (eigenvector centrality) as Google Page Rank (Brin & Page, 1998) and Place rank (El-Geneidy & Levinson, 2011) also is. Opposed to Page Rank it includes agglomeration effects, thus making it preferential. That in practice means that the distribution of urban activity seen as a section through a city has a higher kurtosis than in many other models. The activity is more concentrated in central areas compared to what an eigenvector model would suggest.

A model such as this one (presented in papers II to III) could be a building block in a future theory of the interaction between transport systems and land use (including agglomeration effects).

4.5 The problem of finding, collecting, cleaning, and validating spatial data

4.5.1 Finding and using model network data

Urbanization is a process happening globally in heterogeneous systems of planning and control. Together with the varied availability and quality of data sources, this poses a huge problem when creating globally valid predictive models. General and simple models using data that is readily available for most countries, would make it possible to predict urbanization and its consequences in the transformation of land use.

The first paper's research relies on finding road network data for many very different cities around the world. To make such a worldwide comparison, such a common data source needs to have the same kind of data classification and collection process. Publication restrictions and copyright issues make usage of official land surveys or proprietary navigational street data (e.g. TomTom, Navteq, Google) hard.

4.5.2 The paradigm of big data and volunteered geographical information.

To counter these problems and test a new research approach, Open Street Map (OSM) was used as a source for the street networks (© OpenStreetMap contributors). Papers II, III and IV could have used readily available national road databases, but to simplify the research procedure and to be able to do comparisons between countries, OSM was used in them as well. One can say that a necessary component in this thesis was the usage of freely available big data such as OSM. OSM is an initiative to create public domain map data. It is open for anyone to edit and create new features on the map. It has worldwide coverage, although the level of detail might differ between different areas. It has shown to be on par with other geographical data regarding the quality (Haklay, 2010). For all papers, OSM was used to make the different studies easy to compare with other studies. There is also a module for importing OSM (Boeing, 2017) built into the model software which makes it convenient and quick to use.

4.5.3 Finding empirical validation data

To test and validate the model proposed in papers II, III and IV, it is necessary to compare it to the real world. That is done by using various empirical data in statistical analysis, to investigate the found correlation between those two. These empirical datasets are used as indicators of urban land use since the proposed model is aimed at predicting that. Many empirical data sets can be used in this comparison, and there is no consensus on which kind of data is the best one. The choice of empirical data is limited to the available data, and the presence of historical data series is found to be quite sparse. Another question is to which extent the empirical data chosen reflects the extensive and intensive urban land use. The empirical validation data for papers II and III were provided by The Swedish national land survey and the Swedish national tax agency. In paper IV, the empirical data was collected from Statistisk Sentralbyrå (SSB, 2021).

5 Discussion and Conclusion

To sum up the results and their further implications, this chapter will discuss the results related to the aims and research questions to come up with a conclusion that can lead forward and raise other questions to develop this rich research field.

5.1 Time scales and equilibria

Urban growth is a slow process since many of the components in it are slow as mentioned in the previous chapters. First, there is a need for political decisions, then it sometimes takes years for plans to be accepted. Further, it takes several years for the planned things to be built. The question of whether infrastructure investments have effects on urban land use and if we can predict and understand them requires a careful selection of what we measure, in which time and to use methods that can handle temporal data.

The model proposed in Papers II and III can be said to do a prediction of how the urban landscape would be, all other things being equal, and enough time has elapsed so that all attractive and exploitable places are being developed and all people, as well as firms, have moved into place. That could be called a state of equilibrium.

This equilibrium will not happen in practice since most urban places undergo constant changes, so the (and any!) proposed model will not be true for any case. It will always be a little bit wrong since the long time required to reach that equilibrium state is never reached before other faster changes occur. Therefore, the proposed model in paper II, III, and IV is not expected to reach extremely high predictive power (closer to 50% rather than 100%). Likewise, the results of the analysis proposed in paper I will never be unambiguous.

However, in the study made in paper IV, it is possible to see that the effects of fixed links (bridges and tunnels instead of ferry connections) appear as a steady slope of the urban growth index line. That is also an indication that the systems do not, at least for the studied time, reach equilibrium but strive to do that. It is also the reason why the study in paper IV focuses on growth (or stagnation or decline) rather than the probably non-reachable state of equilibrium.

5.2 Predicting and understanding urban growth.

Some attempts to describe, predict and understand urban growth have been made in this thesis. Using a complex system approach to this understanding of cities, more specifically their infrastructure-induced growth, seemed to work well overall.

A dynamic adaptive complex urban system is by definition not possible to entirely predict since predictions (and the following stakeholders' actions) will affect the model outcome. But as shown in this thesis, there is a possibility to model equilibrium states that land-use distributions seem to "strive" to reach, although they still are likely to suffer from errors due to predictions and speculations, for instance, land markets that adapt to predicted rises in prices on land that will gain from increased accessibility by infrastructure investments.

The process of infrastructure planning is slow, although land use planning and exploitation is a little bit faster process. However, the results reached in the studies indicate that a model of an urban system can reach quite high predictive capability (roughly >50%). But the predictive capability will probably never be much higher than in these studies since a model is, by definition, a simplification of reality (and therefore never 100% correct). With respect to the above discussion on equilibria one also can raise the question of what we try to predict; Demand for land, land prices, opportunities, or the "final" built environment. With support in paper I and earlier discussion about top-down and bottom-up forces, can it be that cities strive to reach an equilibrium (organic) but are often interrupted in their process and respond to that by trying to reach a new equilibrium?

The limited predictive power of the proposed model compared to more detailed models is a drawback, but as this thesis has shown, these kinds of minimal models are a lot easier to use, both regarding data requirements, and parameter estimations as well as when it comes to understanding and give a theoretical explanation of urban development in a concise way. Therefore, they are likely to be useful in the practice of urban and transport planning in the future.

5.3 Can we say how infrastructure interventions cause urban growth?

Well, maybe. More research is needed, theories need to be further supported and more counterfactual experiment situations need to be found until we can with a certain confidence claim that new road investments cause urban growth.

However, this thesis has contributed to this question in several ways, such as providing a sound and simple theory, showing that growth happens after road investments and that there is a (non-linear) correlation between new roads and urban growth. What is left to establish this causal link is to prove that this correlation is not spurious. This in essence means that no unknown and unhandled confounders may exist, since they could be the "real" cause behind both the other phenomena. But it is impossible to prove the absence of confounders, it is just possible to try to find them and if that fails, we can be more certain that they do not exist (Popper, 1962). Some kinds of experiments (Such as RCT) are very good at revealing and excluding confounders, but with this kind of empirical data in these research fields, those revealing forms of experiments are impossible. We therefore must continue the search for alternatives (such as DID, IV, ITS, and natural experiments) and test this hypothesis to make it more and more probable.

5.4 Which implications can these results have on urban planning and its actors?

As shown by the papers of this thesis, it seems like large parts of the land-use distribution in urban areas, in the long run, are determined by the extent and structure of the transport system. That makes the situation for urban design and planners, architects, as well as other land-use planners tricky. There is often a lack of knowledge among them on how infrastructure projects transform cities and how various (often market) forces utilize the potential created by these infrastructure projects. Architects and urban planners are here faced with strong (bottom-up) market forces and an agenda for land-use and development strongly driven by good access to land, which typically is what new road infrastructure creates.

To be able to do land-use planning in both the short and long term, it is necessary to understand all forces acting in the development of land. That means that to be able to plan, develop and build the cities, neighborhoods, and buildings we wish to have, we must understand both, bottom-up and top-down forces acting on city development. To only put focus on land use would probably be problematic since spatial accessibility seems to have so large influence on the usage of land and transport patterns.

However, even if the results of this thesis indicate that urban growth to a large extent is driven by transport infrastructure, it does not imply that the transport infrastructure planners are aware of the results of their interventions. It is more probable that transport infrastructure planners in general are uncertain about the unintended effects of their work. These uncertainties are rather explicitly admitted in the latest infrastructure plan for Sweden (Trafikverket, 2022).

This partitioning into road planners and land use planners has caused the peculiar situation today that land use and urban development can be said to be to some extent driven by road authorities and states whose intentions are not to drive any land use and urban development. There have been suggestions that this situation has been caused by the phenomenon that planners and researchers are caught in their current paradigm (Hagson, 2004).

To be able to reach the goals in both transport and urban (land-use) planning, there is a need to take a comprehensive view of land-use planning and infrastructure development together, not just planning the various parts in the various professional categories as often done today.

5.5 Future research and development

There is an obvious need for more research regarding minimal models for predicting urban growth and understanding the interaction between transport systems and land use since that could be useful for planners to predict urban development. This area is a new and promising area of research.

Perhaps some qualitative research and comparisons of the different planning paradigms (roads, rails and land-use) could give more insight into and knowledge about the different forces governing the development of cities. That could be useful for planners to understand their different roles and possibilities to influence urban development.
There is also a need for more research regarding the theoretical underpinnings for modeling of the interactions in cities between transport systems and land use. This is particularly hard due to the different rates of change, which not only complicates the theoretical framework but also makes empirical studies harder.

Not only is there a knowledge gap between this research field and practice, but also a lack of easily usable and simple tools. This thesis has tried to lay the foundation for knowledge and tools for a better understanding of infrastructure impact. A minimal model like the one suggested and tested in papers II, III and IV could be further developed to be easy to use in urban and transport planning. The low requirements for input data and parameters could make the use of such a tool an attainable task for many different kinds of planners, compared to today's tools that often require specialist knowledge to handle and use.

This thesis can hopefully contribute to urban planning and design in several ways. First, it could give some understanding of cities as complex systems and that the system can respond and behave in unexpected ways. Then it might serve as an inspiration for further development and testing of predictive minimal urban models, building the theoretical underpinnings of such a model and proving the causal relation behind the prediction. Finally, it could serve as a help for the different politicians and actors in community planning to understand the current impact of their plans and their possibilities to make the desired changes.

6 Appendix: Summary of the papers

Paper I is investigating several cities around the world to understand urban growth and the characteristics of urban road networks. It is shown that cities considered to have “organic” patterns of growth also have the sign of a complex network, while in the cities with many large infrastructure investments, that pattern is not present. The purpose of showing this is to underpin that the transportation network is the slowly changing skeleton that can shed light on a city’s development. It is also the purpose to understand the driving forces in urban growth, that there are top-down as well as bottom-up forces that drive the urban development together.

Paper II is an attempt to create and validate a new minimal predictive model for urban development on a city scale. The model does not only serve as a predictive model, but it also attempts at explaining the process of urban development by using the concepts of accessibility and agglomeration as an explanation. It uses land taxation value as an empirical proxy for urban activity since that value does not have a theoretical limit (which could be a problem with a preferential model). The model does a good prediction of where the city center is located and gives a quite good similarity between model predictions and actual land values. To make the regression valid (BLUE) (Anselin & Rey, 2014) it was necessary to use a spatial error model, which is a strong indication of more processes going on than the simulated one. It could also be that different areas have not reached equally far toward the equilibrium state or that there is speculation of future land-value changes reflected in the taxation value. Since building infrastructure is such a slow process, that is expected.

Paper III is further research on this predictive model, scaling up the prediction and validation to entire regions. The conclusion is that the model performs quite well in predicting land values over large areas, which is the urban indicator used as a benchmark for urban growth. The results also indicate, by needing a spatial error model to be a valid regression, that there are, just like in the previous paper, some unknown phenomena that are not captured in the model. This unknown part of the regression model seen is not large though. Another interesting finding, which was anticipated, is that the model is successful at predicting polycentrism in an urban landscape. This solves both the earlier need to á Priori define a city center as well as get away from monocentric models.

Paper IV is an interrupted time-series study of this predictive model in another context than the two previous papers. This one is studying the population growth on several islands, some close to bigger cities and some far away in rural areas when they get a fixed connection to the mainland (instead of ferries). It is built on earlier research (Andersen et al., 2018; Andersen et al., 2016; Gutiérrez et al., 2016;

Tveter et al., 2017; Welde et al., 2019) and try to take off from that research and further explain the phenomena that all of the islands do not grow equal after a fixed link is opened. This paper aims to further strengthen the predictive model presented in papers 2 and 3, as well as investigate whether the theoretical description of the model is sufficient to understand urban development and growth

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